NOTES AND CORRESPONDENCE

CloudSat as a Global Radar Calibrator

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(Manuscript received 19 January 2010, in final form 18 May 2010)

ABSTRACT

The calibration of the *CloudSat* spaceborne cloud radar has been thoroughly assessed using very accurate internal link budgets before launch, comparisons with predicted ocean surface backscatter at 94 GHz, direct comparisons with airborne cloud radars, and statistical comparisons with ground-based cloud radars at different locations of the world. It is believed that the calibration of *CloudSat* is accurate to within 0.5–1 dB. In the present paper it is shown that an approach similar to that used for the statistical comparisons with ground-based radars can now be adopted the other way around to calibrate other ground-based or airborne radars against *CloudSat* and/or to detect anomalies in long time series of ground-based radar measurements, provided that the calibration of *CloudSat* is followed up closely (which is the case). The power of using *CloudSat* as a global radar calibrator is demonstrated using the Atmospheric Radiation Measurement cloud radar data taken at Barrow, Alaska, the cloud radar data from the Cabauw site, Netherlands, and airborne Doppler cloud radar measurements taken along the *CloudSat* track in the Arctic by the Radar System Airborne (RASTA) cloud radar installed in the French ATR-42 aircraft for the first time. It is found that the Barrow radar data in 2008 are calibrated too high by 9.8 dB, while the Cabauw radar data in 2008 are calibrated too low by 8.0 dB. The calibration of the RASTA airborne cloud radar using direct comparisons with *CloudSat* agrees well with the expected gains and losses resulting from the change in configuration that required verification of the RASTA calibration.

1. Introduction

The prelaunch calibration of the *CloudSat* cloud-profiling radar (CPR; Stephens et al. 2002), in-flight calibration, and stability over the period of operation has been very recently reported in Tanelli et al. (2008) and Stephens et al. (2008). This in-flight calibration relies on monthly comparisons of ocean backscatter measured at 10° incidence off-nadir using dedicated *CloudSat* maneuvers and the corresponding ocean backscatter predicted by different theoretical models. The rationale for using 10° is that at this incidence the ocean backscattering cross section becomes nearly independent of surface wind speed (Durden et al. 2003) and takes a value of about 7 dB. Direct comparisons of *CloudSat* measurements of ice cloud reflectivity and ocean backscatter with measurements gathered by an airborne cloud radar within the *CloudSat* beam have demonstrated that the calibration of *CloudSat* was accurate to within 0.5–1 dB (Protat et al. 2009, hereafter PAL09), which is better than the initial *CloudSat* specification of 2 dB (Stephens et al. 2008, 2002). This result has also been confirmed using statistical comparisons between

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DOI: 10.1175/2010JTECHA1443.1

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continuous ground-based cloud radar observations over five different sites (PAL09). PAL09 also suggested that *CloudSat* could also now be used as a means to calibrate other ground-based or airborne uncalibrated radars. This idea is not new; it was proposed earlier for the lower-frequency spaceborne radar on board the Tropical Rainfall Measurement Mission (TRMM) in the pioneering works of Anagnostou et al. (2001) and Bolen and Chandrasekar (2000). In the present paper, this idea is developed further using two ground-based radars for which calibration problems are suspected by their operators and recent airborne Doppler cloud radar data taken in the Arctic along the *CloudSat* track. The paper is organized as follows: The principle of the statistical calibration using *CloudSat* as a reference is recalled in section 2, and some further refinements with respect to the PAL09 method are discussed. The calibration of the Barrow and Cabauw ground-based radars is discussed in sections 3 and 4. The calibration check of the airborne cloud radar is described in section 5. Conclusions are given in section 6.

