

Response to Reviewer 2 Comments:

Blowing snow detection from ground-based ceilometers: application to East Antarctica

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For clarifying our answers to the referees' comments, the following scheme is used: comments of the referees are denoted in **bold**, our answers are denoted in black and quotes from the revised text are in *italic*. Please note that reference to figures in the answer refer to the original manuscript, or to the improved figure displayed in the Response document. Figures referenced in the italic text are relative to the new manuscript.

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General comments: The calibration of the ceilometer remains an issue and I wonder if it will be possible. This is important since the use of a ceilometer would start to be relevant for blowing snow studies if a quantitative retrieving of blowing snow characteristics (height of the blowing snow layer, amount of transported snow) may be done. Is it the intention of the authors to perform such a calibration in the future? This point must be considered in the discussion and the conclusion in order to advice the reader about the potentialities and weaknesses of the study. Nevertheless the paper represents a sufficient amount of work to be published. To my opinion the technical description should be improved for a TC reader, especially a modeller. In fact there is too much or not enough. An alternate possibility should be to shorten the technical description and to do it in an other more specialized journal. I had difficulties with a double meaning of some sentences (see specific comments below).

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Thank you for your comments, we have replied to each of the comments below.

Calibration of the ceilometer to quantitatively retrieve the amount of transported snow is indeed an issue, as this can not be derived from the ceilometer attenuated backscatter signal. With the current instrumentation this is not possible. Furthermore, we derived a blowing snow algorithm for instruments already present at Princess Elisabeth station. Lidars can be used to define the lidar ratio, but these instruments are (1) more expensive and (2) less abundant than ceilometers. Even after ceilometer

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calibration, the amount of transported snow can not be derived from particles properties only. We would require to estimate the transport rate also.

We present here our novel BSD algorithm, designed to retrieve blowing snow events, but not drifting snow, from ground-based remote-sensing ceilometers. Ceilometers can retrieve the presence of blowing snow, but other properties such as size, shape and density measurement is only possible if the ceilometer is calibrated, which is very challenging for such a remote location, and not done in this paper.

The algorithm has been adapted to derive precipitation/cloud occurrences from the ceilometer profile directly, and the new version of the paper contains an improved technical description of the algorithm (containing the bin numbers and threshold values, text below), together with a scheme of the concept of the blowing snow algorithm (Fig.1 below, Fig. 5 in the new manuscript).

The approach used for the blowing snow detection (BSD) algorithm is similar, but there is no wind speed criterion in our analysis. In addition, the ceilometer is ground-based, allowing the detection of blowing snow during overcast conditions. The algorithm method is displayed in Fig.5. To detect blowing snow, the intensity of the backscatter signal at the lowest usable bin must exceed a certain threshold (section 3.3), and the intensity of the signal must decrease in the next range bins indicating a particles density greater in the lower levels than at the top of the layer. As previously highlighted, clean air molecules cannot be distinguished because the signal associated with it is smaller than the noise generated by the hardware (Wiegner et al., 2014; Kotthaus et al., 2016) and by the background light (Vande Hey, 2015), polluting the signal in the lowest bins. To distinguish the presence of scatterers (aerosols, blowing snow particles, cloud particles...) present in the atmosphere from these artifacts, we need to investigate the signal intensity representative for cloudless conditions. I.e., the average β_{att} of the second range bin received by the ceilometer during scatterer-free conditions. Clear sky days are manually selected for the whole period using the daily quicklooks (Fig.1) and are days where the quicklook background is uniform and without precipitation or clouds, and where the time series of the signal in the second range bin is stable around a low value (corresponding to hardware and background noises), to avoid low-level disrupting signal. Next, we compute the 99th percentile of all clear-sky β_{att} signal in the second range bin as threshold value (for calculation, see section 3.3). As such, it is representative of the presence of scatterers exceeding the value for clear sky. Since the noise is instrument-dependent, individual pre-processing and thresholds have to be defined for each instrument the BSD algorithm is applied to.

