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An improved algorithm for cloud base detection by ceilometer over the ice sheets by K. Van Tricht et al.

Q: is a question I would like you to answer, or rewrite the sentence so that it is clear.
R: is a suggested text/work to be removed.
Additions to the text are highlighted

Specific comments:

Abstract

Optically thin ice clouds play an important role in polar regions due to their effect on cloud radiative impact and precipitation on the surface *(Q: why it does not have effects on precipitation which is not reaching the surface?).* Cloud bases ***of liquid, optically thick clouds*** can be detected by *R: lidar-based* ceilometers that run continuously and therefore have the potential to provide basic cloud statistics including cloud frequency, base height and vertical structure. *R: Despite their importance,* Thin clouds are *R: however* not well detected by the standard cloud base detection algorithms of most ceilometers, also these operational at Arctic and Antarctic stations. *(Note: standard algotithms by their definition do not aim at all at a detection of thin clouds, regardless of whether the thin cloud are impotrant or not)* This paper presents the Polar Threshold (PT) algorithm that was developed to detect optically thin hydrometeor layers (optical depth $\tau \geq 0.01$ *Q: at what range of cloud thickness? at what range of cloud altitudes?*). The PT algorithm detects the first hydrometeor layer in a vertical attenuated backscatter profile exceeding a predefined threshold in combination with noise reduction and averaging procedures. The optimal backscatter threshold of 3 × 10 km sr for cloud base detection was *R: objectively* derived based on a sensitivity analysis using data from Princess Elisabeth, Antarctica and Summit, Greenland. The algorithm defines cloudy conditions as any atmospheric profile *(Q: of what temporal and horizontal resolutions?)* containing a hydrometeor layer at least 50 m thick *(Q: this is very thin cloud, are you shure that by applied averaging you are able to detect statistically significant amout of 50m-thin clouds?)*. A comparison with relative humidity measurements from radiosondes at Summit illustrates the algorithm's ability to significantly differentiate between clear sky and cloudy conditions. Analysis of the cloud statistics derived from the PT algorithm indicates a year-round monthly mean cloud cover fraction of 72 % at Summit without a seasonal cycle. The occurrence of optically thick layers, indicating the presence of supercooled liquid *(Q: particles and/or dropplets?)* , shows a seasonal cycle at Summit with a monthly mean summer peak of 40 %. The monthly mean cloud occurrence frequency in summer at Princess Elisabeth is 47 %, which reduces to 14 % for supercooled liquid cloud layers. Our analyses furthermore illustrate the importance of optically thin hydrometeor layers located near the surface for both sites, with 87 % of all detections below 500 m for Summit and 80 % below 2 km for Princess Elisabeth. These results have implications for using satellite-based remotely sensed cloud observations, like CloudSat, that they may be insensitive for hydrometeors near the surface. The results of this study highlight the potential of the PT algorithm to extract information in polar regions about a wide range of hydrometeor types *(Q: range of types? Or range of sizes? Anyway, you are not able to distingwith type nor size from ceilometer data, are you?)* from measurements by the robust and relatively low-cost ceilometer instrument.

Introduction

Clouds have an important effect on the polar climates. Locally, polar tropospheric clouds influence the energy and mass balance of the ice sheets (Bintanja and Van den Broeke, 1996; Intrieri, 2002; Bromwich et al., 2012; Kay and L'Ecuyer, 2013). *R: However,* The changes in the polar cloud properties may modify the climate of regions ***at lower latitudes***. *R: well beyond these high latitudes as well* (Lubin et al., 1998). Climate models still have difficulties in correctly projecting the polar climate, *R: an important part of* which is ***among others*** due to uncertainties in *R: their* cloud parameterizations of *R: such as* macro- and microphysical properties ***of clouds*** (Bennartz et al., 2013; Ettema et al., 2010; Gorodetskaya et al., 2008) and feedback mechanisms (Dufresne and Bony, 2008).