2. The principle of the calibration technique

The principle of the statistical approach that is used to compare the calibration of a spaceborne radar with that of a ground-based radar has been described in detail in PAL09 and Protat et al. (2010). It is only briefly reviewed here. This statistical calibration technique consists of comparing mean vertical profiles of nonprecipitating ice cloud radar reflectivity as derived from the ground-based observations and from an extraction of all *CloudSat* data in a radius of 200 km around the ground-based site. The average of the reflectivity difference weighted by the number of points at each height corresponds to the calibration error. Probability distribution functions (PDFs) of radar reflectivity, cloud-top height, cloud geometrical thickness, and cloud base can also be compared, as shown in PAL09. The devil is in the details for these comparisons (PAL09). One needs to (i) carefully degrade both radars to the same sensitivity as a function of height (the sensitivity of *CloudSat* is around -30 dBZ in the troposphere), (ii) make sure that the definition of radar reflectivity is identical [the complex refractive index is taken as 0.93 for the 35-GHz Atmospheric Radiation Measurement (ARM; see Stokes and Schwartz 1994; Ackerman and Stokes, 2003) radars, while it is taken as 0.75 for *CloudSat*], (iii) screen out the precipitating ice cloud profiles [because they are not attenuated the same way in nadir- or zenith-viewing geometries, and also because of a different impact of multiple scattering in the radar beams (e.g., Bouniol et al. 2008)], and finally (iv) convert reflectivities to the same wavelength when they are not in the first place (the ARM radars operate at 35 GHz, *CloudSat* operates at 94 GHz). So far, the differences found between *CloudSat* and four well-calibrated ground-based radars were less than 1 dB statistically, and the PDFs of the macrophysical properties were in good agreement (PAL09).

For the two sites considered here it appears, as will be shown in sections 3 and 4, that the calibration error was much larger than that. In this case, a new problem had to be solved. In the processes of adjusting the ground-based radar data to conform to the *CloudSat* sensitivity threshold, too few data points are discarded from the set if the ground-based radar overestimates the reflectivity, or too many data points are discarded if it underestimates the reflectivity. The resulting difference in the mean vertical profile can be very large. Therefore, the technique described in PAL09 has been refined by simply iterating the approach until it reaches a stable calibration difference. For an 8–10-dB difference, five iterations have been necessary to reach a stable solution. The PDF of cloud-top height has to be checked for consistency, because if too few (too many) data are screened out, then the cloud-top height statistics should show that the ground-based radar data detects more (fewer) high cloud tops than the spaceborne radar. This point will be illustrated in sections 3 and 4 in both cases for the Barrow and Cabauw cloud radars.

3. Calibration of the Barrow ARM cloud radar

The U.S. Department of Energy ARM program has deployed the millimeter-wave cloud radar (MMCR; Moran et al. 1998) around the world for cloud and precipitation observations. Five sites are currently equipped with this radar: the Southern Great Plains Facility (SGP) in Oklahoma (which is the historical first ARM site); the North Slope of Alaska (NSA) site at Barrow, Alaska; and three in the tropical western Pacific (in Darwin, Northern Australia, and on the Manus and Nauru Islands). The Darwin MMCR has been compared with *CloudSat* in PAL09 as part of a multisite comparison. It was shown that the Darwin MMCR and *CloudSat* reflectivities agreed to within 0.5 dB.

At the two last ARM Cloud Properties Working Group workshops (held in November 2008 and September 2009) it was suspected that the NSA MMCR was reporting radar reflectivities much higher than those expected for the type of clouds typically encountered there. A thorough technical check of the radar calibration did not show any problem. Thus, for some time now data have been collected by this radar and distributed with a message on the ARM site stating that the reflectivities are probably 10 dBZ too high. This number has been obtained by

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qualitatively comparing the Barrow MMCR with the Canadian National Research Council (NRC) Convair-580 94- and 35-GHz airborne radars during the Indirect and Semi-Direct Aerosol Campaign (ISDAC) in April 2008 (Ghan et al. 2007). However, there has been no quantitative evidence that this was indeed the case. At the last meeting it has therefore been suggested that the Barrow radar calibration should be checked using the PAL09 technique. This is what is reported in the present section.