After comparing the backscatter signal in the second range bin to the clear-sky threshold, the BSD algorithm investigates the shape of the β_{att} profile. A regular clear sky ceilometer profile (signal intensity versus height) does not show intense vertical variations (Fig.6): in the infrared, the transmission term is close to one and decreases only slightly with height. This implies that any important variation in the β_{att} signal can be attributed to the particles backscatter. The blowing snow and blowing snow with precipitation lines in Fig. 6 shows a typical sharp decrease until bin 8-10 (75 - 95 m height), above which the signal keeps decreasing steadily (blue line): this is the signature of clear sky blowing snow. The red profile, on the other

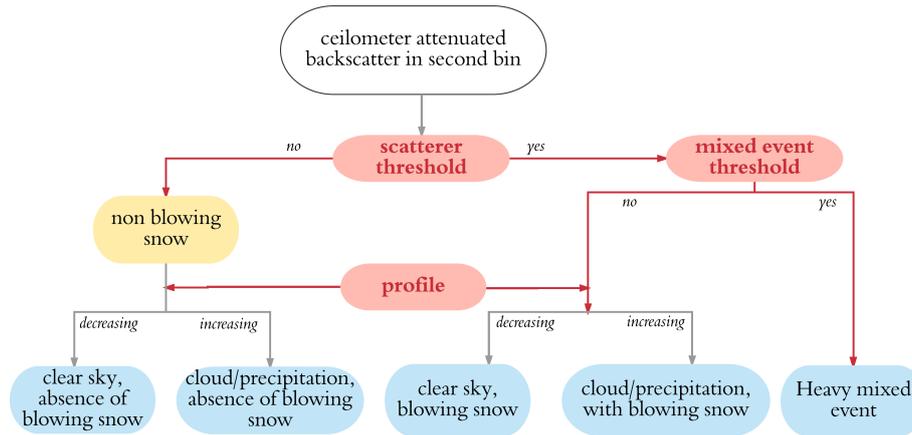


Figure 1. Chart of the blowing snow detection method

hand, shows a re-increase in intensity around the 15th bin (145 m height), overlying the blowing snow signal: this indicates the presence of scatterers interpreted as precipitation (denoted by the arrow on the graph). If there is no blowing snow while precipitation is present, the profile does not decrease prior to the increase at higher levels (black line in Fig.6). The algorithm therefore investigates the shape of the profile in order to detect blowing snow. A condition is set, that a blowing snow profile implies that the mean of the overlying bins 3 to 7 (25 to 65 m) must be lower than the signal in the second range bin (15 m). In this way, the discontinuity, as described in section 3.1. (visible in Figures 1 and 6 between 35 and 45 m), is not affecting our retrievals. In order to detect blowing snow occurring during clouds or precipitation, the profile shape is analyzed to identify a second increases in the signal intensity above the 7th bin (65 m height). A clear differentiation between clouds or precipitation cannot be made on the basis of the ceilometer alone, but the presence of clouds and/or precipitation can be identified. This analysis is carried out for both blowing snow and the absence of blowing snow measurements. The information retrieved from the Micro Rain Radar (hourly precipitation rates) is collocated to ceilometer blowing snow detection, to determine the time (in hours) since the last precipitation event at PE station.

Inherent to this profile-based method, the detection of blowing snow during precipitating events is limited to cases when the blowing snow signal is preserved close to the ground. In case of precipitation associated with storms, there is always blowing snow due to the high wind displacing the snow, and no distinction between precipitation and blowing snow is possible, as the ceilometer signal is entirely attenuated near the surface (Gorodetskaya et al., 2015), it is not possible to get signal in the overlying bins, and the profile of the backscatter intensity might not decrease upwards. Such intense precipitating events mixed with snowfall are identified as having a second bin signal higher than $1000 \cdot 10^{-5} \cdot \text{km}^{-1} \cdot \text{sr}^{-1}$ (threshold adapted from Gorodetskaya et al. (2015)). In those cases, the events are classified as a mixed blowing snow event, and the profile analysis is eluded by the algorithm.

