The Evaluation of *CloudSat* and CALIPSO Ice Microphysical Products Using Ground-Based Cloud Radar and Lidar Observations

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ABSTRACT

In this paper, the statistical properties of tropical ice clouds (ice water content, visible extinction, effective radius, and total number concentration) derived from 3 yr of ground-based radar–lidar retrievals from the U.S. Department of Energy Atmospheric Radiation Measurement Climate Research Facility in Darwin, Australia, are compared with the same properties derived using the official *CloudSat* microphysical retrieval methods and from a simpler statistical method using radar reflectivity and air temperature. It is shown that the two official *CloudSat* microphysical products (2B-CWC-RO and 2B-CWC-RVOD) are statistically virtually identical. The comparison with the ground-based radar–lidar retrievals shows that all satellite methods produce ice water contents and extinctions in a much narrower range than the ground-based method and overestimate the mean vertical profiles of microphysical parameters below 10-km height by over a factor of 2. Better agreements are obtained above 10-km height. Ways to improve these estimates are suggested in this study. Effective radii retrievals from the standard *CloudSat* algorithms are characterized by a large positive bias of 8–12 μm. A sensitivity test shows that in response to such a bias the cloud longwave forcing is increased from 44.6 to 46.9 W m^{-2} (implying an error of about 5%), whereas the negative cloud shortwave forcing is increased from -81.6 to -82.8 W m^{-2}. Further analysis reveals that these modest effects (although not insignificant) can be much larger for optically thick clouds. The statistical method using *CloudSat* reflectivities and air temperature was found to produce inaccurate mean vertical profiles and probability distribution functions of effective radius. This study also shows that the retrieval of the total number concentration needs to be improved in the official *CloudSat* microphysical methods prior to a quantitative use for the characterization of tropical ice clouds. Finally, the statistical relationship used to produce ice water content from extinction and air temperature obtained by the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite is evaluated for tropical ice clouds. It is suggested that the CALIPSO ice water content retrieval is robust for tropical ice clouds, but that the temperature dependence of the statistical relationship used should be slightly refined to better reproduce the radar–lidar retrievals.

1. Introduction

The importance of clouds on the evolution of climate through their direct effect on the earth radiation budget and water cycle is well recognized. However, despite significant improvements brought to the representation of clouds in models, clouds still remain by far the largest source of spread among future climate projections produced by climate models (e.g., Potter and Cess 2004; Bony et al. 2006; Dufresne and Bony 2008). Among the different clouds forming in the troposphere and preferential regions of high cloud occurrence, tropical ice clouds are of particular importance, owing to their extensive

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horizontal and vertical coverage and long lifetime (e.g., Sassen et al. 2008). Because of difficulties in estimating the large-scale radiative effect of these clouds, even the sign of the net radiative effect of these tropical ice clouds remains uncertain. Recent cloud radar and lidar observations collected on a global scale as part of the A-train mission (Stephens et al. 2002) represent an unprecedented and unique opportunity to address these crucial scientific questions at regional and global scales. Being the first mission of its kind, a thorough evaluation of the measurements and standard products is presently undertaken. The prelaunch calibration of *CloudSat*, in-flight calibration, and stability over the period of operations has been very recently reported in Tanelli et al. (2008). Direct comparisons of *CloudSat* measurements of 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 1 dB (Protat et al. 2009, hereafter PAL09), which is better than the initial specification. This result has also been confirmed using statistical comparisons between continuous ground-based cloud radar observations over five different sites (PAL09). Because the *CloudSat* calibration has been assessed, the scientific community has been making increased use of the more elaborate products of the *CloudSat* mission relating to the microphysical and radiative properties of ice clouds for process studies (see summary in Stephens et al. 2008) and model evaluation (e.g., Waliser et al. 2009; Bodas-Salcedo et al. 2008). However, despite the first attempts to evaluate the microphysical products from *CloudSat* [Austin et al. (2009) with in situ observations, Barker et al. (2008) using airborne cloud radar observations, and Woods et al. (2008) using cloud-resolving model outputs], there is still clearly a need for a thorough evaluation of those products, using directly comparable references such as dedicated airborne and ground-based radar–lidar observations collected from around the globe.

In this paper, the same ground-based–spaceborne statistical comparison strategy as that described in PAL09 is used to evaluate the accuracy of the two standard ice cloud microphysical products derived from the *CloudSat* observations. Also, a third simple statistical method has been applied to the *CloudSat* observations and is evaluated at the same time. The performance of the statistical relationship used to produce the standard Cloud-Aerosol Lidar Infrared Pathfinder Satellite Observations (CALIPSO) ice water content product (Heymsfield et al. 2005) is finally assessed by comparing with ground-based radar–lidar ice water contents. For this purpose, we use 3 yr of continuous cloud radar–lidar observations from the Darwin, Australia, Atmospheric Radiation Measurement (ARM; Stokes and Schwartz 1994) Climate Research Facility and extractions of the *CloudSat* microphysical products within a 200-km radius around this Darwin site. The paper is organized as follows: Ground-based radar–lidar retrievals are discussed in section 2. The standard and nonstandard *CloudSat* and CALIPSO microphysical products used in the present study are briefly described in section 3. The statistical comparison between ground-based and *CloudSat* microphysical properties is then analyzed in section 4. The performance of the CALIPSO-like ice water content retrieval is assessed in section 5. Conclusions and perspectives are finally discussed in section 6.

2. Ground-based radar–lidar retrieval techniques for ice clouds

a. Discussion on radar–lidar techniques

To evaluate *CloudSat* measurements of cloud microphysics, ice cloud properties from ground-based observations need to be derived. The most suitable techniques for obtaining these properties are the radar–lidar combination and the Doppler radar velocity–reflectivity combination (e.g., Heymsfield et al. 2008). Ground-based cloud radars will penetrate most clouds layers but will miss a portion of the thin cirrus clouds (Comstock et al. 2002; Mace et al. 2006; Protat et al. 2006). Conversely, ground-based lidars will detect these thin cirrus clouds, but the backscatter signals will often be extinguished by supercooled liquid cloud layers in mixed-phase clouds or clouds of optical depth larger than 2–3 (e.g., Sassen and Cho 1992; Protat et al. 2006). There is an overlap region in which radar–lidar observations can be used simultaneously to derive accurate retrievals of cloud properties (e.g., Donovan and van Lammeren 2001; Wang and Sassen 2002; Okamoto et al. 2003; Tinel et al. 2005; Delanoë and Hogan 2008, hereafter DH08). However, it has been estimated that this overlap only corresponded to about 10%–15% of the total ice cloud volume of mixed-phase and ice clouds over the Cloudnet sites (Illingworth et al. 2007). This problem has recently been overcome using the variational radar–lidar retrieval technique of DH08, which produces a solution for all instrumental combinations (radar alone, radar–lidar, and lidar alone). Methods relying on radar reflectivity and Doppler velocity measurements (Matrosov et al. 2002; Mace et al. 2002; Sato and Okamoto 2006; Delanoë et al. 2007) also show considerable promise, as they can be applied to all ice clouds detected by a cloud radar. These methods produce ice water content estimates almost as accurate as radar–lidar retrievals (e.g., Delanoë et al. 2007; Heymsfield et al. 2008) and virtually unbiased estimates of visible extinction at midlatitudes (Delanoë et al. 2007). These methods also allow additional cloud parameters, such as

the in-cloud vertical air velocity and terminal fall speed of the hydrometeors to be retrieved. Methods using radar reflectivity and temperature (e.g., Hogan et al. 2006b; Protat et al. 2007) can also be considered to produce estimates of ice water content (Illingworth et al. 2007; Protat et al. 2007), but they are not expected to be more accurate than the standard *CloudSat* products to be evaluated (Heymsfield et al. 2008). In view of these considerations, the microphysical and radiative properties that will be considered as the reference for the evaluation of the *CloudSat* ice microphysical products are derived using the variational technique of DH08, producing solutions for the radar-only, lidar-only, and radar–lidar cloud volumes.

b. Description of the DH08 radar–lidar method

As discussed previously, the unique aspect of the DH08 variational approach is to retrieve the ice cloud properties seamlessly between regions of the cloud detected by both radar and lidar and regions detected by just one of these two instruments. The general principle of this type of variational method is to define a forward model that depends on the cloud variables to be retrieved, an a priori value for these variables (also called first guess in some papers), and to retrieve those cloud variables by minimizing in the least squares sense the difference between this forward model and the observations (in the present case the radar reflectivity and the lidar backscatter coefficient). The forward model contains an assumed microphysical model describing the shape of the normalized particle size distribution (a two-parameter modified gamma distribution), following Delanoë et al. (2005), as well as relationships between particle mass, cross-sectional area, and maximum size. The ice particle mass is assumed to follow the Brown and Francis (1995) mass–maximum diameter relationship derived from aircraft data in ice aggregates. The corresponding cross-sectional area–maximum size relationship is taken from Francis et al. (1998), derived from the same aircraft dataset as Brown and Francis (1995). Using the method proposed in Hogan (2006), multiple scattering effects are accounted for in the forward modeling of the lidar attenuated backscatter. Ancillary information is also required for each component of the forward model. This includes the thermodynamic state of the atmosphere (in particular, profiles of temperature, pressure, and humidity), as well as instrumental properties (in particular the lidar field-of-view needed to calculate the contribution from multiple scattering). These ancillary parameters are usually provided by a weather forecast model [the European Centre for Medium-Range Weather Forecasts (ECMWF) model analysis when the method is applied to ground-based radar–lidar sites as in the present study].