The direct application of the PAL09 method using the 1 March 2008–30 October 2008 observational period leads to the conclusion that the calibration of the Barrow radar is too high by around 4 dB. However, the PDF of the cloud-top height derived from the corrected data show larger occurrences of the highest cloud tops detected by the Barrow radar when compared with *CloudSat* (Fig. 1), which suggests that although the radar data below the *CloudSat* sensitivity threshold have been screened out, the Barrow radar is still more sensitive than *CloudSat* and the calibration of the Barrow radar is still too high. This result is caused by too few data points being screened out when degrading the ground-based radar to the spaceborne radar sensitivity, as discussed in section 2. An iterative procedure has therefore been developed in order to progressively refine the calibration value. The iterative procedure is stopped when the difference between the new calibration number and that of the previous iteration is smaller than 0.1 dB. After five iterations a reflectivity difference ($Z_{\mathrm{CloudSat}} - Z_{\mathrm{Barrow}}$) of −9.8 dB was obtained. The calibration error estimated at each step is given in Fig. 1b. The next iteration gave the same value as the fifth to within 0.1 dB, so it was concluded that the Barrow radar was calibrated too high by 9.8 dB. This result confirms the qualitative inferences made from the qualitative comparisons with the airborne cloud radar observations during ISDAC discussed previously. The corresponding mean vertical profiles of radar reflectivity and cloud-top height PDFs for the fifth iteration are given in Fig. 2. From the mean vertical profiles of Fig. 2a, it appears clearly that the vertical gradients of radar reflectivity are in excellent agreement overall, which can be viewed as a general validation of the approach and of the careful screening of the precipitating ice cloud profiles. The conversion of Barrow reflectivities from 35 to 94 GHz produces reflectivity differences of less than 1 dB at all heights, and slightly larger differences at lower heights. This is expected, because reflectivity is larger at lower heights, and thus the non-Rayleigh scattering effect that explains the difference between the 35- and 94-GHz reflectivities is more pronounced. The cloud-top height PDF (Fig. 2b) shows that with a calibration correction of −9.8 dB the sensitivity of both radars is similar, because they produce similar occurrences of the highest cloud tops, which was not the case in Fig. 1 prior to calibration. The ARM radar team now needs to investigate what could explain this failure of the calibration cycle.

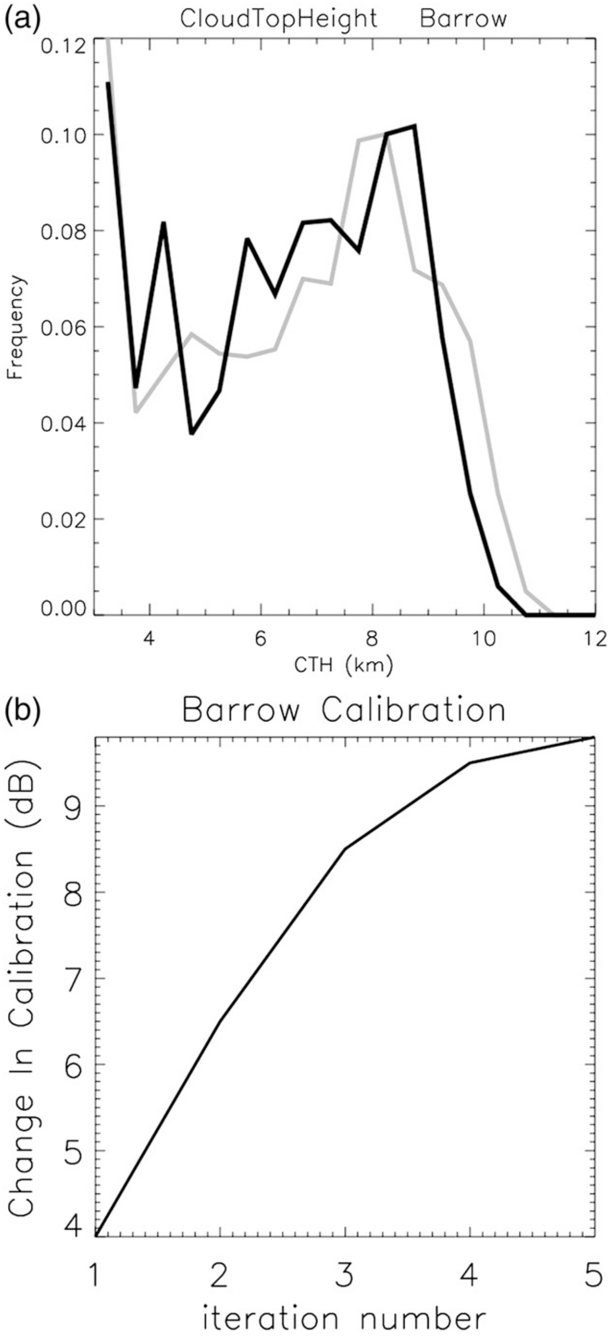

FIG. 1. (a) PDFs of cloud-top height derived from the original Barrow radar observations (gray) and from the *CloudSat* observations within a 200-km radius around the Barrow site for the same period (black). (b) Estimate of the calibration error for each iteration.