Despite the great importance of clouds on the surface mass and energy balance, cloud research at *R: these* high latitudes is still hampered by a lack of sufficient cloud observations. The harsh and remote environment of *R: in* Arctic and Antarctic *R: regions* has limited the amount of ground stations used for climatic research. The research sites that are present are equipped with robust instruments that can withstand very cold conditions. One of the most robust instruments that is used for observing clouds is the ceilometer, a ground-based low-power ***lidar*** *R: laser device*. It can operate continuously in all weather conditions (Hogan et al., 2003) and is one of the more abundant (> 10) instruments at Arctic and Antarctic stations, including at Summit, Atqasuk, Barrow, Ny-Alesund (Arctic study sites) and at Princess Elisabeth, Rothera, Halley (Antarctic study sites) (Bromwich et al., 2012; Shanklin et al., 2009; Shupe et al., 2011).
A macrophysical property inferred from ceilometer data is the cloud base height (CBH) which is defined as the lower boundary of a cloud. The CBH is used for different purposes, including visibility determination, *R: the study of* cloud height occurrence statistics *R: (e.g. cloud heights)* and validation of other remotely sensed cloud measurements, such as satellite observations. Most often, the CBH is calculated by built-in algorithms developed by the instrument's manufacturers such as the Vaisala cloud base detection algorithm (Garrett and Zhao, 2013; Shupe et al., 2011). *R: However,* These built-in algorithms are primarily designed to report the altitude where the horizontal visibility *R: to a pilot* is drastically reduced ***to a pilot*** (Flynn, 2004). ***Thus,*** these algorithms ***usually cannot*** *R: therefore struggle to* identify cloud bases over the ice sheets, where clouds are often optically thin. Bernhard (2004) showed that at the South Pole 71 % of all clouds have an optical depth ***below 1.*** *R: between 0 and 1 and the* Arctic clouds are also frequently optically thin (Sedlar et al., 2010; Shupe and Intrieri, 2004). Despite the low optical depth of ice clouds, their detection is important in terms of determination of the cloud radiative impact or potential precipitation growth (Sun and Shine, 1995; Curry et al., 1996; Pruppacher and Klett, 2010; Kay and L'Ecuyer, 2013).

Ceilometers typically detect cloud bases at a distinct height and increasing backscatter (see e.g. Fig. 1). (*Q: whay do you mean? Where is it in Fig.1? At what height range?)* Although there are clearly regions with increased backscatter below, the standard Vaisala CBH detection algorithm reports the CBH usually at *R: rather* higher levels, that are likely related to liquid-containing portions in case of a mixed-phase cloud (Bromwich et al., 2012; Curry et al., 2000; Hobbs and Rangno, 1998; Pinto, 1998; Uttal et al., 2002; Verlinde et al., 2007). The optically much thicker top layer most probably related to supercooled liquid has a much higher backscatter coefficient is compared to the optically thiner layer below. This is leading to incorrectly reported CBH by the conventional algorithms in the case of the mixed-phase clouds. There are also other CBH detection algorithms, *R: have been developed* ***that use different approaches to infer CBH, as for instance*** *R: compared to the standard algorithms. An example is* The temporal height tracking (THT) algorithm developed by Martucci et al. (2010), that uses backscatter maxima and backscatter gradient maxima to calculate the CBH. However, also this algorithm has not been designed to detect optically thin clouds in a polar atmosphere, which is apparent from the CBH detections by the THT algorithm in Fig. 1. Other more advanced instruments are also reporting CBH,
such as the Micropulse Lidar (MPL) (e.g., Clothiaux et al., 1998; Campbell et al., 2002), but these instruments are less abundant over the different study sites in the Arctic and Antarctic, mostly due to their complexity and higher cost as well as a *(Q: and the fact that you need a person to operate the system on site? Isn't it an important limitation for polar applications?)* (Barnes et al., 2003).

An algorithm that is capable of calculating the CBH from ceilometer data in polar regions, including the detection of optically very thin hydrometeor features *(Note: I feel it is not clear what you mean by this: hedrometeor = liquid particles and/or ice particles?, feature = leyer?)*, therefore would greatly improve cloud statistics in these areas.

The goal of this study is to develop a simple method that uses ceilometer measurements and *R: that is sensitive enough* to detect *R: these* optically thin ice clouds *R: abundant* in polar regions. We propose to use a fairly straightforward backscatter threshold approach. We describe here the theoretical framework of the new algorithm, the determination of the optimal backscatter threshold and results that were obtained by applying the algorithm on the ceilometer measurements at an Arctic and an Antarctic station.