The core of the method is the radar–lidar retrieval. The visible extinction α and extinction-to-backscatter ratio (assumed constant) are retrieved using the lidar backscatter and molecular signal after traversing the cloud, which provides an integral constraint on extinction. The other cloud variables to be retrieved are the following: the ice water content (IWC), the effective radius (R_e), and the total number concentration N_T. In the DH08 method, they are linked through a free parameter of the normalized particle size distribution, which must be estimated too: the ice normalized number concentration parameter N_0^* (defined in Delanoë et al. 2005). DH08 showed that a very good a priori value for N_0^* can be found using $N_0^* = N_0^*/\alpha^b$ with $b = 0.67$. An a priori N_0' as a function of temperature, derived from a set of in situ microphysical measurements (see DH08), is used in the variational formulation. Two lookup tables, relating (IWC/N_0^*) and (α/N_0^*) to (Z/N_0^*), are used as additional constraints in the variational formalism, which produces a forward model with as many equations as unknowns. These two relationships have been demonstrated to be very robust for a given mass–maximum-dimension relationship (Tinel et al. 2005). The effective radius is then calculated from IWC and α, following the definition of Stephens et al. (1990). The total number concentration is estimated using another lookup table relating N_T to α. One aspect of these types of methods is the characterization of the error covariance matrices, which is not discussed here; the reader is referred to DH08 and Delanoë and Hogan (2010) for that.

When the lidar signal is unavailable (e.g., because of strong attenuation), the variational framework ensures that the retrieval reverts back to a radar-only retrieval, using two empirical relationships between ice water content, radar reflectivity, and temperature (e.g., Liu and Illingworth 2000; Hogan et al. 2006b; Protat et al. 2007) and between extinction, radar reflectivity, and temperature (Hogan et al. 2006b), but with an improved a priori of N_0^* derived from the part of the cloud sampled by radar and lidar. When a supercooled layer is detected, the lidar signal in and above the liquid is not used even if it is identified as also containing ice. This is because the lidar signal is strongly attenuated by liquid water. In such regions, it is assumed that radar returns are primarily from ice and that supercooled liquid water attenuation of the signal can be neglected (Hogan and Illingworth 2003). In this situation, the retrieval reverts back to a radar-only retrieval as well.

In the same way, when the radar signal is unavailable (such as in optically thin cirrus), a lidar-only retrieval is performed. This part of the retrieval is not used in the present study and is therefore not described further.

Figure 1 shows the vertical profile of the percentage of points retrieved using the radar–lidar or the radar-only part of the DH08 retrieval, for the 3 yr of radar–lidar observations used in the present study. As can be seen from this figure, the radar–lidar part (which is expected to be the most accurate part) largely dominates the statistics up to 12–13 km, and from 14 km the two parts of the retrieval method contribute equally. For this reason it is believed that the DH08 ground-based retrievals can be used with confidence as a reference against that the simpler radar-only or lidar-only satellite retrievals can be evaluated; however, it is very difficult to estimate with confidence the accuracy of ground-based ice cloud retrieval methods. There are three ways usually explored, with none of them being perfect:

(i) a comparison with airborne in situ microphysical observations. The advantage here is the more direct measurement of some microphysical quantities, such as IWC; however, its shortcomings are a volume, temporal, and spatial mismatch with the ground-based observations—similar assumptions required, for instance, the mass–maximum dimension relationship—and measurement uncertainties, for example, the shattering of ice crystals (Heymsfield 2007; McFarqhuar et al. 2007);
(ii) the use of a radiative transfer code in which the retrieved ice cloud properties are used and comparisons with shortwave (SW) and longwave (LW) radiation at surface and top-of-atmosphere. The advantage here is that it ensures that the ice cloud properties retrieved produce the good interaction with incoming and outgoing radiation; however, it has the shortcoming that assumptions in retrieval should be identical to assumptions in radiative code—the effect is too small for some cloud types—and validation of the vertically integrated effect, which can mask compensating errors; and
(iii) the use of synthetically generated profiles of measurements and cloud variables, as done for instance in Hogan et al. (2006a) or Heymsfield et al. (2008). The advantage is that it uses the best collocated measurement and ice cloud properties profiles; however, its shortcoming is that some assumptions similar to those of the radar–lidar retrieval methods must be made, such as the mass–maximum dimension relationship.

The accuracy of the DH08 method has been estimated using synthetically generated radar–lidar profiles following Hogan et al. (2006a). These estimated errors range from 10%–20% for the radar–lidar part of the method, 20%–40% for the radar part of the method, and can be larger than 50% for the lidar part of the method

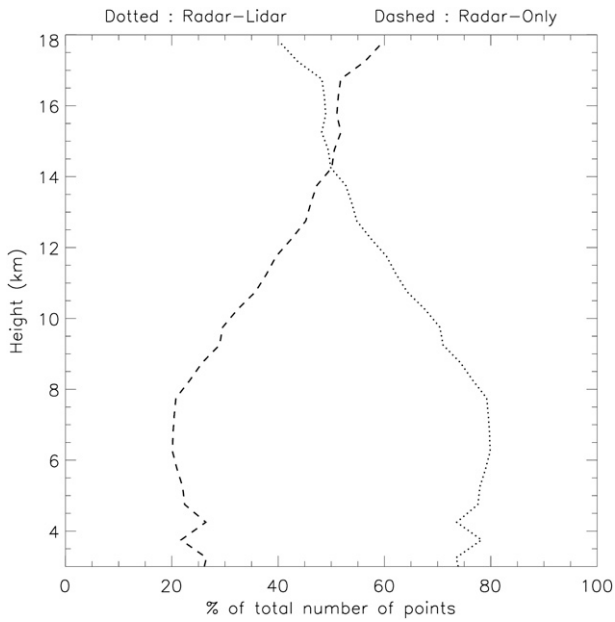

FIG. 1. Vertical profile of the percentage of radar–lidar (dotted) and radar-only (dashed) parts of the DH08 retrieval. This has been obtained from the 3 yr of Darwin radar–lidar observations used in this study.

(except for extinction, for which the method is more accurate; DH08). These error estimates are probably optimistic because they do not include all possible sources of errors, although they probably accurately reflect the errors associated with the measurement uncertainties (through the calculation of the error covariance matrices, see Delanoë and Hogan 2010). Errors associated with the use of a single mass–maximum dimension relationship are not included, for instance, because there is no robust measurement of reference to compare with. However, in the context of this study, as will be discussed in the next section, the assumption made for the mass–maximum dimension relationship to derive the *CloudSat* microphysical products is either much cruder (ice spheres with solid ice density for the 2B-CWC-RO product) or exactly the same [the Brown and Francis (1995) ice aggregates for the "ZT"] as that held in the DH08 method. This method has not been evaluated against in situ microphysical observations and using radiative transfer code and radiation measurements yet. This evaluation is presently being carried out in the framework of an ARM radar–lidar method intercomparison exercise.

3. The CloudSat and CALIPSO microphysical products

In this section, the principle of three methods for the retrieval of the ice cloud microphysical properties

from *CloudSat* reflectivities and auxiliary products is described. The first two methods are those used to produce the standard *CloudSat* microphysical radar-only (RO) and radar and visible optical depth (RVOD) products named 2B-CWC-RO and 2B-CWC-RVOD, respectively. The third method is not used routinely. It has only been applied to the extractions of *CloudSat* data in the vicinity of the Darwin ARM site. If the method proves to be sufficiently accurate, it would be fairly straightforward to derive a new standard product from it. The CALIPSO method for the retrieval of IWC is then described. It is important to note that in the near future radar–lidar techniques (such as that used to process ground-based observations, DH08) will provide more accurate retrievals of cloud microphysics from A-train mission observations (e.g., first results in Delanoë and Hogan 2010).

a. *Description of the 2B-CWC-RO and 2B-CWC-RVOD methods*

In this section, the retrieval methods used to produce the latest release (release 04, or R04) of the *CloudSat* 2B-CWC-RO and 2B-CWC-RVOD products are briefly described. A detailed description of the 2B-CWC-RO method is given in Austin et al. (2009), as well as an evaluation of the method using in situ observations and other satellite products from the A-train mission [Microwave Limb Sounder (MLS) on the Aura platform; see Wu et al. (2009)]. The main difference between the two methods is that the 2B-CWC-RO method is a radar-only retrieval, whereas the 2B-CWC-RVOD radar and visible optical depth method makes use of the optical thickness derived from the visible channels of the Moderate Resolution Imaging Spectroradiometer (MODIS) on the *Aqua* platform of the A Train as an additional integral constraint for the visible extinction retrieval in the variational process (e.g., Benedetti et al. 2003; Austin et al. 2009).

The underlying assumptions of the two methods are similar. Both methods assume that the ice particle size distribution can be described by a lognormal size distribution (a modified gamma distribution was used in earlier versions of the method, see Austin and Stephens 2001, 2008), which is itself defined by the three following parameters to be retrieved: the characteristic diameter D_g, the total number concentration N_T, and the distribution width ω. In the latest version of the *CloudSat* R04 algorithms, these three parameters and their variation as a function of height are retrieved (in contrast to earlier versions in which height-invariant quantities were retrieved; Austin et al. 2009), and appropriate temperature dependent a priori values are set. The D_g and ω are derived as a function of temperature from fits to in situ microphysical observations. A more complex procedure is used for N_T, which depends on D_g, ω, IWC, and Z, and the temperature dependence of N_T is introduced using the Liu and Illingworth (2000) IWC–Z–T relationship (see Austin et al. 2009 for further details). This is very different from the a priori information used for the equivalent of N_T in the normalized particle size distribution framework used in DH08.