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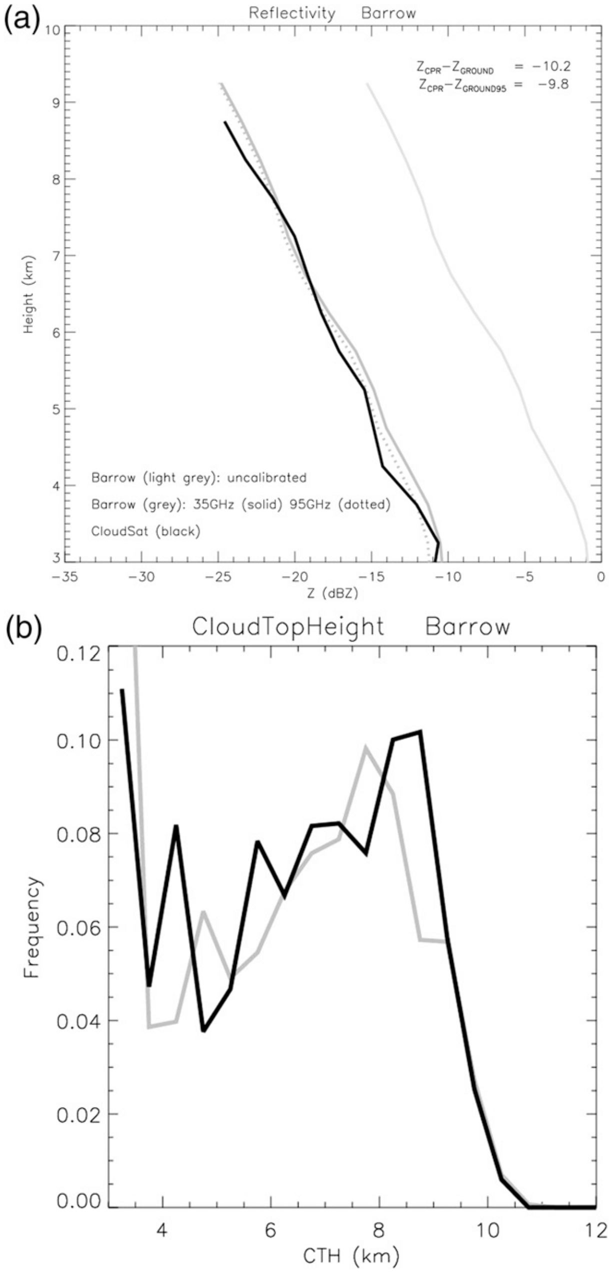

FIG. 2. (a) Mean vertical profile of radar reflectivity from the Barrow ARM radar (gray profiles: light gray is the initial profile, solid gray is the calibrated profile, and dotted gray is the calibrated profile converted at 94 GHz for comparison with *CloudSat*) and the *CloudSat* CPR radar (black profile). The weighted-mean differences between the Barrow radar (initial and converted to 94 GHz) and *CloudSat* are given as numbers in the upper-right part of the figure. (b) Same as Fig. 1, but using the calibrated Barrow radar data.

4. Calibration of the Cabauw cloud radar

The 35-GHz Doppler cloud radar was installed at the Cabauw site, the Netherlands, in summer 2001. This cloud radar has been developed by Degreane Horizon (France). The design is based on Degreane's wind profiler systems. During the Baltic Sea Experiment (BALTEX) BRIDGE Campaign (BBC; Crewell et al. 2004) in 2001 at Cabauw, the 35-GHz cloud radar data were compared for selected days with the data from the calibrated 94-GHz MIRACLE cloud radar (Quante et al. 1998). This intercomparison showed a good agreement between the data of both cloud radars: differences were within a range of 1–2 dB. The 35-GHz cloud radar transmitted power and noise figures are determined once per day during a calibration cycle using a calibrated noise source. No further independent calibration is performed. This calibration has been checked in March 2004 during the Cloudnet project (Illingworth et al. 2007) against the mobile 95-GHz Doppler cloud radar of the Site Instrumental de Recherche par Télédétection Atmosphérique (SIRTA) site in France (Haeffelin et al. 2005). The same calibration result as that of the 2001 intercomparison was found. However, the installed 35-GHz traveling waveguide tube (TWT) showed a significant decrease in output power from 2001 to 2005. Therefore, a new TWT was installed in autumn 2005, but no independent calibration of the system had been performed since this date. Furthermore, in summer 2007 problems with the signal strength in the receiver chain were noted. These were only partly resolved, and an increase in the noise figure remained unresolved. This increase rendered the procedure implemented by the manufacturer for the calibration of the noise figure inadequate. An alternative calibration of the system's noise figure is presently under investigation but has not been applied to the data used in the study. As a result, the last calibration reference for the Cabauw cloud radar is from 2004. The measured sensitivity of the radar in 2001 and 2004 was −64 dBZ at 1-km range in pulse compression mode, −54 dBZ at 1-km range in uncompressed mode.

