Cloud ice water content retrieved from the CALIOP space-based lidar

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[1] Ice water content (IWC) profiles are derived from retrievals of optical extinction from the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) satellite lidar, using a parameterization derived from particle probe measurements acquired during several aircraft field campaigns. With more than five years of data now available, CALIOP IWC is well suited for characterization of the climate-sensitive upper troposphere/lower stratosphere where reliable global IWC measurements are needed to reduce climate model uncertainty. We describe CALIOP IWC and compare it with global satellite-based and regional airborne IWC measurements made during August 2007. IWC distributions in a convective cloud sampled during the Tropical Clouds, Chemistry, Composition and Climate experiment show temperature-dependent differences between *in situ* measured IWC, IWC retrieved from CloudSat and CALIOP, and IWC parameterized from the airborne Cloud Physics Lidar (CPL) 532 nm volume extinction coefficients. At temperatures above −50°C the CALIOP IWC retrieval indicates less cloud ice than the other instruments, due to signal attenuation and screening for horizontally-oriented ice crystals. Above 12 km where temperatures drop below −50°C CALIOP compares well with *in situ* IWC measurements. *In situ* measurements are limited above 12 km, and more cold-temperature comparisons are needed. Global zonal in-cloud IWC averages at altitudes above 9 km show that CloudSat IWC is roughly an order of magnitude higher than CALIOP IWC, consistent with a higher detection threshold. When averaged to the vertical resolution characteristic of Microwave Limb Sounder (MLS), global zonal averages of CALIOP and MLS IWC were found to agree to about +/−50%. **Citation:** Avery, M., D. Winker, A. Heymsfield, M. Vaughan, S. Young, Y. Hu, and C. Trepte (2012), Cloud ice water content retrieved from the CALIOP space-based lidar, *Geophys. Res. Lett.*, *39*, L05808, doi:10.1029/2011GL050545.

1. Introduction

[2] Cloud-climate feedbacks represent the largest source of uncertainty in climate change predictions [*Dufresne and Bony*, 2008]. Determining the cloud radiative impacts on climate depends on, among other things, knowledge of the cloud vertical structure, particle phase and total water content. Cloud ice water content is a critical cloud parameter linking bulk thermodynamic properties of the atmosphere, particularly temperature, with cloud microphysical and radiative properties. Current global climate models show large disparities in even the globally-averaged amount of cloud ice predicted [*Waliser et al.*, 2009], with important implications for our confidence in model predictions of climate change. Global observational datasets to constrain model estimates have been lacking, until recently. New vertically resolved measurements from MLS, CloudSat, and CALIOP offer the potential for greatly improved constraints on cloud ice.

[3] Historically, retrievals of column-integrated cloud ice from passive sensors have been problematic due to issues of cloud multilayer structure, complex microphysical properties, and the tendency for passive retrievals to be dominated by local properties near the cloud top. One of the major science objectives of the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite, launched in April 2006, is to provide vertically resolved global cloud mapping, particularly for thin cirrus, polar and multi-layered clouds. With the May, 2010 V3.01 data release, the CALIPSO team provides a cloud ice water content product parameterized from Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) optical extinction retrievals, that can be used to evaluate global climate models, and to characterize seasonal to interannual cloud variability.

[4] This paper describes the CALIOP ice water content (IWC) product. Evaluation of CALIOP V3.01 IWC is initiated by comparisons with other IWC measurements and retrievals. During August 2007, the Tropical Clouds, Composition, Chemistry and Climate (TC4) Experiment provided intensive remote and *in situ* aircraft measurements in tropical convective clouds [*Toon et al.*, 2010]. On August 5, 2007 there was good coincidence between NASA aircraft flight tracks and a CALIOP overpass, and IWC measurements are compared for this day. Zonally averaged global CALIOP, CloudSat and Microwave Limb Sounder (MLS) IWC retrievals are also compared for August 2007.