Using integrals of the ice particle size distribution expressed as a function of the diameter of an equivalent mass ice sphere, calculations of bulk microphysical properties of ice clouds are conducted. These ice spheres are assumed to hold the density of solid ice (0.917 kg m^{-3}). It should be noted that the definition of an effective radius is the same in all retrieval methods used in the present paper, following Stephens et al. (1990).

b. *Description of the* CloudSat *ZT method*

The ice water content retrieval from reflectivity and temperature (Protat et al. 2007) and the visible extinction retrieval from ice water content and temperature [Heymsfield et al. (2005), which is also the standard method for the retrieval of ice water content from the CALIPSO lidar extinctions, see section 3c] can be simply combined to produce a simple statistical estimate of the vertical profiles of bulk microphysical properties of ice clouds. The method uses as inputs the *CloudSat* reflectivities from the 2B-GEOPROF product and the ECMWF from the auxiliary *CloudSat* product named ECMWF-AUX. From the obtained *CloudSat* Z and ECMWF-AUX T at each radar range bin, the IWC–Z–T relationship from Protat et al. (2007) is used to derive IWC. Then from this IWC and the ECMWF-AUX T the extinction is derived using the Heymsfield et al. (2005) α–IWC–T relationship. From IWC and α, the effective radius R_e is also estimated using again the definition of Stephens et al. (1990). However, unlike the DH08 method and the 2B-CWC-RO and 2B-CWC-RVOD *CloudSat* methods, this method does allow for the retrieval of total number concentration N_T. This method has been applied to extractions of *CloudSat* reflectivities 200 km around the Darwin site and will be also assessed in the next section using the ground-based radar–lidar retrievals.

c. *Description of the CALIPSO IWC retrieval method*

In the third release of the CALIPSO standard products (not available at the time this paper is being written), an estimate of the IWC will be provided. This IWC is derived using the Heymsfield et al. (2005) α–IWC–T relationship discussed in section 3b earlier. The way to use this relationship will, however, be different from the way it is used in the *CloudSat* ZT retrieval method. The

visible extinction is first derived from the CALIPSO lidar backscatter using the standard extinction algorithm (Young and Vaughan 2009). This extinction estimate and the air temperature provided by the ECMWF model are then used as inputs to the statistical relationship to derive IWC.

4. Statistical assessment of the CloudSat microphysical products

In this section, results of the statistical comparisons between the ice cloud properties derived from cloud radar–lidar observations at Darwin and those derived from the satellite methods described in section 3 are discussed. The methodology used to carry out these comparisons is highlighted (further details and sensitivity tests can be found in PAL09). Then, the differences obtained between the ground-based and satellite retrieval methods are analyzed.

a. Methodology

As in PAL09, great caution has been exercised to come up with ground-based and satellite samples that are fully comparable. First, the ground-based radar observations have been carefully degraded to the same sensitivity as *CloudSat* (around −30 dBZ; Tanelli et al. 2008; PAL09) prior to any comparison. To compare the ground-based and spaceborne radar observations, *CloudSat* data from a radius of 200 km around the Darwin site have been considered (as described in PAL09). As the diurnal variability of the ice cloud properties can have an impact on the comparisons, two curves will be shown for the ground-based statistics to characterize this—one that includes all ground-based observations and one constructed from a subsample of ground-based observations within one hour of the two daily *CloudSat* overpasses.

The ice cloud profiles (which do not have a liquid layer below) and the convective ice profiles (i.e., the ice part of convective systems) have also been carefully separated using the following two-step procedure. The altitude of the 0°C isotherm altitude is estimated from the *CloudSat* ECMWF-AUX product, and it is assumed that all returns from above the 0°C altitude are from ice clouds and below are from liquid clouds. In both the space-borne and ground-based analyses the occurrence of supercooled liquid water is treated as ice. Following this separation, if more than 90% of the profile below the 0°C altitude contains liquid water, then the profile is classified as convective ice, otherwise it is classified as ice cloud profile. The 90% threshold is used (as opposed to 100%) to allow for total extinction of the *CloudSat* beams before reaching the ground in the most intense storms. It is noteworthy that our results are not sensitive to a change in percentages ranging from 70% to 100%. A similar (although much more elaborate) separation has been carried out with the ground-based observations using the "target categorization" approach (Illingworth et al. 2007; available online from http://www.met.rdg.ac.uk/~swrhgnrj/publications/categorization.pdf; and DH08) to ensure that the same type of ice clouds is included in the ground-based and satellite statistics and minimize the impact of the different viewing geometries. This technique consists of classifying each observed radar–lidar volume as a meteorological or nonmeteorological target using cloud radar, lidar, and microwave radiometer measurements and assigning a phase (liquid, ice, and mixed-phase) and a data quality flag to each cloud volume. In the following, only the statistical properties derived from the ice cloud profiles are compared. Also, to produce as fair as possible a comparison with *CloudSat*, the lidar-only retrievals produced by the DH08 method have not been included in the statistics of ice cloud properties.

The wavelength of the ground-based radar (35 GHz) is also different from that of *CloudSat* (94 GHz). To account for this wavelength difference a conversion procedure has been derived from in situ microphysical observations in PAL09. This conversion has been applied to the ground-based radar reflectivities to update the comparison of reflectivities with a dataset larger than that included in PAL09. However, as the radar wavelength is accounted for in the DH08 method, there is no need to do so for the retrieval of the ice microphysical properties.

b. 2B-CWC-RO versus 2B-CWC-RVOD

This study offers the opportunity to characterize the added value of using the visible optical thickness from MODIS as an additional constraint in the *CloudSat* standard retrievals. For this purpose the microphysical properties in the 2B-CWC-RO and 2B-CWC-RVOD products have been compared (see Fig. 2 for ice water content). The comparisons for effective radius and total concentration are not shown, as the conclusions are the same as those drawn for ice water content. Figure 2 shows that most points are aligned along the 1:1 line with some scatter. However, the probability distribution functions (PDFs) and mean vertical profiles of these ice cloud properties are nearly identical, the fractional differences between the two PDFs being less than 0.1% (not shown). This, presumably, is in part because of the fact that at night both products are identical. This result indicates that in the current release (R04) there is no statistical added value to using the MODIS derived visible optical thicknesses as an additional constraint in the current version of the standard 2B-CWC *CloudSat*

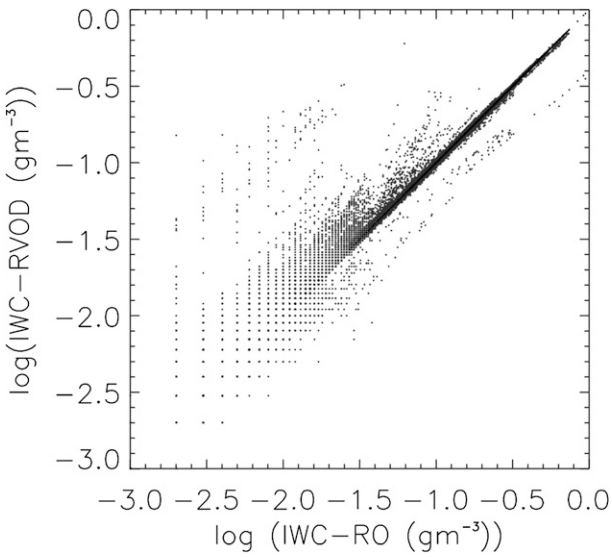

FIG. 2. Scatterplot of IWC retrieved using the 2B-CWC-RO or the 2B-CWC-RVOD methods. The 1:1 line is also displayed for comparison.

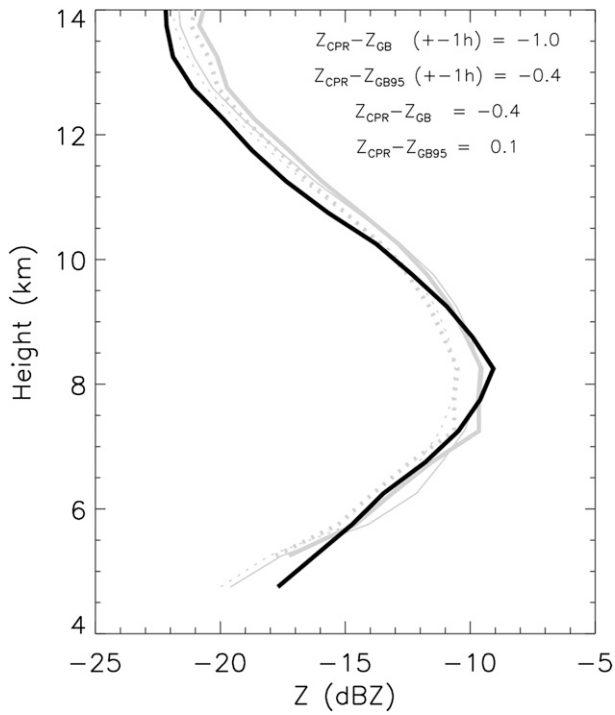

FIG. 3. Mean vertical profile of radar reflectivity as derived from the ground-based Darwin ARM radar (gray profiles) and the *CloudSat* CPR radar (black profile). Four profiles are displayed for the ground-based radar: all observations included (thin gray lines), only ground-based measurements ±1 h around the *CloudSat* overpass (thick gray lines), and with reflectivity conversion from 35 to 95 GHz (dashed gray lines) or without (solid gray lines). The weighted mean differences for these four cases are given as numbers in the upper-right part of the figure.