Data

Study area

The locations of the two research stations used in this study are shown in Fig. 2. They were chosen based on their characteristic climatology and available instrumentation. The Antarctic data originate from the Princess Elisabeth (PE) station ***(Pattyn et al., 2009),*** located in the escarpment zone of Dronning Maud Land, East-Antarctica *R: (Pattyn et al., 2009).* The station is situated on the Utsteinen Ridge near the Sřr Rondane mountains at an elevation of 1382 m a.s.l, 220 km inland (71.95 S, 23.35 E). Its location makes the station well protected from katabatic winds, however with a significant influence of coastal storms of 50 % of the time (Gorodetskaya et al., 2013a). Cloud measurements are carried out in the context of the HYDRANT project, for which a unique instrument set has been installed, including a ceilometer, an uplooking infrared radiation pyrometer, a vertically pointing micro rain radar and an automatic weather station (Gorodetskaya t al., 2013b). Data are currently limited to summertime

Ceilometer

The Greenland Summit station is equipped with the Vaisala CT25K laser ceilometer, while the Antarctic PE station has the newer Vaisala CL31 laser ceilometer. Both instruments are *R: These ceilometers both are devices* emitting ***low energy*** laser pulses and their vertical range extends up to 7.5 km. *R: for both.* The CL31 instrument is more sensitive than the CT25K due to *R: because it has* a higher average emitted power *R: (12 mW vs. 8.9 mW).*
Further technical details of both ceilometers are given in Table 1.
The output used in this study is the range and sensitivity corrected attenuated backscatter coefficient βatt (km sr), which describes how much light from the emitted laser pulse is scattered into the backward direction, not corrected for attenuation by extinction. It is the product of the volume backscatter coefficient β at a certain height range and the squared transmittance of the atmosphere between the ceilometer and the scattering volume (Münkel et al., 2006). It is found after multiplying the received power by all instrument specific factors, constants and the squared distance. Since the transmittance of the atmosphere is in general unknown, conversion of attenuated backscatter βatt to corrected backscatter β is not straightforward.
Note: I am not sure what you trying to say. Are you converting βatt to βcorrected, which is not equal to βtrue?! Thereturned signal of the pulses is averaged over a period of 15 s which determines the temporal resolution of the measurements. The vertical resolution is 30 m for the CT25K *Note: This was my concern for the abstract, can you claim to be able to detect 50m thin layer when you average over 30m? I am sceptic here.* at Summit and 10 m for the CL31 at PE.

An additional difference between both ceilometers is the precision of the reported backscatter. The CT25K reports integer values of attenuated backscatter in 1 × 10 km sr , while the CL31 reports in 1 × 10 km sr , i.e. a factor 10 more precise. Calibration of the raw CT25K data was necessary, which was done based on the autocalibration method by O'Connor et al. (2004). They showed that supercooled water layers have essentially the same characteristics as warm stratocumulus clouds for which the method was developed. We therefore selected cases with supercooled water layers that completely attenuate the laser beam ***(but without saturating the detectors)***, for which the lidar ratio is assumed to be constant and known (see Sect. 4.3). We filtered these cases to retain profiles with a minimum amount of ice precipitation, since ice precipitation violates the constant lidar ratio assumption. Due to the low beam divergence of the CT25K ceilometer (Table 1), the effect of multiple scattering is small. *Note: for answering the question of multipple scattering effects you should take to account not only the laser beam divergence but also the size of the field of view of the two instruments. And you did not specify this number for neither of the two in struments. I reckon, you should give a comment on that.* Applying the autocalibration method resulted in a scale factor of 3. The inevitable presence of ice in certain profiles invalidates some of the assumptions in the O'Connor method and introduces an additional uncertainty in the calibrated data. Despite this, the autocalibration method significantly improved the large biases that were encountered in the raw CT25K measurements. After calibration of the Summit ceilometer, the minimum detection limit is 3 × 10 km sr , while 1 × 10 km sr is the minimum detection limit for the PE ceilometer.

Radiosondes

Among the observations at Summit, ***twice a day a*** *R: is a twice-daily* radiosonde program for characterizing the atmospheric state ***is run*** (Shupe et al., 2013). Relative humidity (RH) is measured with the Vaisala RS92-K and RS92-SGP sondes and reported at a temporal resolution of 2 s, resulting in a vertical RH profile. Due to the low atmospheric temperatures, we report the RH with respect to ice (RHice), using Tetens formulation as described by Murray (1967). ***This formulation requires an extreme accuracy at low temperatures.*** The high uncertainty of the RH measurements at low temperatures (dry bias) for the RS80 and RS90 sondes (Miloshevich et al., 2001; Rowe et al., 2008; ***Wang et al., 2013***), is mostly resolved with the RS92 sondes (Suortti et al., 2008). ***Additionally, quantitative studies show that this issue is less severe in polar regions (Vömel et al., 2007),*** *R: Yet, solar radiation heating of the sensors may occur due to the absence of a silver cap found on the RS80s that acts as a radiation shield, leading to a dry bias (Wang et al., 2013). Vömel et al. (2007) who first quantified this bias however indicated that this issue is less severe in polar regions (Note: I suggest to remove that, it is too many details)* because the solar elevation angle is lower at high latitudes. Suortti et al. (2008) moreover identified the RS92 sonde as being superior to other radiosonde sensors.