2. CALIOP Ice Water Content Characteristics

[5] CALIOP IWC is derived from CALIOP 532 nm cloud particle extinction profiles. CALIOP is a dual wavelength, dual polarization elastic backscatter lidar, described by *Winker et al.* [2009], and *Hunt et al.* [2009]. The ∼70 meter diameter laser footprints are separated by 335 m along-track, producing along-track attenuated backscatter profile curtains. Clouds and aerosol layers are detected by applying a threshold technique to the profile data [*Vaughan et al.*, 2009]. Clouds are differentiated from aerosol layers [*Liu*

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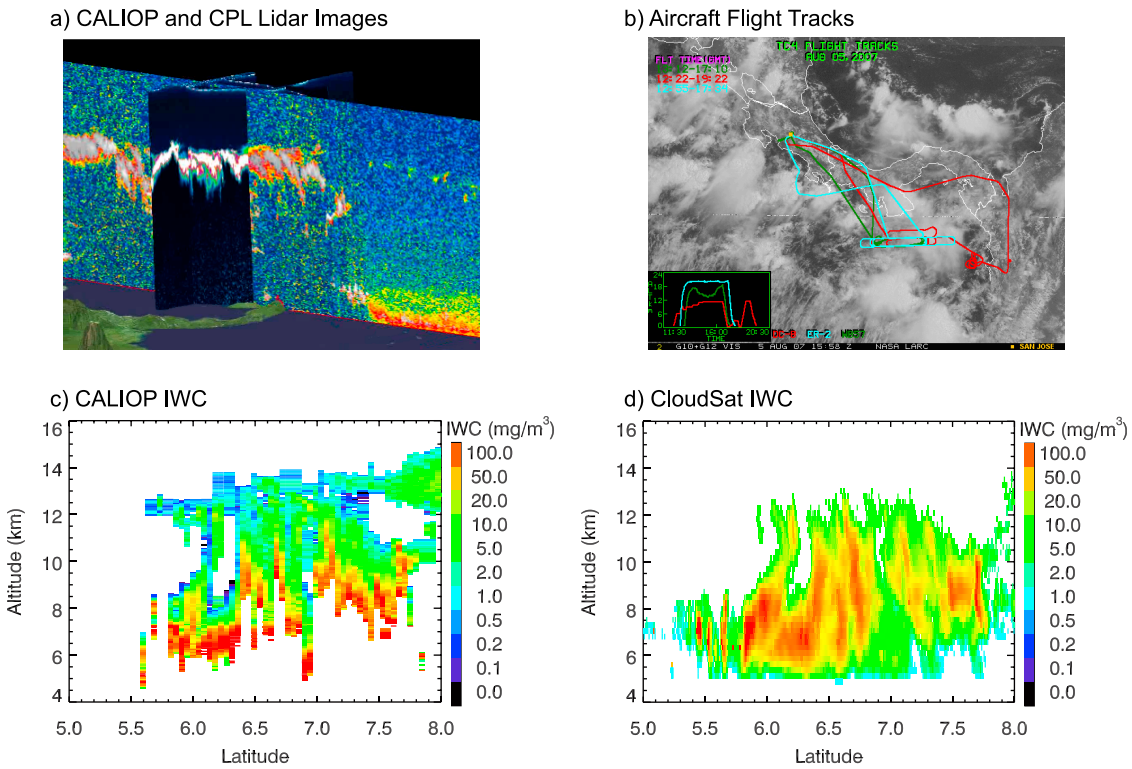

Figure 1. (a) Composite of CALIOP and CPL 532 nm attenuated backscatter measured on August 5, 2007 in a convective cloud complex during the TC4 experiment. The composite shows good agreement between aircraft sampling and A-train overpass of the convective complex 3 hours later. (b) The visible GOES cloud image and the ER-2, WB-57 and DC-8 flight tracks from August 5, 2007. (c) The V3.01 ice water content (IWC) retrieval from the CALIOP lidar for the cloud complex sampled by the aircraft. (d) The CloudSat R04 CWC-RVOD IWC retrieval.