method. This study does not address this on a global scale or on an individual case study basis, which would be interesting to investigate as part of further studies. In the remainder of the paper, only the results from the 2B-CWC-RO method will be shown, but these results also apply to the 2B-CWC-RVOD method.

c. *Update of the* CloudSat *calibration assessment*

Three years of Darwin ARM site data (from 1 June 2006 to 30 May 2009) have been considered in this study, where the analysis of the *CloudSat* calibration in PAL09 used only 6 months of data (from December 2006 to May 2007). This study is, thus, the opportunity to update the results of PAL09 using a longer time series. Figure 3 shows the updated comparison of the mean vertical profiles of reflectivity as derived from the Darwin ARM radar and *CloudSat*. Compared to Fig. 8 in PAL09, it appears clearly that the inclusion of more observations tend to produce a better agreement between the vertical distribution of radar reflectivities. Four mean vertical profiles have been produced from the ground-based observations: with and without the reflectivity conversion to 95 GHz, and considering all available ground-based observations or those ±1 h around the two daily *CloudSat* overpasses only. The comparison of these profiles indicates that the diurnal cycle and the reflectivity conversion have little effect on the mean vertical profile of reflectivity at all heights (less than 1 dB difference). The largest difference (of about 1 dB) is produced by the reflectivity conversion at around 8-km height. To compare quantitatively the four profiles with the *CloudSat* profile, the weighted mean difference (the sum of the differences per height bin accounting for the number of data points in each height bin) between the ground-based and *CloudSat* vertical profiles of reflectivity was calculated. The weighted mean difference ranges from −1.0 to +0.1 dB, depending on which ground-based profile is considered. This result confirms with a much longer time series the conclusions of PAL09 showing that the *CloudSat* radar is calibrated to within 1 dB.

d. *Assessment of the* CloudSat *2B-CWC-RO and ZT products*

Figures 4 and 5 compare the PDFs and mean vertical profiles of microphysical properties of tropical ice clouds over Darwin as derived using the ground-based DH08 radar–lidar method and the *CloudSat* 2B-CWC-RO and ZT methods. Figure 6 also shows the height-dependent PDFs (HPDFs; see also Protat et al. 2010) of these microphysical parameters to gain further insights into the characterization of the differences observed on the PDFs and mean vertical profiles. HPDFs (defined in Protat

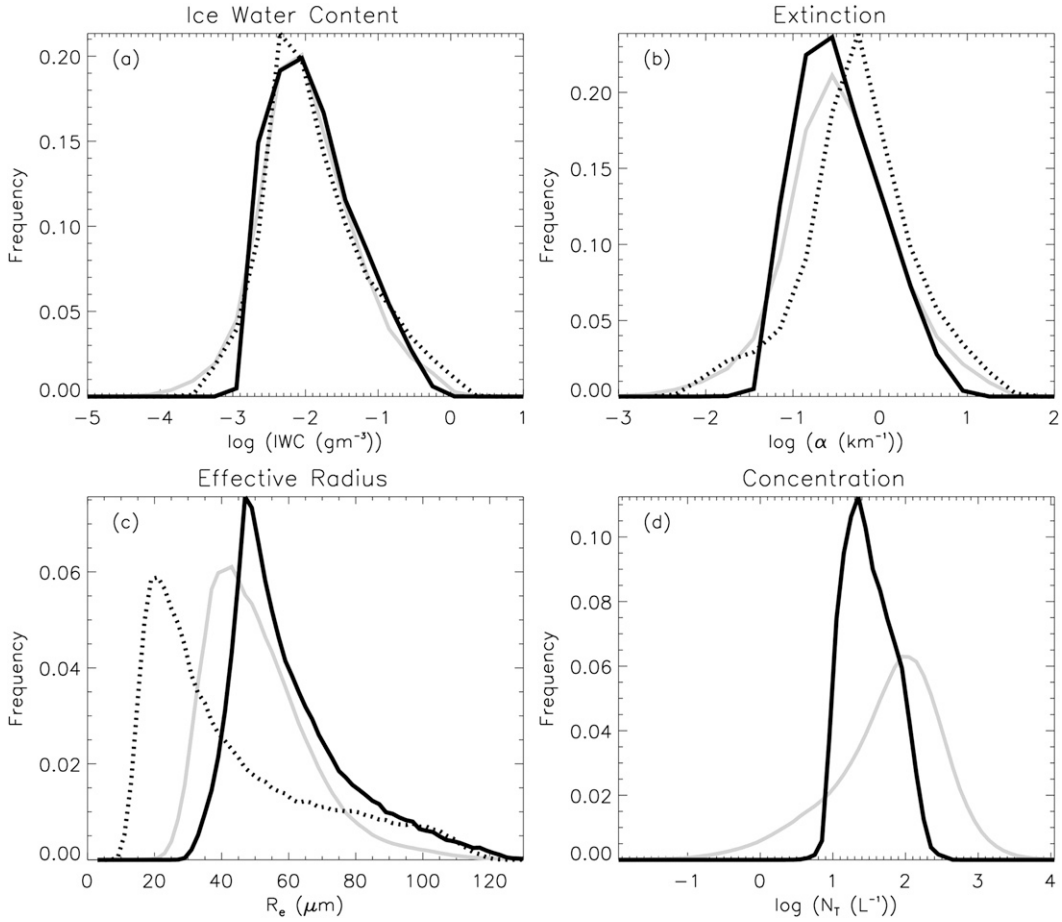

FIG. 4. PDFs of (a) ice water content, (b) visible extinction, (c) effective radius, and (d) total number concentration derived from the ground-based radar–lidar observations at the Darwin ARM site (gray) and from two methods applied to the *CloudSat* observations 200 km around the Darwin site for the same period (black): the standard 2B-CWC-RO method (solid) and the ZT statistical method (dotted).

et al. 2010) are similar to the Contoured Frequency by Altitude Diagrams (CFADs) proposed by Yuter and Houze (1995), but the normalization is made by the total number of points per altitude slab and not by the total number of points. Because the difference between ground-based statistics of microphysical properties were very similar when all observations or observations from ±1 h around the daily *CloudSat* overpasses were used, only the profiles including all observations are shown in the following. Two vertical profiles are given in Fig. 5 for the ground-based method, corresponding to the radar–lidar retrievals (solid curve) and the radar-only retrievals (dashed curve). The similarity of these two profiles highlight that the radar-only and radar–lidar parts of the DH08 method produce very similar statistical properties of the ice cloud properties. This result implies that a satellite radar-only method should therefore in principle be able to reproduce the ground-based statistics.

1) ICE WATER CONTENT

Figures 4 and 5 show that there are large differences between IWC derived using the ground-based method and the *CloudSat* 2B-CWC-RO method; however, there are also some encouraging agreements. Figure 4, for instance, shows that the IWC PDFs are in good agreement. There is a clear cutoff in IWC observed at 1 mg m^{-3} for 2B-CWC-RO because of the fact that the *CloudSat* IWCs are reported as integers in mg m^{-3} (which implies a minimum IWC of 1 mg m^{-3}). In contrast, there are many instances where the ground-based IWCs are smaller than 1 mg m^{-3} (see HPDFs of IWC in Fig. 6a). This problem has been brought to the attention of the *CloudSat* team and should be solved in the next release (G. Stephens and N. Wood 2008, personal communication). The rest of the PDF is remarkably similar for 2B-CWC-RO (Fig. 4a).