The Cabauw radar reflectivities for all of 2008 have been compared with the *CloudSat* reflectivities. The direct application of the PAL09 technique using the 2008 observational period leads to the conclusion that the calibration of the Cabauw radar is too low by about 3 dB (not shown). However, the PDF of cloud-top height derived from the corrected data show lower occurrences of the highest cloud tops detected by the Cabauw radar when compared with *CloudSat* (Fig. 3), which suggests that adding 3 dB to the Cabauw reflectivities and degrading the Cabauw radar sensitivity to that of *CloudSat* still results in the Cabauw radar being less sensitive than *CloudSat*. This is opposite to the case of the Barrow radar: when the ground-based radar is calibrated too low, too many data are screened out when degrading the ground-based radar to the spaceborne radar sensitivity, as discussed in section 2.

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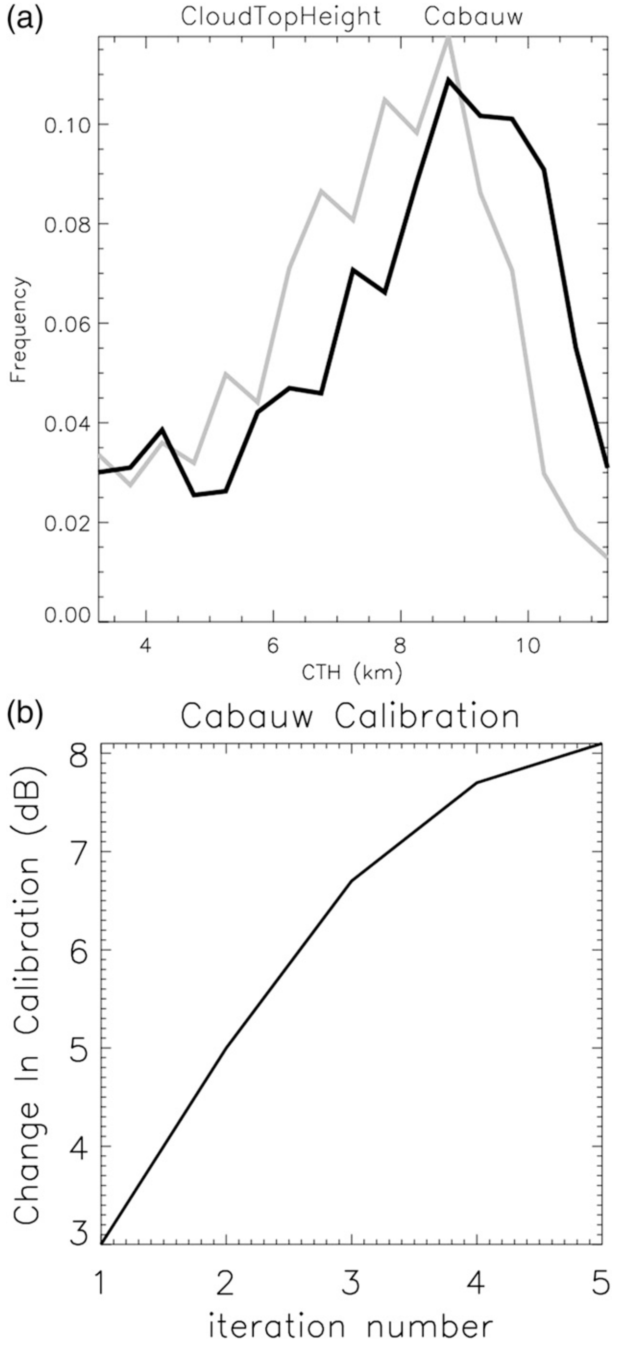

FIG. 3. Same as in Fig. 1, but for the Cabauw radar.