In addition to the detection of blowing snow, the BSD algorithm quantifies the height of the layer (see Fig. S3, supplements) This is done as follows; if the profile decreases steadily (indication of absence of precipitation), the range gate at which the

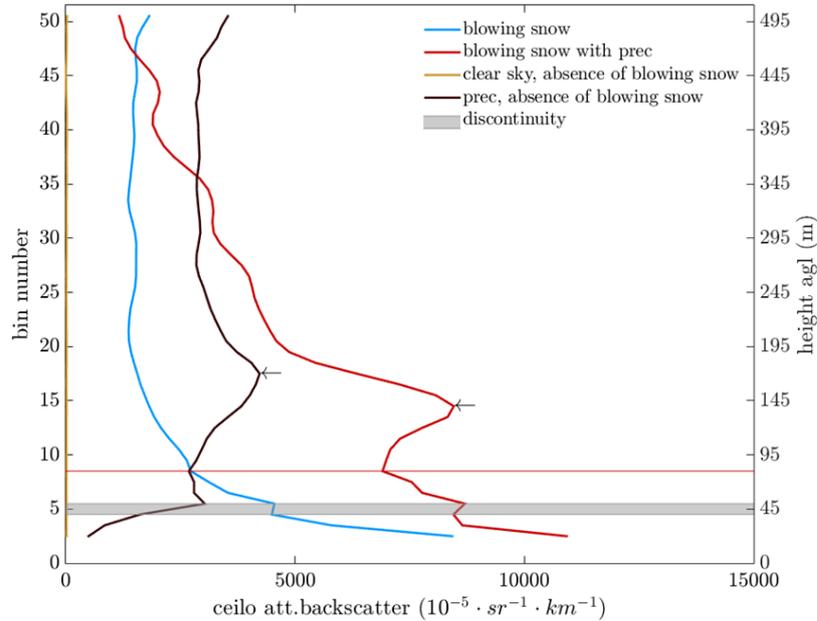


Figure 2. Different types of profiles relevant for blowing snow measured by the ceilometer at PE station: blue line - typical blowing snow signal with no precipitation nor clouds (24-04-2016); red line - blowing snow overlaid by precipitation (10-02-2016); black line - precipitation with no blowing snow (10-02-2014); yellow line - near-zero signal for clear sky conditions (24-04-2016). The height above ground is indicated on the right axis and the corresponding bin number on the left axis. All profiles exclude the lowermost bin, and start at the second bin (15 m agl.). The grey lines represent the discontinuity between bins 4 and 5 (35-45 m). The arrows indicate the presence of precipitation.

intensity of β_{att} drops under the clear sky threshold value is the top of the layer. Anything above this height is considered clear sky. If there is precipitation or a cloud during the blowing snow event, the shape of the backscatter profile does not decrease monotonously, but shows an increase in higher levels. In that case, the range gate at which the profile increases again is the top of the blowing snow layer, and the base of the cloud and/or precipitation (around the 7th bin in Fig.6, for the black and the red profiles). Layer height definition is illustrated in Fig. S3 in the supplements.

1 Question 1: p. 2, line 5. : the word “suspension” is defined here but is not used in the rest of the paper (see e.g., line 18 p.7), so that its introduction here is not clear.

Indeed. I have re-worked this part of the introduction.

10 This phenomenon occurs approximately on 70 % of the Antarctic continent during winter (Palm et al., 2011) and snow is transported as "drifting snow" (if the vertical extend of the layer is lower than 2 m), or as "blowing snow" (layers more than 2

m height). These transport involve a mix of suspension and saltation transport modes (Leonard et al., 2011), with a dominance of saltating particles (Bagnold, 1974) in the case of drifting snow, and suspended particles in blowing snow layers (Mellor, 1965).

2 **Question 2: p.2, line 24, note that the precipitation process is also poorly constrained in Antarctica so that the**
5 **authors have to face to one equation on SMB with at least two unknowns: precipitation and snow erosion by the**
wind.