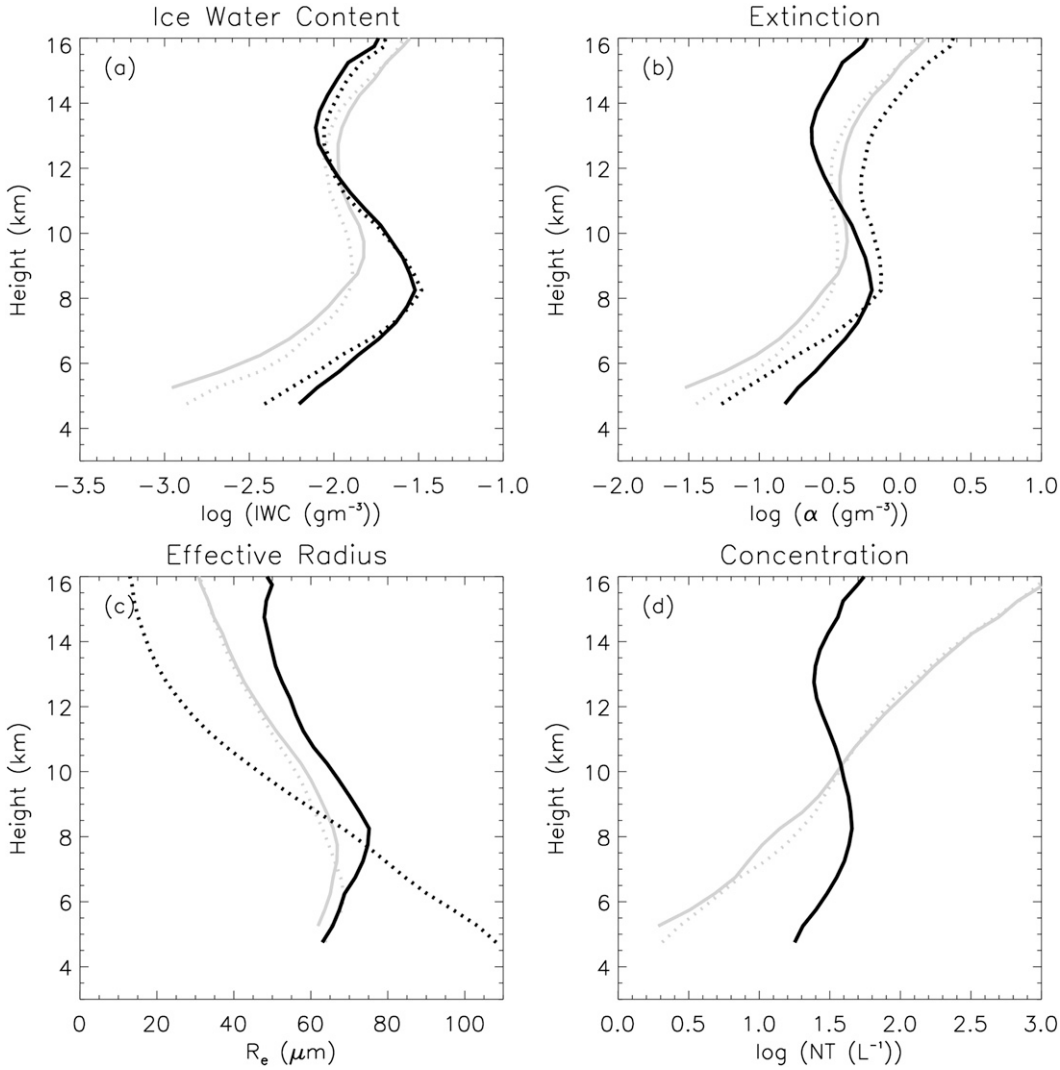

FIG. 5. As in Fig. 4, but for mean vertical. The gray solid and gray dotted lines are derived from the radar–lidar and radar-only parts of the ground-based retrievals, respectively.

Retrievals of the IWC PDF using the simple ZT method applied to *CloudSat* reflectivities are very similar to that retrieved using the ground-based method (Fig. 4a). Using the ZT method, there are no issues with truncation at low IWC with the PDF of IWCs comparing well across the IWC range. However, the ZT method is less accurate than the 2B-CWC-RO method for the high values of IWCs, producing larger occurrences of high IWCs (greater than 100 mg m^{-3}). This is probably because of the fact that the ZT method is based on linear relationships between log(IWC) and Z for different temperature intervals. The non-Rayleigh scattering effect tends to produce departures from linearity at high IWCs (see discussion and figures in Protat et al. 2007). There could also be potential problems in the 2B-CWC-RO a priori estimates of IWC, which are also linear relationships between log(IWC) and Z. However, it does not appear as clearly as in the PDF of IWC derived using the ZT method.

Mean vertical profiles of IWC (Fig. 5a) are also similar except for a large overestimation of IWC by both the 2B-CWC-RO and ZT methods for altitudes below 10–11 km (especially considering that this is a plot in logarithmic scale), although they are in relatively good agreement above 10–11-km altitude. Quantitatively, at 8-km altitude the 2B-CWC-RO and ZT IWCs are both of about 30 mg m^{-3}, whereas the ground-based IWC is of about 12–15 mg m^{-3}. It is difficult to establish if this difference is because of the truncation problem discussed previously. This will be the subject of further study when the truncation problem is solved in the next *CloudSat* data release. Other problems may be causing this relatively large overestimation of the IWCs. Where

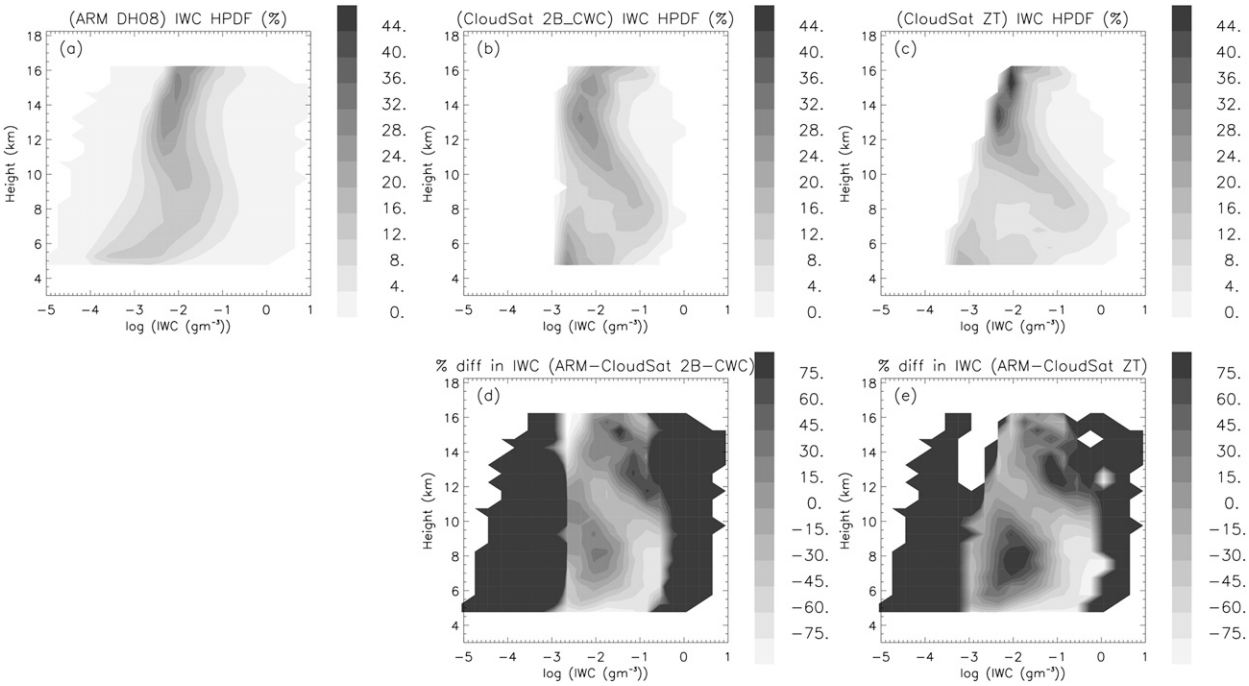

FIG. 6. Height-dependent probability distribution functions (HPDFs) of ice water content (IWC) derived from (a) the ground-based retrieval method, (b) the *CloudSat* 2B-CWC-RO method, and (c) the *CloudSat* ZT method. Also given are the fractional differences in HPDF between the ground-based and satellite retrievals for (d) the 2B-CWC-RO method and (e) the ZT method.

aggregation is the dominant process, the use of equivalent mass ice spheres of solid ice density may not be appropriate to treat the ice aggregates of much lower density than solid ice (e.g., Brown and Francis 1995), which are ubiquitous in thick tropical anvil ice clouds (e.g., Heymsfield et al. 2002; Heymsfield and Miloshevich 2003; Stith et al. 2002; Stith et al. 2004; Protat et al. 2010). Because the density of ice aggregates is assumed in the calculations for the ZT retrieval method (Protat et al. 2007), this overestimation may be due to the previously mentioned problem of linear fits producing significant overestimates because of the non-Rayleigh scattering effect on the IWC–Z relationship. Unraveling these different error sources will be the subject of future research.

The HPDFs of IWC give further insight into the differences between the ground-based and satellite statistics previously identified using PDFs and mean vertical profiles. The first overall result is that satellite retrieval methods produce IWC in a smaller range of values than the ground-based method (Fig. 6). This is highlighted by calculating the fractional difference between the HPDFs (Fig. 6d for 2B-CWC-RO and Fig. 6e for ZT), in which the missing ranges of values in the satellite retrievals of IWC are shown in purple (arbitrarily set at 200% for clarity). The good agreement for 2B-CWC-RO (Fig. 6b) at altitudes greater than 11 km corresponds to very similar widths of the distributions at these heights. The relatively large overestimations found below 8 km on Figs. 4a and 5a are clearly because of the fact that the PDFs of IWC retrieved at these heights are biased toward larger values (Figs. 6a,b). The difference between the HPDFs can be characterized by a dipole with fractional differences of about ±30%–40% centered at around 8-km altitude (Fig. 6d). The HPDFs for the 2B-CWC-RO are also narrower at all heights on the high IWC side. Although these high IWC values are characterized by relatively small occurrences on the ground-based statistics (1%–2%, see Fig. 6a), it appears clearly that values larger than 0.5 g m^{-3} are completely missed by the 2B-CWC-RO method (Fig. 6d).

The IWC HPDF derived from the *CloudSat* ZT retrievals (Fig. 6c) shares many similarities with that of 2B-CWC-RO. The agreement with the ground-based HPDF is good above 10 km, with the IWC distributions being slightly narrower for the ZT retrieval than for the ground-based reference and the 2B-CWC-RO method. Below 10 km, the width of the IWC PDFs as a function of height is generally larger than that of the ground-based PDFs with the maximum occurrences shifted toward larger IWC values, resulting in larger HPDF differences than for the 2B-CWC-RO method at those heights. This translates into roughly the same mean error for both methods, as seen on the mean vertical profiles of Fig. 5a. However, as seen on the HPDF difference plot of Fig. 6e, the ZT

method produces high IWC values, which were missing in the 2B-CWC-RO retrievals, but with an overestimated frequency of occurrence, especially in the 6–8-km height layer [see large negative log(IWC) ranging from −0.7 to 0 in Fig. 6e].