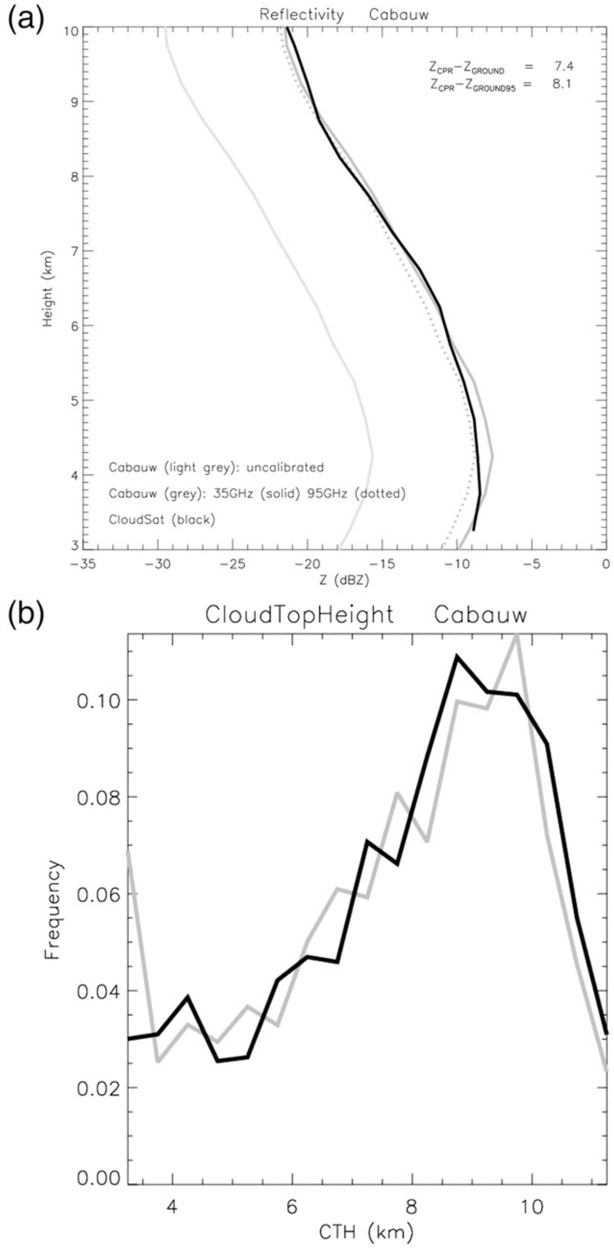

FIG. 4. Same as in Fig. 2, but for the Cabauw radar.

Therefore, as was done for the Barrow radar, an iterative procedure was applied, and after five iterations a reflectivity difference ($Z_{\text{CloudSat}} - Z_{\text{Cabauw}}$) of +8.0 dB was obtained. The calibration error estimated at each step is given in Fig. 3b. The corresponding mean vertical profiles of radar reflectivity and cloud-top height PDFs for this last iteration are given in Fig. 4. The vertical gradients of radar reflectivity are again in very good agreement overall (Fig. 4a), as was the case at Barrow (Fig. 2a). The cloud-top height PDF (Fig. 4b) this time shows that with a calibration correction of +8.0 dBZ the sensitivity of both radars is similar, because they now produce occurrences of the highest cloud tops in much better agreement than in Fig. 3 prior to calibration. It is noted, however, that the agreement of the highest cloud-top statistics is still not perfect, which would imply that the calibration error should be increased further. The problem is that if we iterate more, then the calibration constant remained unchanged, which means that the calibration cannot be

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improved further with our method, although the cloud-top height statistics is not in perfect agreement. The most likely reason for this slight difference is that the basic assumption of the comparison (the invariance of the cloud-top height and reflectivity PDF over a 200-km range around the ground-based radar) is better satisfied at Barrow than at Cabauw.

5. Checking the calibration of the RASTA airborne cloud radar

In 2006 and 2007, the 95-GHz airborne Doppler cloud radar named the Radar System Airborne (RASTA; see Protat et al. 2004; PAL09) was operating on the French Falcon 20 platform. The calibration of the radar has been achieved using the ocean surface backscatter technique (Li et al. 2005; Bouniol et al. 2008). RASTA has been used to evaluate the calibration of *CloudSat* using two field experiments (PAL09). The resulting sensitivity has been estimated as −31.5 dBZ at 1-km range. Since then, RASTA has been integrated in another French research aircraft, the ATR-42, in a dual-beam downward-looking configuration that participated in an April 2008 field experiment in the Arctic called the Polar Study Using Aircraft, Remote Sensing, Surface Measurements and Models, of Climate, Chemistry, Aerosols, and Transport (POLARCAT; see http://www.polarcat.no/ for further details). The radar in this new configuration has not been calibrated yet using the ocean surface backscatter technique, but a budget of gains and losses has been carried out: a change in range bin size from 60 to 30 m (a 3-dB loss), a change in ambiguous range from 15 to 7.5 km (a 3-dB gain), an increase in integration time (with a 6-dB gain expected), a change of antenna size from 45 to 30 cm (a 6-dB loss), and the removal of an attenuating radome (a 3-dB gain). This budget indicates that the new configuration should be approximately 3 dB more sensitive than the Falcon 20 configuration (i.e., −34.5 dBZ at 1-km range).