Indeed, although there are products available such as stake measurements (SAMBA dataset (Favier et al., 2013), and observations from the Cloudsat satellite (Palermé et al., 2014)) which allow precipitation estimates on large areas over the continent. In addition, at the Princess Elisabeth station, we have a micro-rain radar that enables to measure precipitation rates. Erosion by the
10 wind is much more difficult to predict there, and is treated as a residual term, containing all the uncertainties on the other terms.

*Currently, simulations of the AIS SMB are highly uncertain since both precipitation and blowing snow processes are poorly constrained and probably lead to inconsistencies between the atmospheric modeled precipitations and the measured snow accumulation value (Frezzotti et al., 2004; Scarchili et al., 2010; Groot Zwaafink et al., 2013; Gorodetskaya et al., 2015; van
15 de Berg et al., 2005).*

3 **Question 3: p.3, section 2. What are the altitude of both stations PE and Neumayer. Is their climate (e.g., SMB, summer temperature, ...) different? This will help the reader when considering the development of the BSD by using observations at Neumayer and using it for another location.**

A table has been added in the new manuscript (Table 2), presenting the climate at both stations (see Table 1 below).

20 PE station is located on Utsteinen ridge, 1392 m a.s.l. and 173 km inland. Neumayer station is located on the ice shelf at 43 m a.s.l. Their climate is indeed different. Neumayer is subject to higher wind speeds ($9 \text{ m} \cdot \text{s}^{-1}$) than PE station ($5 \text{ m} \cdot \text{s}^{-1}$) and higher relative humidity. PE is located further from the ocean, and is shielded from the katabatic winds by the Sør Rondane mountains. Accumulation is lower due to the distance to the coast. Surface temperature are similar, around $-16 / -17 \text{ }^\circ\text{C}$. For extended information on Neumayer III and PE meteorology, see König-Langlo and Loose (2007) and Gorodetskaya et al.
25 (2013).

4 **Question 4: p.3, section 2.1. An introductory sentence stating that the ceilometer was not initially set up for measuring blown snow events would clarify the section. More generally the description here should contain more information related to a possible use of the measurements for a determination of blown snow characteristics.**

Indeed, although it is already stated at the end of the introduction (previous section), the paragraph has been adapted accordingly. The ceilometer measurement can not be used to determine anything else than blowing snow occurrence. Quantification
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Table 1. Climatic conditions at Princess Elisabeth , and Neumayer III stations. For extended climatology, see Gorodetskaya et al. (2013) for PE station and König-Langlo and Loose (2007) for Neumayer station.

variable	Princess Elisabeth	Neumayer III
coordinates	71 °57' S; 23 °21' E	71 °56' S; 23 °20' E
distance from the coast	173 km	approx. 7 km
elevation	1392 m asl	43 m asl
average air temperature	-18 °C	-16 °C
average wind speed	5 m · s ⁻¹	9 m · s ⁻¹
average wind direction		
• synoptic disturbances	90 °to N	100 °to N
• katabatic conditions	180 °to N	170 °to N
relative humidity	56 %	90 %
pressure	827 hPa	986.5 hPa

of blowing snow displacement, and the determination of blowing snow properties such as particles density, shape or number can not be derived from the ceilometer attenuated backscatter signal.

Initially set up to measure cloud base height, ceilometers are rather simple and robust instruments. The algorithm described in this paper was built to derive blowing snow occurrence from the signal received by these devices.

and section 2.1.

The quantitative information that can be derived from the ceilometer measurements, is the attenuated backscatter intensity at defined heights (Wiegner et al., 2014; Madonna et al., 2015). Other properties such as optical depth, size and density would require to know the lidar ratio, and a reliable estimate of lidar ratio is complicated (Wiegner et al., 2014). In addition, this is only possible if the ceilometer is calibrated, which is very challenging since the signal to noise ratio has to be large enough in the troposphere (Wiegner et al., 2014) and is not done in the present study. This implies that quantification of blowing snow displacement, and the determination of blowing snow properties such as particles density, shape or number can not be derived from the ceilometer attenuated backscatter signal at Neumayer III and PE stations

5 Question 5: p.4, line 1. : what is the raw resolution in time of the ceilometer?

The reporting interval is of 2 s. This is stated in Table 1 in the original manuscript, and the sentence has been removed, for clarity.