2) VISIBLE EXTINCTION

The PDFs (Fig. 4b) and mean vertical profiles (Fig. 5b) of visible extinction exhibit roughly the same characteristics as those discussed for IWC. The cutoff observed on the PDF of small *CloudSat* extinctions reflects that of IWC because the 2B-CWC-RO extinctions have been estimated in the present study from the IWC and effective radii reported in the 2B-CWC-RO product. The 2B-CWC-RO method produces smaller amounts of large extinctions (larger than $10^{0.5} = 3\ \mathrm{km}^{-1}$) in the 2B-CWC-RO product when compared to the DH08 ground-based retrievals (Fig. 4b). The vertical distribution of the differences as seen from the mean vertical profiles of extinction in Fig. 5b indicates that the 2B-CWC-RO method produces a large overestimation of extinction below 11-height (0.4 versus 0.15 km^{-1} at 7 km, for instance, more than a factor 2) and an underestimation above 11 km (0.2 versus 0.5 km^{-1} at 13 km altitude, for instance), which is larger than the underestimation observed for IWC.

The ZT method produces very different statistics of extinction and error characteristics. The extinction–IWC–*T* relationship in the ZT method (Heymsfield et al. 2005) is presently being used to produce IWCs from the CALIPSO retrieval of extinction in version 3 of the CALIPSO products. As can be seen from Fig. 4b, this method produces a very good agreement of the PDFs for extinctions smaller than $10^{-1.6}\ \mathrm{km}^{-1}$ (=0.025 km^{-1}) but relatively large and systematic overestimates for the larger extinctions in the tropical ice clouds sampled at the Darwin ARM site. The vertical distribution of the differences (Fig. 5b) shows that the ZT method produces systematic overestimations of extinction throughout the troposphere even at heights greater than 11 km, where IWC is slightly underestimated by ZT. The ZT method tends to produce a better agreement with the ground-based extinctions than 2B-CWC-RO for altitudes below 8 km and higher than 12 km and a slightly worse agreement than 2B-CWC-RO in the 8–12-km layer. Going back to the Heymsfield et al. (2005) paper, it appears that this extinction–IWC–*T* statistical relationship was derived from in situ microphysical measurements obtained both in midlatitude and tropical regions, including anvils and cirrus cloud samples. However, the variability of this relationship as a function of latitude has not been studied and could be causing the differences found when applied exclusively to tropical ice clouds. These observed overestimations could also result from the fact that the visible extinction is derived here from radar only retrievals of IWC in the present case.

To characterize the differences seen on the PDFs and mean vertical profiles in terms of distribution widths at different heights, the HPDFs of extinction are shown in Fig. 7 as well as the HPDF differences. This figure shows that the satellite retrieval methods produce extinctions in a narrower range than the ground-based method, as was the case for IWC. Above 11-km height the extinction distributions exhibit similar widths (see Figs. 7a–c), but the 2B-CWC-RO extinction PDFs are shifted toward negative values (negative bias, see dipole in the HPDF difference between 12 and 16-km height, Fig. 7d), whereas the ZT retrieval method produces an unexpected truncated distribution on the left part of the distributions (i.e., for the smaller extinctions). This means that the ZT method does not allow for the retrieval of small extinctions at low temperatures. This artifact will be the subject of future investigations to assess if this could be due to an extrapolation of the statistical relationships out of their validity range or if this is due to an insufficient number of points to constrain the statistical relationships from Protat et al. (2007) and Heymsfield et al. (2005) at cold temperatures where the number of points is usually sparse. As shown in Fig. 5b, this artifact translates (as expected) into a positive bias on the extinction estimates above 11 km. However, as shown in Figs. 7c and 7e the right-hand side of the HPDFs are in encouraging agreement with the ground-based distributions. Below 11-km height the same conclusions as those drawn for IWC are reached, with a deteriorating agreement between the satellite and ground-based retrievals than above 11-km height, which is associated with wider distributions in the ZT retrieval (Figs. 7c,e) and a positive bias and a narrower distribution for 2B-CWC-RO (Figs. 7b,d). At these heights, it is also seen that the ZT method produces a range of extinction values that is in better agreement with the ground-based estimates than 2B-CWC-RO. It is particularly clear for the large extinctions (larger than 10 km^{-1}), which are completely missed by the 2B-CWC-RO method but which are too frequent (by a factor 2) in the ZT method. These large occurrences are most likely because of the previously discussed overestimation of the occurrence of large IWCs at the same heights. Therefore, better estimates of extinction should be produced by the ZT method when the problem is solved for IWC. Overall, as seen in the vertical profiles of Fig. 5b, the ZT retrieval of extinction is slightly better than that of 2B-CWC-RO. As previously noted, this result also applies to the 2B-CWC-RVOD retrieval method, which uses the MODIS optical thicknesses as an additional constraint for the retrieval.

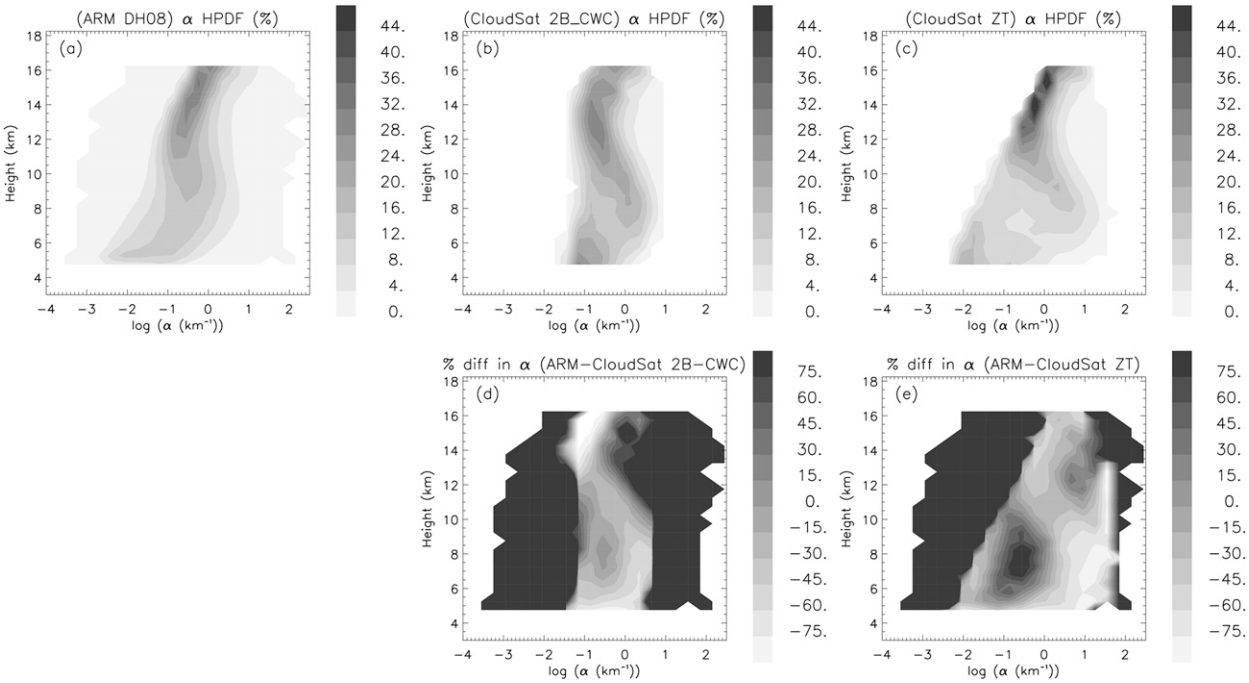

FIG. 7. As in Fig. 6, but for α.

3) EFFECTIVE RADIUS

The R_es are calculated by taking the ratio of IWC to extinction, which corresponds to the definition of Stephens et al. (1990). Figures 4c and 5c show that the ground-based and satellite methods produce very different PDFs and mean vertical profiles of effective radius. The ground-based PDF of effective radius is unimodal, characterized by a modal radius of 40 μm. The distribution is also highly skewed toward larger effective radii. The overall shape of the ground-based R_e PDF is very well reproduced by the 2B-CWC-RO method, although it is slightly narrower. In contrast, the ZT method produces a large population of large effective radii far from the modal value. The modal values are very different from the ground-based modal radius for both satellite methods: 20 μm for the ZT method and 47 μm for the 2B-CWC-RO method. It is also noteworthy that these two satellite methods produce much larger occurrences of large effective radii. Figure 5c shows that the 2B-CWC-RO method produces a systematic overestimation of effective radii by about 8–12 μm throughout the troposphere (although less obvious below 7 km), whereas the ZT method produces much larger estimates of effective radius below 8-km height and much smaller estimates above. Such a bias on effective radius is expected to have a significant influence on the magnitude of SW and LW radiative impacts of tropical ice clouds. This effect has been estimated through a sensitivity study using the *CloudSat* 2B-FLXHR algorithm that provides high vertical resolution profiles of radiative fluxes and atmospheric heating rates on the global scale. The standard 2B-FLXHR algorithm, described in detail by L'Ecuyer et al. (2008), was modified by subtracting a 10-μm bias from the 2B-CWC-RO effective radii, which provide the standard microphysical inputs to the product. The algorithm was then rerun over all *CloudSat* orbits included in the present analysis and the impact of the effective radius bias on the SW and LW cloud forcing (defined as the difference in outgoing SW and LW radiation between clear-sky and all-sky conditions) has been estimated. The result is that cloud LW forcing is increased from 44.6 to 46.9 W m^{-2} (implying an error of about 5%), whereas the negative cloud SW forcing is increased from -81.6 to -82.8 W m^{-2}. Further analysis reveals that these modest effects (although not insignificant) can be much larger for optically thick clouds (not shown). These clouds are characterized by large radiative forcings, but occur less frequently in the Darwin region than their very common optically thin counterparts (it has been estimated in the course of this study that in the Darwin area 75% of the cloud profiles were characterized by a radiative impact >10 W m^{-2}, not shown). Further study is required to extrapolate the importance of these thicker clouds on the global scale.