et al., 2009], and cloud thermodynamic phase is determined using vertically resolved depolarization signals and temperature information [*Hu et al.*, 2009]. Profiles of particulate volume extinction coefficient are then retrieved from attenuated backscatter profiles, as described in detail by *Young and Vaughan* [2009]. Whenever possible, extinction retrieval is constrained by layer transmittance measurements. Otherwise, extinction is retrieved using *a priori* particulate extinction-to-backscatter ratios (lidar ratios) that are assigned based on cloud type and phase. Small-angle forward scattering from cirrus particles reduces the apparent particle extinction. To correct for this, the retrieved apparent extinctions are divided by a multiple scattering factor of 0.6 [*Winker et al.*, 2009; *Young and Vaughan*, 2009]. Ice water content is then calculated from the retrieved extinctions in those regions where the cloud phase has been determined to be ice, using a power-law parameterization determined from a least-squares fit of volume extinction coefficients and IWC measurements [*Heymsfield et al.*, 2005, hereinafter HWZ05].

[6] The HWZ05 IWC parameterization has the form:

$$\mathrm{IWC} = a\sigma^{b} \tag{1}$$

with coefficients a = 119 and b = 1.22 for IWC in g/m^3 and extinction (σ) in inverse meters.

[7] HWZ05 derived this relation from *in situ* measurements and retrievals made during three aircraft field campaigns measuring tropical, subtropical, and mid-latitude ice clouds. The majority of this data was collected at temperatures warmer than −60°C, and the IWC-extinction relation was found to have only a small dependence on temperature. *Protat et al.* [2010], evaluated the HWZ05 parameterization using ground-based radar-lidar measurements, and HWZ05 was found to work well except at very cold temperatures where HWZ05 was found to underestimate IWC relative to other retrievals.

[8] Since the development of the HWZ05 IWC parameterization, it has been recognized that particle probe inlets can cause larger cloud particles to shatter, producing anomalously high concentrations of small particles which cause the optical extinction to be overestimated [*Jensen et al.* 2009; *Korolev et al.*, 2011]. Modifications to equation (1) to account for effects of particle shattering are now being investigated (A. Heymsfield, manuscript in preparation, 2011).

[9] The CALIOP 532 nm extinction coefficient detection threshold for cirrus clouds averaged horizontally to 5 km is roughly 0.005 to 0.02 km^{-1} [*McGill et al.*, 2007; *Davis et al.*, 2010], corresponding to an IWC of 0.1 to 0.4 mg/m^3 using equation (1) with a = 238. The detection threshold for CALIOP is lower at night and larger during the day due to improved signal-to-noise ratio at night. The CALIOP signal can penetrate ice clouds to an optical depth of 3–5. However, extinction retrievals become more sensitive to errors in the lidar ratios as optical depth increases [*Winker et al.*, 2009] during cloud penetration, resulting in a useful upper limit on IWC of the order of 100 mg/m^3. Signal attenuation also limits the sampling, and extinction error is roughly inversely proportional to overhead two-way transmittance. Above 8 km CALIOP two-way transmittance is greater than 0.1 in 95% or more of the profiles, except in a 5–10 degree latitude