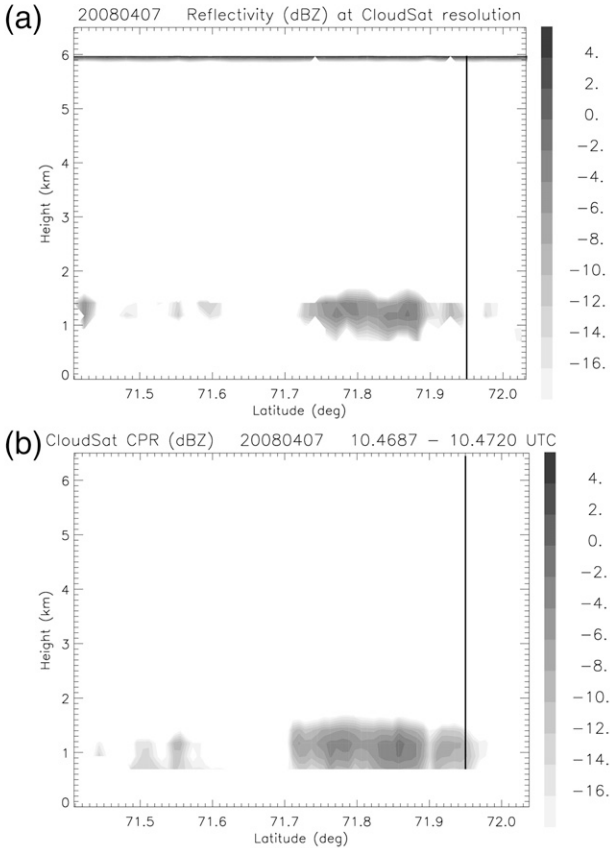

FIG. 5. Latitude–height contour plot of (a) the RASTA reflectivities averaged at the *CloudSat* resolution during the 7 Apr 2008 flight of the POLARCAT field experiment and calibrated using a −2.5-dB calibration constant, and (b) the *CloudSat* reflectivities of the corresponding overpass. The time intervals (in decimal hours) corresponding to this vertical cross sections are [10.46; 10.65] h for RASTA (684 s, 11.4 min) and [10.4687; 10.4719] h for *CloudSat* (11.5 s). The exact overpass occurs at 10.4703 h, corresponding to latitude 71.95°N on the figure. The ground clutter has been screened out in both radar observations.

Three POLARCAT flights have been conducted along the *CloudSat* track on 1, 7, and 10 April 2008. The collocation in time and space was particularly good for the two latter flights, which have been used for the checking the RASTA calibration. The RASTA reflectivities have been first degraded at the resolution of *CloudSat* [an approximately 1.5-km footprint and 240-m vertical resolution (Tanelli et al. 2008)]. Then, the mean difference ($Z_{\mathrm{CloudSat}} - Z_{\mathrm{RASTA}}$) has been estimated—2dB for the 7 April flight (Fig. 5), and 3 dB for the 10 April flight (Fig. 6), with standard deviations of the difference ranging from 1 to 3 dB, depending on the time window considered for the comparison. The smallest standard deviation of the difference (1.0 dB) is found for the 10 April flight with a short time window of ±2 min or so around the exact overpass time, corresponding to the latitude interval (70.55°–70.80°N) in Fig. 6a. The overall conclusion of this direct comparison is that the calibration of RASTA is too high by about 2–3 dB, which corresponds to a sensitivity of −35 to −34 dBZ at 1-km range. This number agrees very well with the expectations drawn from a simple budget of gains and losses (−34.5 dBZ, as discussed above). The impact of the new RASTA calibration on the *CloudSat* comparisons can also be qualitatively checked by comparing the calibrated RASTA reflectivities in Figs. 5a and 6a with the *CloudSat* reflectivities in Figs. 5b and 6b. This result demonstrates the power of *CloudSat* as a validation reference for airborne cloud radars in need of a calibration check.