Methodology

The development of a CBH detection algorithm depends on *R: which* atmospheric features *R: are* considered to be a cloud. In this study a cloud is defined to be any hydrometeor layer that is at least 50 m thick in the atmospheric column detected by the ceilometer. This includes ice particles and supercooled liquid droplets as well as any form of precipitation *(Q: why? Precipitation is NOT a cloud? Is your algoritm coulting it as a cloud? Please clarify this.),*
R: all of which are important for the radiative budget and mass balance of the ice sheets (Bintanja and Van den Broeke, 1996; Bromwich et al., 2012; Curry et al., 1996; Intrieri, 2002; Pruppacher and Klett, 2010; Sun and Shine, 1995). Note: this information is relevant but placed here it breaks the story flow. Please move it to the Introduction.
The CBH detection algorithm *R: then* determines the height of the first detectable occurrence of defined in this way hydrometeor layer.

R: Our goal was to develop a cloud detection method that is able to detect the CBH in optically thin layers even when liquid is present higher in the profile. The new Polar Threshold (PT) algorithm therefore
Since our aim was to detect the CBH in optically thin layers, even if liquid water dropplets are present above them, the developed Polar Threshold (PT) algorithm compares the measured attenuated backscatter to a predefined backscatter threshold. This

allows the algorithm to be sensitive to optically thin hydrometeor layers characterized by low attenuated backscatter returns and a lack of sharp gradients***. This is an essential way by which our approach differs from both*** the standard Vaisala algorithm (Flynn, 2004) and the THT algorithm (Martucci et al., 2010) that look at visibility or backscatter (gradient) maxima, respectively. A threshold method has been used before, e.g. by Platt et al. (1994). However, they used a multiple of the standard deviation of the background
fluctuations as a threshold to be exceeded by the attenuated backscatter signal. As the physical variability of the background signal obtained for clear polar air is low, *(Note: I assume this physical, atmospheric variability is what you are talking about, bacause of course the variability in the polar clear air signal is very high due to the high noise and measurment at a detection limit...)* we propose an absolute attenuated backscatter threshold to be exceeded for CBH detection. In this section we first describe the noise reducing and averaging procedures to be carried out prior to the actual CBH detection, followed by the principle of the PT algorithm and the procedure to determine the optimal backscatter threshold.

Noise reduction and averaging

For a sensitive algorithm to work properly noise levels should be reduced and
useful signal should be emphasized. The ceilometer being a low-power ***lidar*** *R: laser instrument* inherently reports attenuated backscatter with a considerate degree of
noise (e.g., Clothiaux et al., 1998). ***The fast*** *R: Especially* decrease of signal with range, ***and its*** *R: further exacerbated by the (Note: the range correction DOES NOT worsen the signal, as after the range correction some features in the signal can be seen more clearly! However, it increases the noise level in the signal.)* range correction (evident from the lidar equation in e.g. Münkel et al., 2006) leads to increasing noise levels at each higher altitude of the profile. We therefore first remove noisy data detected by investigating the signal-to-noise ratio (SNR) and afterwards average the raw ceilometer attenuated backscatter data. The SNR was calculated for every separate height range bin as:

Eq. 1 ***please rewrite***

which is the ratio of the mean of an attenuated backscatter interval of 10 min at a certain
height in the profile over the standard deviation (std) of that backscatter interval.
Note: I reckon you should rewrite Eq.1 in a more mathematical way or leave it out and re-write it nmore clearly in the text as a definition. Now, the Eq. and the text do not describe the same.

The atmospheric fluctuations in this interval are small compared to the instrument
noise such that the standard deviation over the interval mainly contains internal noise
from the instrument. *(Q: well, that should depend on height you are taking to account. I would say, at low altitudes the atmospheric variability is much higher than the noise, isn't it?)*
This method is different from the common techniques used for lidars to estimate the ceilometer's noise level from the background light (see e.g. Heese et al., 2010; ***Stachlewska et al., 2010; Wiegner and Geiß, 2012*** *Note: As there are not many paper on this subject I would add references to these positions*). However, as Vaisala ceilometers report background light only as voltage, the mentioned methods are not ***straight-forward*** applicable.
Noisy data are characterized by a low mean backscatter (averaged over positive and negative values) and a high standard deviation, resulting in low SNR values. The SNR threshold was set to 1 as was also done by Heese et al. (2010), and pixels with a lower SNR were removed. *(Q: does that mean that if you obtain low, positive mean backscatter from this averaging you must still remove it?)*
In a second step, the noise-reduced data were smoothed by applying a running mean over an interval of 2.5 min. *(Q: so... for SNR calculation and pixel removal you average over 10 min and then what is left over you average to final profile of 2.5 min? I feel this may be not clear enough.)*
Due to the impact of the averaging method on the results as reported in Stachlewska et al. (2012), we varied the running mean interval between 1 and 15 min, but the impact on our results was below 1 %. Fig. 3 shows an example ceilometer attenuated backscatter image with a typical backscatter profile before and after the noise reduction and averaging procedures.