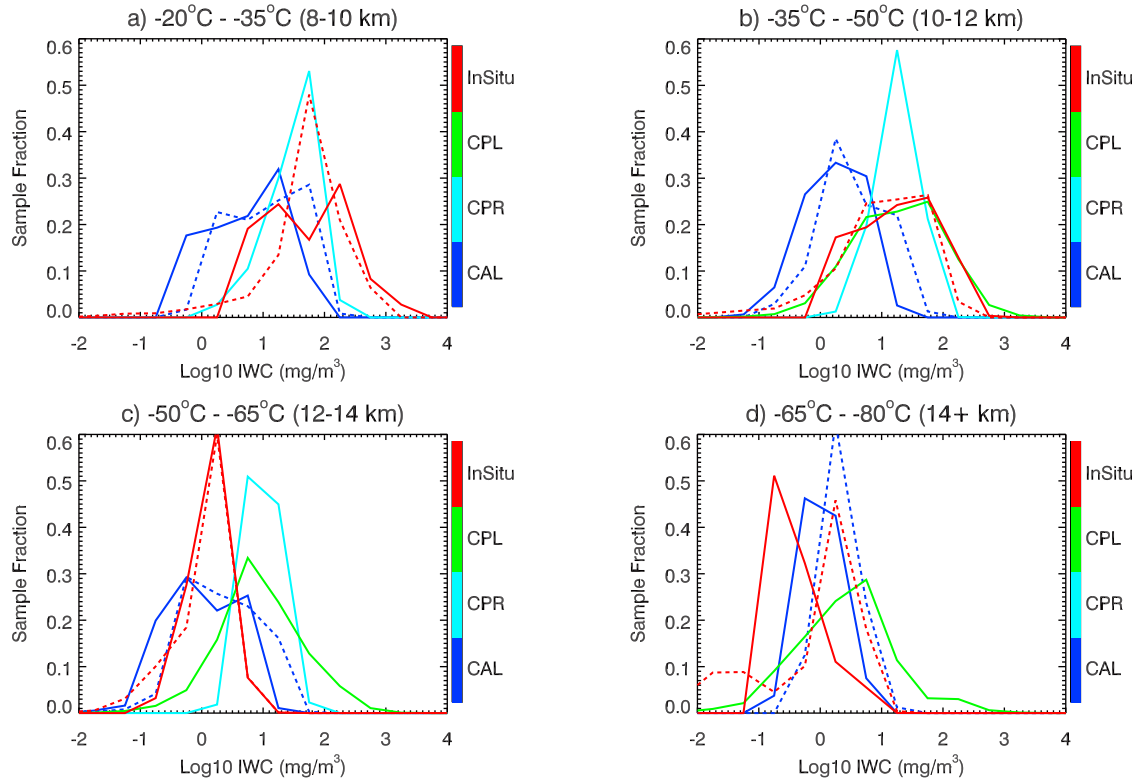

Figure 2. Cloud IWC normalized measurement frequency curves at four different temperature ranges in a tropical convective cloud complex sampled extensively on August 5, 2007 during TC4. Cloud ice water was retrieved from CALIOP on CALIPSO and CPR on CloudSat. V3.01 CALIOP IWC is shown as a solid line, and as a dotted line it is multiplied by a factor of two. The doubled CALIOP V3.01 IWC parameterization was applied to CPL 532 nm extinction retrievals. The *in situ* condensed water content measurements (solid line) were made (a and b) using the CVI instrument on the DC-8 and (c and d) with the CLH instrument on the WB-57. *In situ* IWC measurements shown with a dashed line were made by the 2D-S probe on both planes.

band centered at the ITCZ, where this fraction drops to 75% [*Winker et al.*, 2010]. Consequently the comparisons shown in this paper are limited to 8 km and above, where CALIPSO IWC retrievals are more reliable.

[10] Uncertainty in the CALIOP IWC retrievals is driven primarily by uncertainty in the *a priori* values used for the cloud lidar ratio in the extinction retrievals, and by multiple scattering corrections, as well as by the IWC parameterization itself. Because error in the extinction retrieval propagates into IWC, data has been screened to eliminate extinctions that require large adjustment of the *a priori* lidar ratios for convergence of the solution. In transition regions between cloud ice and liquid water, horizontally oriented ice (HOI) crystals can form [*Hu et al.*, 2009], producing anomalously high backscatter from the near nadir-pointing CALIOP beam and reliable extinction estimates cannot be retrieved in these cases. Therefore, CALIOP cloud layers containing HOI have been screened out using the cloud thermodynamic phase flag, although this may cause IWC values at temperatures below −50°C to be biased low when compared with data sets that include HOI.