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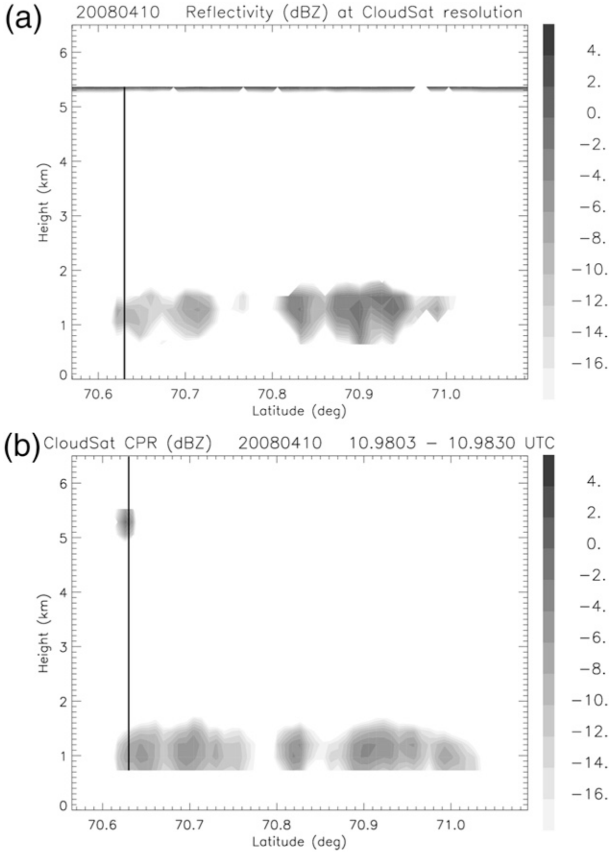

FIG. 6. Same as in Fig. 5, but for the 10 Apr 2008 flight. The time intervals (expressed in decimal hours) corresponding to this vertical cross-sections are [10.96; 11.135] h for RASTA (630 s, 10.5 min) and [10.9803; 10.9830] h for *CloudSat* (9.7 s). The exact overpass is at 10.9815 h, corresponding to latitude 70.63°N on the figure.

6. Conclusions

The objective of this paper is to demonstrate the power of using *CloudSat* as a radar calibrator for ground-based radars (using a statistical approach) and airborne radars (using direct comparisons with flights carried out along the *CloudSat* track). To do so, two ground-based radars for which calibration uncertainties were reported have been considered (Barrow, North Slope of Alaska, from the ARM program, and Cabauw, the Netherlands). It has been found that the Barrow and Cabauw radars were measuring reflectivities respectively 9.8 dB too high and 8.0 dB too low with respect to *CloudSat*. These are very large values. The vertical gradient of mean radar reflectivity is in excellent agreement on both cases with *CloudSat*, which is an indirect validation of the statistical calibration method. After this study has been conducted, it has been found that the low-noise amplifier of the Cabauw radar had degraded, and that the original antenna specs and waveguide loss estimates provided by the manufacturer were used, although these numbers may have changed.

This paper also highlights that direct comparisons between *CloudSat* and any airborne cloud radar flying under the *CloudSat* track allows for a validation of the airborne cloud radar calibration, if appropriate. This is the other way around with respect to how things are usually done, but because the calibration of *CloudSat* has been carefully assessed and is checked routinely during its lifetime, the main objective of this paper is to demonstrate that it is a good reference to use. To do so, we have used observations gathered recently in the Arctic by the RASTA airborne cloud radar, which is integrated for the first time with a very different configuration (and therefore with expected calibration differences) in a new research aircraft (the French ATR-42 aircraft). It is found, using two flights from this POLARCAT field experiment, that the RASTA radar in this new configuration measures reflectivities 2.5 dB higher than *CloudSat*. Once this difference is accounted for in the RASTA calibration constant, the RASTA sensitivity is −34 dBZ at 1-km range, which is in good agreement with the gains and losses estimated from the change of configuration.

Acknowledgments. This work has been partly supported by the U.S. Department of Energy Atmospheric Radiation Measurement (ARM) program, and partly by the French Space Agency (Centre National d'Études Spatiales). The Barrow NSA ARM radar data were obtained from the ARM Program Archive. The Cabauw site is acknowledged for providing the 35-GHz radar data used in this study. The NASA *CloudSat* CPR data and products were obtained from the *CloudSat* Data Processing Center run by the Cooperative Institute for Research in the Atmosphere (CIRA).

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