HPDFs of effective radius are shown in Fig. 8. Above 10–11-km altitude the distribution produced by 2B-CWC-RO is actually broader than that produced by the

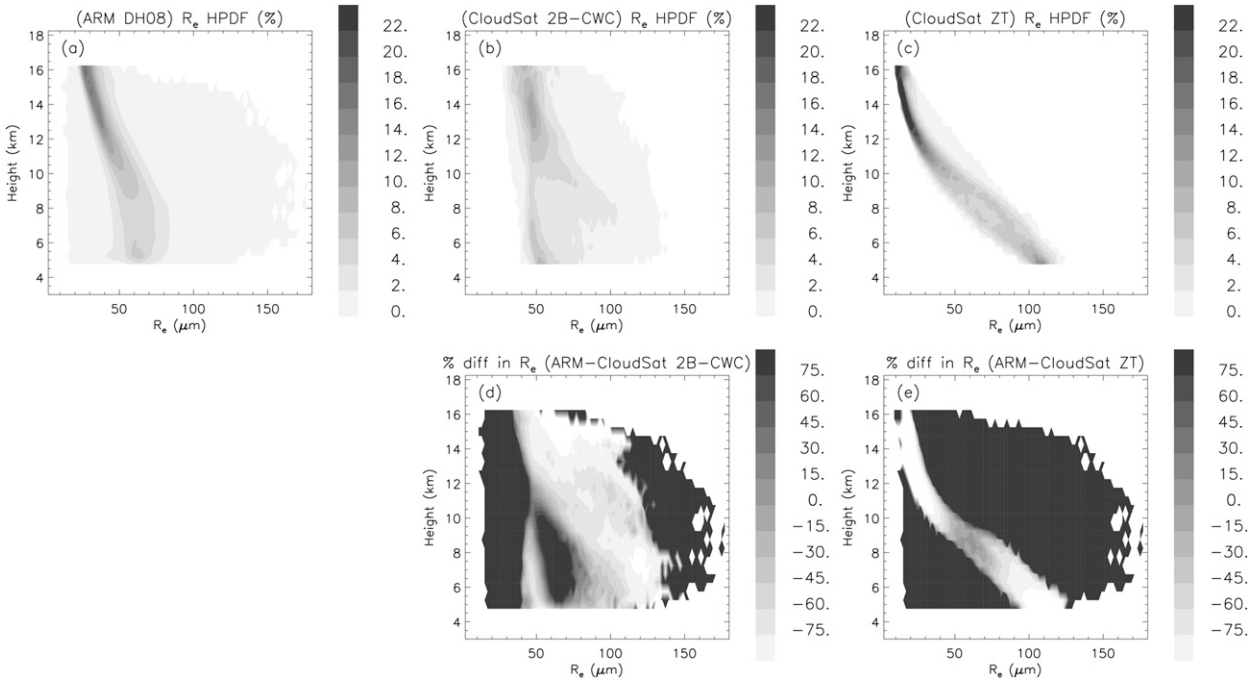

FIG. 8. As in Fig. 6, but for R_e.

ground-based method, with a positive bias of around 10 μm, which is virtually constant with height. Below 10–11-km height the distribution derived from the ground-based retrievals is still unimodal and broadening at lower heights. In contrast, the 2B-CWC-RO method produces a bimodal distribution, characterized by the lower modal value 10 μm less and the second modal value being much greater that the modal value of the ground-based estimates. Importantly, the combination of the two distributions results in a relatively good agreement in mean vertical profiles below 7-km height but not for any good reason. This demonstrates the importance of using HPDFs in addition to PDFs and mean vertical profiles. Figure 8c shows the HPDF derived using the ZT retrieval of effective radius exhibiting a very large disagreement with the ground-based retrievals. The ZT method produces a much narrower distribution of values, large underestimations above 9 km, and large overestimations below. This result indicates that the combination of the Protat et al. (2007) IWC–Z–T relationship and of the Heymsfield et al. (2005) extinction–IWC–T relationship produces an inaccurate dependency of effective radius as a function of Z (which controls the width of the distribution of effective radius as a function of height–temperature) and an overestimate of the gradient of effective radius with height. More work is needed to improve this estimate of effective radius as a function of radar reflectivity and temperature.

4) TOTAL NUMBER CONCENTRATION

As the total number concentration of ice particles N_T is a microphysical parameter poorly linked to radar reflectivity, radar-only methods are not expected to yield very accurate results. It is much better constrained by the inclusion of lidar measurements, as lidar backscatter (second moment of the particle size distribution) exhibits a larger sensitivity to the total number concentration of particles (zeroth moment of the particle size distribution) than the radar reflectivity (sixth moment of the particle size distribution in Rayleigh scattering approximation). As a result, the 2B-CWC-RO retrieval of total number concentration does rely heavily on the a priori information about this quantity (Austin et al. 2009). The same comment applies to the radar-only part of the DH08 method, but to a lesser extent to the radar–lidar part of the DH08 method as the lidar provides a better constraint on N_T. As seen from the ground-based statistics using radar-only retrievals or radar–lidar retrievals, the radar–lidar and radar-only parts of the DH08 algorithm do produce estimates that are in good agreement at all heights (see Figs. 4d and 5d), including in cirrus where the total number concentration is large. This suggests (although this point would require thorough comparisons with collocated airborne in situ microphysical observations) that radar-only retrievals of total number concentration in the DH08 method are reasonably accurate,

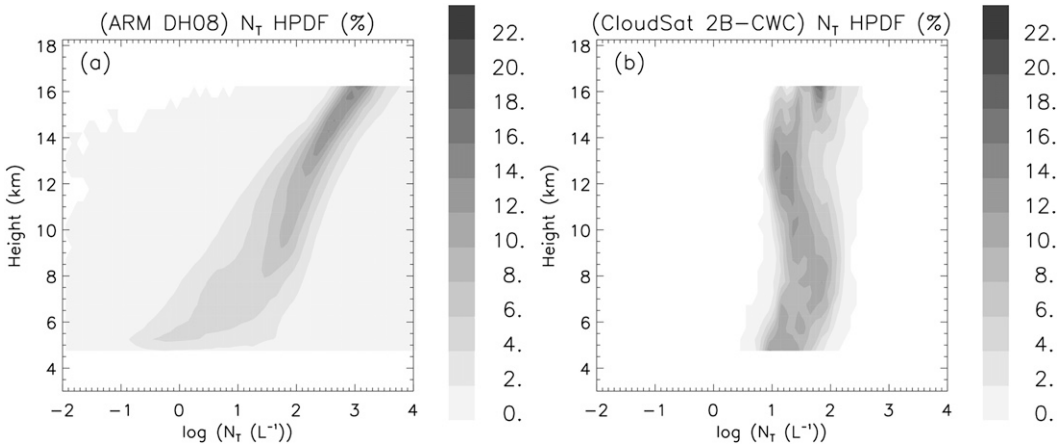

FIG. 9. Height-dependent PDFs of N_T derived from (a) the ground-based retrieval method and (b) the *CloudSat* 2B-CWC-RO method.

owing to a good a priori estimate of this quantity. In contrast, the 2B-CWC-RO method produces N_T in a much narrower range (Fig. 4d), and the HPDF indicates that this is true at all heights (Fig. 9), and with inadequate vertical variability (Fig. 5d) when compared to the ground-based retrievals (span approximately 3 orders of magnitude in N_T). This probably indicates that the a priori estimate of N_T used in the 2B-CWC-RO method does not properly account for the real variability (especially the vertical variability) of this quantity in tropical ice clouds. This suggests that further improvements are required before using this satellite estimate of total number concentration in a quantitative manner (at least in the tropics). It would be interesting to carry out such comparisons around midlatitude [such as the Cloudnet sites (Illingworth et al. 2007), or the Southern Great Plains ARM site] and polar (such as the Barrow ARM site in Alaska) ground-based sites to evaluate if this conclusion also holds for ice clouds at higher latitudes.

5. Statistical assessment of the CALIPSO-like IWC retrieval

The 3 yr of ground-based radar–lidar retrievals also provide an opportunity to carry out an evaluation of the IWC retrieval from CALIPSO observations. To our knowledge, such an evaluation has not been conducted for tropical ice clouds. The procedure here is necessarily different from the evaluation of the *CloudSat* microphysical products undertaken in section 4 because the CALIPSO IWC retrievals are not available at the time this paper is written. However, using the ground-based radar–lidar retrievals, the statistical relationship of Heymsfield et al. (2005), which is used to produce the CALIPSO IWCs (see section 3c), can be assessed using the following procedure: the visible extinction derived from the radar–lidar part of the ground-based DH08 method is directly used as an input to the Heymsfield et al. (2005) relationship to produce CALIPSO-like IWC retrievals. These IWC estimates are then directly compared with the direct radar–lidar retrievals of IWC using the DH08 method. It must be noted that errors associated with multiple scattering in the true CALIPSO IWC retrievals are not included in this error analysis. This will require a separate analysis when the CALIPSO IWC retrievals are made available. This assessment should therefore really be viewed only as an evaluation of the statistical relationship itself, not as a full evaluation of the CALIPSO IWC retrieval.