3. Comparisons of Global and Regional Statistics

[11] Comparison between any two sets of IWC measurements can be complicated by severe spatial and temporal sampling differences. The CALIOP lidar curtain is actually a series of 70-meter diameter laser profiles from a satellite that is moving at 7 km/sec, so perfect spatial and temporal coincidences are not possible [*van Zadelhoff et al.*, 2007]. Other satellite instruments have much larger footprints, so CALIOP measurements may not be representative in these larger sample volumes, and only in rare instances do *in situ* measurements coincide spatially and temporally with even a few range bins from CALIOP. To get a first look at how CALIOP V3.01 IWC compares with other measurements, an initial study was performed by constructing temperature-dependent probability distributions from remote and *in situ* aircraft measurements. A second study compares CALIOP averaged global distribution with other satellite-based instruments.

[12] On August 5, 2007, during the 2007 TC4 aircraft mission [*Toon et al.*, 2010], there was a close coincidence between coordinated sampling of a convective cloud complex in the Panama Bight by instruments on the NASA ER-2, WB-57 and DC-8, and an A-TRAIN overpass. After the airplanes sampled the convection, the A-Train passed over the same convective complex 2–3 hours later. Figure 1a shows a composite of CALIOP and ER-2 CPL 532 nm attenuated backscatter, with good agreement between the aircraft and A-train lidar sampling despite the time lag, although GOES imagery and derived optical depths suggest that the convection diminishes just after the A-Train overpass. Figure 1b shows the DC-8 (*in situ*), WB-57 (*in situ*)