Polar threshold algorithm

The PT algorithm processes every vertical profile *(Q: you mean every 2,5 min avarage profile ?)* separately and compares the attenuated backscatter of each range bin to a backscatter threshold in a bottom-up approach. The first 60 m (2 range bins at Summit, 6 range bins at PE) however are excluded to minimize the effects of shallow blowing snow layers. The CBH detection is triggered if the attenuated backscatter at a certain height in the vertical profile exceeds the threshold *(Q: maybe you could give the theshold precisely also here?)*. After the trigger, the algorithm also considers the mean attenuated backscatter 50 m above the trigger point (60 m for the Summit ceilometer). If the backscatter value at this elevated height also exceeds the threshold, the height of the trigger point is set as the CBH. This ensures a certain amount of robustness of the signal at the detected CBH, meaning that a hydrometeor layer should have a minimum geometrical thickness to be detectable by the algorithm. *(Q: why not checking all points at that range? Then you could, at lease for the PE station, try to see thinedr that 50m layers?)*
If not, the algorithm proceeds with the next range bin in the profile. If the end of the vertical profile is reached without a valid CBH detection, the profile is marked as clear sky. This approach was found to perform best in identifying the base of optically thin hydrometeor layers compared to other algorithms. *(Q: well, where the other algorithms developed for the same purpose? No, so it is not the best! It is not even comparable! Note: I reckon the beauty of your approach is that you did optiomize it for the detection of thin polar clouds, and that is the only one at the moment for serving this purpose. This comparison is not approiopriate)* Figure 4 shows the ideal result of the PT-derived CBH compared to the Vaisala and THT algorithms for an example attenuated backscatter profile. The original (not noise-reduced) ceilometer data are shown. It is evident that the threshold-based PT algorithm can be triggered at much lower backscatter values
occurring at the base of an optically thin ice layer compared to the other algorithms that are triggered much higher in the profile, most probably at a liquid-containing layer.
In the next section, the optimal threshold to be used by the PT algorithm in order to achieve results as in Fig. 4, is objectively *(Q: objectively?)* determined.

Determining optimal threshold

The CBH detection by the PT algorithm strongly depends on the backscatter threshold that is used. The optimal threshold is one that allows the detection of hydrometeor layers with a low optical depth while not triggering the algorithm in clear sky conditions.
(Q: well, it may be also difficult to distinguish it form the aerosol layers present within the boundary layer, or you do not detect any aerosol?)

To make an objective threshold choice *Note: could it be you mean: an appriopriate threshold choice ?*, we performed a sensitivity analysis by varying the backscatter threshold between the detection limits of the ceilometers and the maximum backscatter value in the data and evaluating the effect on the cloud detections. The total number of profiles containing a cloud that is detected by the PT algorithm over all cases (= the total number of detections) was calculated for each threshold. The results of the sensitivity analysis for PE are shown in Fig. 5a. At a backscatter threshold just below 3 × 10 − 4 km − 1 sr − 1 there is a sharp decrease in total number of detections. At this transition, the total number of detections is approximately halved, which is related to the fact that PE experiences synoptic influence favouring cloud occurrence about 50 % of the time (Gorodetskaya et al., 2013a). The backscatter threshold at 3 × 10 km sr effectively represents the minimum concentration of hydrometeors detectable by the ceilometer distinguishing cloudy from clear sky profiles. The lowest detection limit after calibration of the ceilometer at Summit corresponds to the backscatter threshold determined for the PE ceilometer (Fig. 5b). Therefore, we used identical backscatter thresholds for PE and Summit.