6 Question 6: p.4, line 2. : “spatial resolution”: do you mean “vertical”?

Yes indeed. The sentence has been adapted accordingly

5 *The ceilometer measures continuously and the standard output, β_{att} is displayed in a time-height cross section, with a 10m vertical resolution and 15 s temporal resolution.*

7 Question 7: p.4, line 20. : please indicate for each instrument which measurement you intend to use in the paper, especially concerning the infrared pyrometer (see also p.6, line 2 where it is not said there for which purpose the cloud base height deduced from the brightness temperature is used). As for the next comment it is preferable to describe the use of an instrument in a single paragraph.

10 The cloud base temperature is used as a near-atmospheric variable. In the case of blowing snow, the measured cloud temperature is actually the blowing snow layer temperature. It was used in the cluster analysis, and in the PCA. However, it was not a determining variable. This information is left out in the new version of the paper. Only the micro-rain-radar is used to retrieve precipitation rates, in addition to the meteorological variables measured by the automatic weather station.

15 *The Metek vertically-profiling precipitation radar, set up since 2010, enables to retrieve snowfall rates, using the return from the vertically profiling Doppler radar operating at a frequency of 24 GHz.*

8 Question 8: p. 5, lines 4-6. The ceilometer is described twice. Please rearrange the text.

The text has been rearranged accordingly.

20 *A cloud and precipitation observatory was set up on the roof of the station (approx. 10 m above the ridge) during the summer season of 2009-2010 and is still operational under the Hydrant/Aerocloud project (www.aerocloud.be). The observatory contains an automatic weather station (AWS) and a set of ground-based remote sensing instruments. The observatory was designed to be operated year-round, including the winter period when PE is unmanned. The station and the set of instruments are controlled remotely via a satellite connection.*

25 *The Vaisala CL-31 ceilometer (firmware 1.72) was installed on the roof of the station in December 2009 and is operational at present. It emits laser pulses at central wavelength of 910 ± 10 nm at 298 K. The measurement vertical resolution is set to 10 m and the reporting interval on 15 s. Several outages of the energy provision system limit the data mainly to Antarctic summer season (December to March is best represented). Only one year of continuous measurements was achieved (2015).*

30 *The Metek vertically-profiling precipitation radar, set up since 2010, enables to retrieve snowfall rates, using the return from the vertically profiling Doppler radar operating at a frequency of 24 GHz. The raw Doppler spectra is post-processed following Maahn and Kollias (2012), to calculate radar reflectivity profiles which are then linked to snowfall rates using the newly*

developed Ze-Sr relation for PE by Souverijns et al. (2017) and has a sensitivity up to -14 and -8 dBz (Souverijns et al., 2017). A full description of micro-rain radars can be found in Klugmann et al. (1996) and the radar set up at Princess Elisabeth is described in Gorodetskaya et al. (2015).

The monitoring of the instruments set up on the roof of the station is done via a webcam. Specifications of the instruments are given in Table 2 (see also Gorodetskaya et al. (2013, 2015)).

9 Question 9: p.5, lines 8-9. Please clarify the description of the MRR.

The description of the MRR has been adapted, and references to MRR description (Klugmann et al., 1996) and the specific radar set up at PE (Gorodetskaya et al., 2013) have been provided.

10 see question 8 above.

10 Question 10: p.8, line 4. Please indicate the reason of the turning on/off of the heater.

The heater is used to stabilize the laser temperature in cold environments (Kotthaus et al., 2016). The heater is turned on until the device attains the temperature, then is switched off. The temperature of the instrument decreases then, due to the cold surroundings, and when a minimum temperature is reached, the heater is turned on again.