The result of this evaluation is shown in Fig. 10. The PDF of IWC obtained using the CALIPSO-like retrieval is very similar to that produced by the radar–lidar part of the DH08 method (Fig. 10a). Both distributions peak at the same value. It is found, however, that the CALIPSO relationship tends to produce larger occurrences of in the 10^{-4}–10^{-3} g m^{-3} IWC range. Further insights are obtained from the mean vertical profiles of IWC (Fig. 10b) showing that these larger occurrences are produced at heights ranging from 10 to 16 km. Overall the CALIPSO-like retrieval tends to produce significantly smaller IWCs than the radar–lidar retrieval above 10 km and slightly larger ones below 8-km height. It is noteworthy, however, that this simple method outperforms the *CloudSat* methods evaluated in section 4 below 8-km height, whereas the opposite applies above 10 km. These results suggest that this simple CALIPSO retrieval is quite robust for the retrieval of IWC in tropical ice clouds. The differences with the radar–lidar retrievals indicate, however, that the temperature dependence of the Heymsfield et al. (2005) relationship would need to be slightly refined

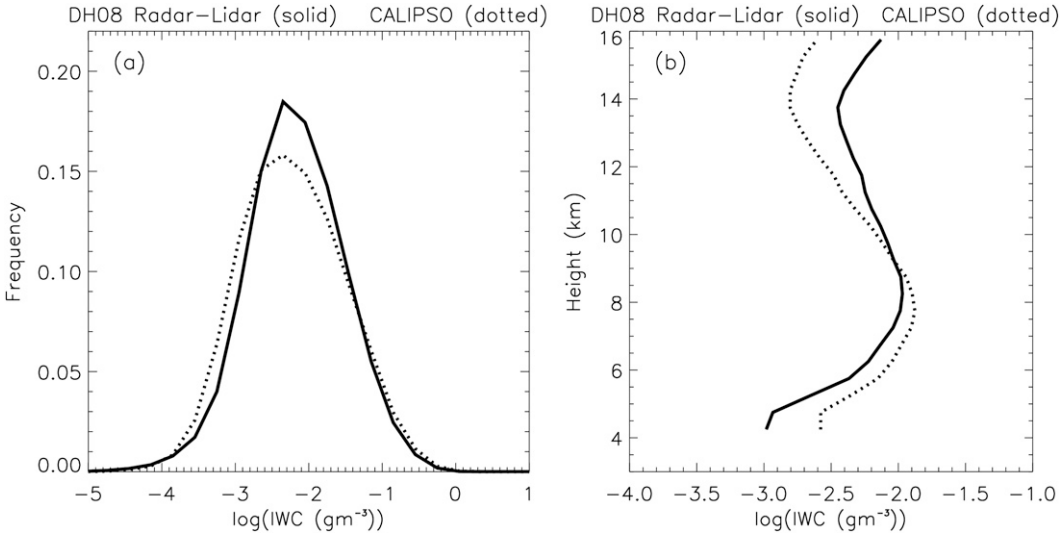

FIG. 10. (a) PDF and (b) mean vertical profile of ice water content derived from the radar–lidar part of the DH08 method (solid), and from the CALIPSO α–IWC–T relationship using the DH08 extinction retrieval (dotted).

to further improve the IWC retrieval in tropical ice clouds from the CALIPSO lidar extinctions.

6. Conclusions

This paper presents statistical properties of tropical ice clouds as derived from 3 yr of ground-based radar–lidar retrievals at the Darwin ARM site compared to the same statistics as derived from the two *CloudSat* standard microphysical retrieval methods (2B-CWC-RO and 2B-CWC-RVOD, Release 04) and from a simple statistical method applied to the *CloudSat* reflectivities (the ZT method, Protat et al. 2007; Heymsfield et al. 2005). The standard statistical method to derive IWC from the CALIPSO extinctions is also assessed in the present study.

The first conclusion reached in this paper was that the 2B-CWC-RO and 2B-CWC-RVOD were virtually identical statistically around the Darwin site in the current release. This seems to indicate that the constraint brought by the MODIS optical thicknesses in the RVOD version of the retrieval does not improve the statistical characterization of the properties of tropical ice clouds (at least those around Darwin).

The comparison with the ground-based radar–lidar retrievals using the DH08 method allowed a detailed characterization of the errors of the current satellite methods, which should be addressed in future studies. The 2B-CWC-RO (and by extension the 2B-CWC-RVOD) and ZT methods well reproduce the probability distribution function of IWC, except for a truncation at 1 mg m^{-3} for 2B-CWC-RO which needs to be addressed (and will be in the next release of the products) and excessive occurrences of IWCs larger than 100 mg m m^{-3} produced using the ZT method, suggesting that further studies are required to account for departures from linearity of the log(IWC)–Z relationship in this ZT method. Both satellite methods tend to produce IWCs in a much narrower range than the ground-based method, which also needs to be addressed. As a result, the mean vertical profile of IWC is largely overestimated by the 2B-CWC-RO and ZT methods below 10-km height, with peak values overestimated by a factor of 2.

The visible extinction PDF is also reasonably well reproduced by the 2B-CWC-RO method, although too narrow above 11 km and shifted toward larger extinction values below 11 km. As a result the 2B-CWC-RO method tends to underestimate the mean vertical profile of extinction above 11 km and overestimate it below (by approximately a factor of 2). The ZT method produces a PDF of extinction with characteristics similar to the ground-based derived extinction PDF but shifted toward larger values. This positive bias is attributed to different causes at different heights. Above 11 km the overestimation is due to the ZT statistical relationship not allowing for the retrieval of small extinctions at low temperatures. This artifact will be the subject of future investigations. Below 11 km, the overestimation of mean extinction is due to the over representation of large values of extinctions, which tends to broaden the extinction distribution. This is probably attributable to the IWC overestimations discussed previously at the same heights. As a result, it is likely that if the problem is solved with IWC, the estimates of extinction by the ZT method will be greatly improved.

Overall, the ZT method seems to slightly outperform the 2B-CWC-RO method for IWC and visible extinction above 12 km and below 8 km, whereas the opposite is true in the 8–12-km layer. However, the effective radius produced from the ratio of these quantities is clearly much more accurately retrieved by the 2B-CWC-RO method than by the ZT method. The 2B-CWC-RO retrieval of effective radius is, however, characterized by a positive bias of about 8–12 μm throughout the troposphere, as see on the mean vertical profile. A sensitivity test shows that in response to such bias the cloud LW forcing is increased from 44.6 to 46.9 W m^{-2} (implying an error of about 5%), whereas the negative cloud SW forcing is increased from -81.6 to -82.8 W m^{-2}. Further analysis reveals that these relatively modest effects can be much larger for optically thick clouds. This effective radius bias is attributed to different causes above and below 11 km. Above 11 km, it is mainly due to a shift of the effective radius distribution toward larger values and a slight broadening of the distributions, whereas below 11 km it is due to the production of a bimodal distribution by the 2B-CWC-RO method, which is not observed in the ground-based statistics. The ZT method produces a much narrower distribution of effective radius than the ground-based method at all heights and an overestimate of the gradient of effective radius with height. This result indicates that the combination of the Protat et al. (2007) IWC–Z–T relationship and of the Heymsfield et al. (2005) extinction–IWC–T relationship produces an inaccurate dependency of effective radius as a function of Z (which controls the width of the distribution of effective radius as a function of height–temperature) and an overestimate of the gradient of effective radius with height. More work is clearly needed to improve this estimate of effective radius using such statistical relationships.

The 2B-CWC-RO total number concentrations are finally compared to ground-based retrievals. As discussed previously, it is a very indirect microphysical parameter to be derived using only radar reflectivity measurements and the accuracy of its retrieval largely depends in the a priori information used in the variational formalism of radar-only methods. The 2B-CWC-RO method produces a much narrower distribution of total number concentration at all heights and with a greatly reduced vertical variability as compared to the ground-based retrievals. This likely indicates that the a priori assumption of N_T used in 2B-CWC-RO does not properly account for the real variability (especially the vertical variability) of this quantity in tropical ice clouds. These results suggest that further improvements are required before using this satellite estimate of total number concentration in a quantitative manner.

Finally, an assessment of the method used presently to derive IWC from the CALIPSO lidar observations (not available yet) was carried out using the ground-based radar–lidar observations. To do so, the visible extinction derived from the radar–lidar part of the ground-based DH08 method was directly used as an input to the Heymsfield et al. (2005) relationship to produce CALIPSO-like IWC retrievals. These IWC estimates were then directly compared to the direct radar–lidar retrievals of IWC using the DH08 method. The PDF produced by this CALIPSO-like retrieval was found to be in good agreement with the radar–lidar retrieval. The comparison of the mean vertical profile of IWC showed that the method was however producing smaller IWCs than the radar–lidar method above 10-km height and slightly larger ones below 8-km height. These results suggest that the statistical relationship used is robust for tropical ice clouds, but that the temperature dependence of the Heymsfield et al. (2005) relationship would need to be slightly refined to further improve the IWC retrieval in tropical ice clouds (especially the highest ones) from the CALIPSO lidar extinctions.

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