The amount of backscatter that reaches the detector is a function of the extinction profile and thus of the optical depth of the atmosphere (Roy et al., 1993). Further increasing the threshold therefore increases the optical depth of the detected clouds and influences both the amount and height of the detected cloudy profiles. Even if the amount of detections does not significantly vary with a changing threshold (flat parts of the curves in Fig. 5), a higher threshold triggers the CBH detection higher in the backscatter profiles, leading to overall higher CBH results. For example, increasing the threshold from 3 × 10 km sr to 30 × 10 km sr at Summit decreases the amount of detections by 10 % and increases the mean CBH by 70 m, while at PE the amount of detections is decreased by only 2 %, though the mean CBH increases by 190 m. *(Q: does that mean that at PE there are more optically thin clouds which are span over the larger altitude range in the troposphere? Is that what you expect? Or is that an artefact due to e.g. different height resolution of PS and Summit instruments?)*

As our purpose is to detect the optically thinnest detectable hydrometeors lowest in the profile, we choose the lowest backscatter threshold indicating the presence of hydrometeors (3×10 km sr for both the PE and Summit ceilometers). *(Q: so then again, why are you trying to compete with the standard slgorithms? Are you trying to say: if Vaisala CBH algoritm is meant to detect bottom of the cloud it will not work for low polar clouds, thus an optimization is necessary, thus our work was necessary?)*

Results

Applying the PT algorithm

The PT algorithm was applied to all available cases at the study sites. Example CBH results for the three tested algorithms are shown in Fig. 6 with the 8 March 2010 case for PE ***(Antarctic Summer)*** and the 19 December 2010 case for Summit ***(Arcitc Winter)*****.** These cases were chosen because they represent different atmospheric conditions on which the PT algorithm could be tested. These conditions include clear sky profiles, ice layers and polar mixed-phase cloud structures (optically thicker layer most probably due to the presence of supercooled liquid over an optically thinner but geometrically thicker ice-only layer). The Summit ceilometer data in Fig. 6b indicate that precipitation reaches the surface after 14 h. Since the first two range bins of the profile were excluded, the CBH is located at 60 m in such conditions. (*Q: but in the case when there is precipitation, than the CBH is at the level of clouds, isn't it? How does your algorithm deal with that?)*

In both cases, the PT CBH is significantly lower compared to the Vaisala and THT CBH. At both study sites, the Vaisala CBH is situated much higher *(Q: well, not always, e.e. Ar subfigure a) at about 4-6 UTC it is not?!)* in the actual cloud, where backscatter values are highest most of the time. This is to be expected since the primary goal of the Vaisala algorithm is to detect visibility changes for pilots. In the case of optically thin features with only low backscatter values, Vaisala sometimes reports the profile as being clear sky *(Q: you mean e.g. Subfigure a) from 0-4 UTC ?).* The THT algorithm detects hydrometeors more often, but the CBH is often placed higher as well. THT takes into account the first derivative of the backscatter profile, while optically thin ice clouds are not characterized by a sharp increase in backscatter. The PT algorithm is more sensitive and is triggered by optically thinner hydrometeor layers. The number of cloudy profiles reported by PT therefore is higher and the detected CBH is reported at lower altitudes. The sensitive nature of the PT algorithm indicates that the noise reduction and averaging procedures have to be an inherent part of the algorithm itself to avoid false triggering by noise ***in the*** signals.

Comparison with radiosondes

Atmospheric sounding by radiosondes has been used in the past for cloud detection validation in polar regions, where higher values of RH *(Q: higher meaning what % of RH?)* are associated with clouds (Gettelman et al., 2006; Minnis et al., 2005; Tapakis and Charalambides, 2012). _Note: please give an exact definition because not always higher RH is a clear indication of cloud._ The RH at the level of the detected CBH should in general be high, assuming the actual presence of hydrometeors at this height. An example case with ceilometer attenuated backscatter measurements and the radiosonde-derived RHice is shown in Fig. 7, which shows that the RHice increases significantly at the cloud base. _(Q: significantly meaning of how much? RH beyond 100% ? and at what range? Heights between 0,5-1,4 km? Where in this range is the CBH in your opinion and what is found by the algorithm? Note, that also at about 2 km there is a significant increase of RH but in Ceilometer data I see no clouds!)_

To assess how the PT algorithm performs, we therefore estimated in a statistical analysis the difference in RHice measurements at the detected cloud base vs. RHice measurements in clear sky profiles. In order to make this analysis as objective as possible, we first derived a probability distribution for the detected CBH over all cases. Then, we randomly selected RHice measurements in clear sky profiles following the same probability distribution in order to set up a sample with an equal amount of clear sky RHice measurements at identical altitudes compared to the CBH RHice measurements. The result is two samples of RHice measurements at the cloud base vs. clear sky, selected at the same altitudes with an equal number of observations in each.