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There are two sources of noise and artifacts affecting the ceilometer backscatter signal: the hardware of the Vaisala ceilometers, and the internal processing of the data (Kotthaus et al., 2016). Firstly, a heater is incorporated in the device to stabilize the laser temperature in cold environments. This heater is placed close to the laser transmitter and the periodic turning on (when a minimum temperature is reached by the instrument) and off (when the laser temperature is high enough) of the heater introduces a small periodic variation in the stability of the emitted signal (and therefore of the detected signal). This effect is stronger in the first range bins, closest to the device.

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11 Question 11: p.14, line 13. What about the role of sastrugi in the evolution of blowing snow intensity?

Indeed, the presence of sastrugis has an impact on blowing snow intensity evolution. However, in this section we investigate the changes in near-surface atmospheric variables during blowing snow conditions. Despite their possible impact, sastrugis are not measured either at PE nor at Neumayer III station.

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Apart from these factors, sastrugis might also have an impact on blowing snow (Amory et al., 2017) but are not measured here.

12 Question 12: p.14 – 15, fig. 8 and 9. How do you quantify from a statistical point of view the differences between blowing snow and non blowing snow wind speed and relative humidity? What is your interpretation of the differences for the other variables?

By means of a t-test significant at the 95 % level. The difference for the other variables is not significant, meaning that blowing snow or non blowing snow conditions give similar distributions for these variables. However, due to the comments received on this section, it has been removed together with Figs. 8 and 9.

13 Question 13: p.16, line 2. What is the advantage of satellite detection?

The advantage of satellite detection is the spatial coverage of blowing snow. This enables Palm et al. (2011) to produce a map of blowing snow frequencies over the whole of the Antarctic continent. A sentence has been added, and the paragraph has been moved to section 5.1 (discussion).

Satellite detections of blowing snow, although covering the whole continent, are limited to clear sky conditions. The BSD algorithm, however, is able to detect blowing snow during most of the storms, which is an improvement compared to satellite detection, as the majority of blowing snow occur together with cloud/precipitation.

14 Question 14: p.16, line 14. Clarify “observations”

Observations referred to the number of measurements ; i.e. the number of times during the measurement period, that a certain time lag after precipitation is reached.

A possible explanation is that the number of measurements decreases with time, and that blowing snow occurred during those measurements.

15 Question 15: p.18, lines 17 – 18: “commission errors”: please clarify.

"Commission error" was stated twice, and should only appear once. The second mention should have been "ommission error". In our case, a commission error is a BSD detection that is not reported by the visual observer. It is similar to a "false alarm", but since we do not consider visual observations as ground truth, but as another means of measuring blowing snow, we chose the omission/commission terms. The omission error refers to missing a blowing snow occurrence that is reported by the visual observer.

Furthermore, the hourly time filtering applied leads to commission errors (events detected by the algorithm, but not reported by the visual observations) and omission errors (short-lived events are likely removed from the running mean).

16 Question 16: p.19, line 2. Is it possible to improve the set-up of the ceilometers on the field, and how?

Indeed, however, most of the ceilometers are intended to forecast the weather for planes landing. Depending on the purpose
5 of ceilometer measurements, the ceilometer could be placed closer to the ground to measure lower level blowing snow, and reporting resolution can be adapted (10 m vertical resolution).

*If setting up a ceilometer in the aim of measuring blowing snow, the device should be placed as close to the ground as possible to also retrieve shallower blowing snow events. The BSD algorithm can be applied to any ceilometer located in
10 Antarctica, but we recommend to use a bin width of 10 m for operating ceilometers to detect blowing snow, which is the case at PE and Neumayer III.*

17 Question 17: p.20, line 3. : ... designed to retrieve blowing snow events but no drifting snow from ground-based ...

The sentence has been adapted accordingly.

15 *We present here our novel BSD algorithm, designed to retrieve blowing snow events, but not drifting snow, from ground-based remote-sensing ceilometers.*

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