The histograms of the two samples (clear sky and cloud base) are plotted in Fig. 8. 9831 The green bars indicate occurrences in a RHice interval for the clear sky sample. Blue bars represent occurrences in a RHice interval for the cloud base sample. It shows that when a cloud base is detected, RHice at this cloud base is mostly around 100 % with only very few cases lower than 80 %. _Note: this 100 and 80% values cannot be seen/assessed easily from the Fig.8_ For clear sky, on the other hand, the radiosonde also detects high RHice , although more occurrences at very low RHice values are present. The high abundance of large RHice values in clear sky conditions is related to the high fraction of cloud bases near the surface (Sect. 4.4). Shupe et al. (2013) found that in this region RHice values are typically high due to the frequent occurrence of moisture inversions near the surface. According to Vömel et al. (2007), a possible dry bias in the RH measurements of the RS92 radiosonde is smallest at low altitudes, suggesting that our conclusions should not be influenced significantly by a possible bias.

We used a one-sided nonparametric two-sample Kolmogorov–Smirnov test to determine if the RHice measurements of cloud bases were significantly higher compared to clear sky RHice values (Hájek et al., 1967). The test indicates that the cloud base RHice values are indeed significantly higher than the clear sky RHice values (p value < 0.01), suggesting that the PT algorithm performs well _(Q: could you explain, I see no connection)._

Q: There is a paper by Lampert et al., 2012 about the humid layers detection at Svalbard. I am wondering how much your results at Summit compare with their paper.

Optical depth of detected features

Translating the attenuated backscatter values of the detected hydrometeor layers to optical depths allows a physical interpretation of what the PT algorithm actually detects. Such translation however is not straightforward since the optical depth depends strongly on the properties of the cloud (Tselioudis et al., 1992; King et al., 1998; Kay et al., 2006) and the calculation of optical depth requires the corrected backscatter coefficients _(Q: again you talk about the corrected backscatter coefficients. Do you want to stress out that they do not represent the true values?)_ and this correction of the observed backscatter for attenuation of the signal is based on knowledge of the extinction profile which is unknown. Thecorrected backscatter was estimated following the procedure described by Platt (1979).
This procedure starts with Eq. (2), which describes the relation between observed attenuated backscatter at a height z ($\beta_{att,z}$) and the true backscatter coefficient at this

height corrected for attenuation (βz):
(Q: once again what is the difference between corrected backsactter and the true backscatter ?)

eg.2 OK

In this equation, the exponential term describes the two-way attenuation in the profile between the cloud base (z_0) and height z and τz is the optical thickness along the path calculated as:

eq.3 OK

where σ is the extinction coefficient and S is the extinction-to-backscatter ratio (lidar ratio). S depends on numerous factors, including size distribution, composition and shape of the particles (Heymsfield and Platt, 1984; Chen et al., 2002). Yorks et al. (2011) found a constant lidar ratio of S = 16 sr for liquid altocumulus clouds and S = 25 sr for ice clouds. As our measurements include a variety of atmospheric conditions from ice to supercooled liquid, we assume an average ratio of S = 20 sr for a rough estimation of the extinction coefficient. *(Q: yes, this is very rough assumption and you do not show that you actually can make that assumption. Thus, I think it would be very helpfull if you made an example calculation/estimation of what range of results you would get if you would use the 16sr and 25 sr, just to give a reader the feeling of how much you risk by taking this average. It will be also a kind of error estimate due to this assumption.)*
After combining Eqs. (2) and (3), the final equation is described by Eq. (4):

eq.4 OK

The procedure assumes that at the cloud base $\beta z_0 = \beta att,z_0$, since attenuation of the signal under the cloud base is negligible. Next, the cloud is divided into a number of thin layers, corresponding to the range bins of the ceilometer. The integral in Eq. (4) is discretized and the corrected backscatter coefficients of the range bins are successively calculated until the upper end of the profile is reached. In the procedure, the effects of multiple scattering are not taken into account. In a final step, the optical depth τ of the detected cloud is cumulatively calculated for the successive range bins, using Eq. (3).

The assumptions for both the lidar ratio S and the derivation of the corrected backscatter from observed backscatter make the optical depth calculations prone to a considerate degree of uncertainty. *(Note: which you should estimate, as this is a new, interesting method...)* Despite many assumptions simplifying a complex problem, this procedure allows us to make a rough estimation of the optical depth of hydrometeor layers detected by the PT algorithm.
We found at Summit optical depths detected by the PT algorithm as low as $\tau = 0.01$ and 32 % of the detected hydrometeor features attenuated the laser beam ($\tau > 3$, in accordance with Sassen and Cho, 1992). At PE, the lower limit of optical depths was 0.01 as well, while 21 % of the detections attenuated the laser beam. The drawback of the high sensitivity of the algorithm (detection of features with $\tau = 0.01$) is that CBH detection can sometimes be triggered by layers of elevated aerosol contents. This only rarely happens over the Antarctic ice sheet due to its remote location and clean air (e.g., Hov et al., 2007). This is not the case for Greenland, ***nor for Svalbard*** , which **are** much closer to industrialized countries. In the events of elevated aerosol contents, some aerosol layers will inherently be identified falsely as cloud (Shupe et al., 2011; ***Lampert et al, 2012***).

Application: cloud properties ***- convincing, no comments***

Conclusions

The importance of ***occurrence of*** polar clouds for the energy and mass balance of the ice sheets indicates the need for an improved understanding of ***evolution of*** macro- and microphysical cloud properties. The ceilometer, which is one of the more abundant ground-based instruments in polar regions, can be used to detect cloud bases. The standard algorithms however are ***not designed to report on the optically thin ice layers frequently occurring in polar regions,*** *R: fail to report on the optically thin ice layers frequently occurring*, as they are primarily designed to detect strong visibility changes. In this paper, we propose the new Polar Threshold algorithm that uses a backscatter threshold ***to detect*** *R: and is developed to be sensitive to* optically thin hydrometeors. The optimal attenuated backscatter threshold of 3 × 10 − 4 km − 1 sr − 1 was *R: objectively (Note, this 'objectively' here and before somewhat suggests that other algorithms may have used thresholds which are not objective. I would skip this word through out the entire paper)* determined by a sensitivity analysis on all available cases for the Princess Elisabeth station in the escarpment zone of East Antarctica and the Summit station in the interior of Greenland. After noise reduction and averaging procedures, the algorithm was shown to identify hydrometeor features *(Note, again here can you be more specific (e.g. humid layers of liquid / ice particles)* with optical depths as low as 0.01. Comparison with observations by radiosondes at Summit indicated that the observed RHice was significantly higher at the cloud base than in clear sky conditions, suggesting that the PT algorithm can successfully differetiate between clear sky and cloudy conditions. Mean cloud cover fraction at Summit is relatively constant year-round when the optically thin hydrometeors are included. Optically thicker features (backscatter threshold 1000 × 10 − 4 km − 1 sr − 1), most probably related to supercooled liquid droplets, show however a clear seasonal cycle with a significantly higher cloud cover fraction in summer compared to winter. The greatest part of all cloud detections at Summit was found near the surface. At Princess Elisabeth, the optically thinnest features occur mostly near the surface as well while optically thicker hydrometeor layers occur higher in the profile, mostly between 1 km and 3 km above the surface. The high abundance of hydrometeors in the lowest ranges has important implications, for example when using satellite observations such as CloudSat's active radar which may be insensitive to near-surface hydrometeors due to surfce reflection of the signal. This study indicates that using an adapted algorithm for cloud base height detection, the robust and relatively low-cost ceilometer can be successfully used to extract information on a ***wide range of hydrometeor types (Note, well, no you did not convince me that you can distinguish type of pareticles, nor thier size. Thus, please rewrite the sentence to stress our what you mean)*** over the ice sheets, including the frequently occurring optically thin ice layers.

Acknowledgements - OK

References - I would add two references:

A.Lampert, J. Ström, C. Ritter, R. Neuber, Y. J. Yoon, N. Y. Chae, and M. Shiobara , Inclined lidar observations of boundary layer aerosol particles above the Kongsfjord, Svalbard, Acta Geophysica, Volume 60, Issue 5, pp 1287-1307, 2012

M. Wiegner and A. Geiß, Aerosol profiling with the Jenoptik ceilometer CHM15kx, Atmos. Meas. Tech., 5, 1953-1964, 2012 Volume 60, Issue 5, pp 1287-1307, 2012

Tables - OK

Figures – generally OK

Fig.4 Why the average profile on the right hand siteis below zero from about 2,5 km, i.e. After the liquid cloud? Are the data not noise corrected here? The PT algorithm aims at detecting lowermost layer, would it be very difficult that it would detect also liquid layer at the same time?

Fig.6 Why PT algorithm does not detect any cloud from 0-3 UTC on the upper subfigure? There are no clouds there? What does detect then the THT algorithm?