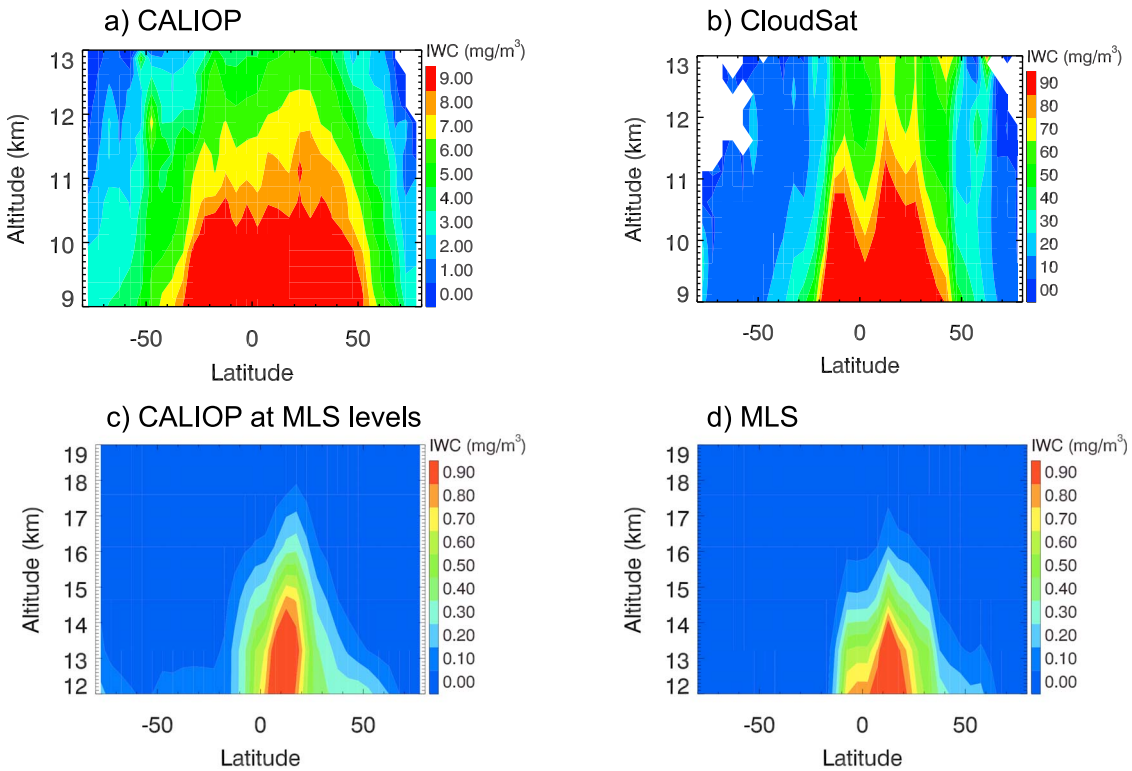

Figure 3. Comparison of contoured 5-degree zonal averaged cloud ice water content in the upper troposphere during August 2007 for (a) CALIOP in-cloud IWC retrievals, (b) CloudSat in-cloud IWC retrievals, (c) CALIOP averaged to 4–5 km vertical bin sizes, corresponding to MLS vertical sampling, and (d) MLS with pressure levels converted to altitude, using an atmospheric scale height of 7.64 km.

and ER-2 (remote) flight tracks. Figures 1c and 1d show the CloudSat R04 CWC-RVOD and the CALIOP V3.01 retrieved IWC curtains, highlighting the sampling difference between the radar and lidar.

[13] Figure 2 shows the distributions of IWC retrieved by CALIOP and CloudSat for 4 vertical ranges within the convective cloud complex; 8–10 km, 10–12 km, 12–14 km and above 14 km, corresponding to 4 temperature ranges in the cloud. CALIOP IWC using HWZ05 is shown (solid) as well as IWC from a doubled HWZ05 parameterization where the coefficient a of equation (1) is doubled to 238 (dashed) to correct for particle shattering effects. The distributions of satellite measurements are shown together with distributions of IWC derived by applying the doubled HWZ05 to Cloud Physics Lidar (CPL) 532 nm extinction retrievals, and *in situ* IWC measurements from the DC-8 and the WB-57. At 8–12 km the *in situ* measurement distributions shown in Figure 2 were made using the Counterflow Virtual Impactor (CVI) [*Twohy et al.*, 1997], with a detection limit of about 0.004 g m^{-3}. The CVI measures total condensed water content, which we are assuming above 8 km is ice. For comparison, IWC derived from size distribution data from the 2D-Stereo optical array probe (2D-S) [*Lawson et al.*, 2006] are also shown. Above 12 km we used measurements from the Closed-path Laser Hygrometer (CLH) [*Davis et al.*, 2007], with a 0.2 mg m^{-3} detection limit, and we also show the 2D-S IWC retrievals from the WB-57. CPL data is not shown for 8–10 km because of signal attenuation under thick clouds at the eastern edge of the flight tracks. CloudSat data is not shown above 14 km because the radar is not sensitive to small ice particles there. Above 12 km the HWZ05 parameterization compares well with the *in situ* data, although the CPL results are somewhat higher. CloudSat IWC, where it is measured, is also larger than CALIOP IWC. More data is needed at colder temperatures and high altitudes, as evidenced by the spread in IWC values measured or retrieved above 14 km. At 10–12 km the CPL measures an IWC distribution that is very similar to the CVI, an encouraging indication that the HWZ05 parameterization is reasonably accurate. The CALIOP IWC measurement distribution is lower than CVI and 2D-S at both 8–10 km and at 10–12 km, which may be due to signal attenuation, to screening out HOI, or to changes in the clouds in the 2–3 hours between aircraft sampling and satellite overpass.

[14] Figure 3a shows zonally averaged CALIOP IWC at 5 degrees horizontal and at 1 km vertical resolution, compared with similarly averaged CloudSat R04 RVOD (radar IWC retrievals constrained with MODIS visible optical depth) IWC data in Figure 3b. Zonal averages in Figures 3a and 3b contain only retrieved IWC, and are only shown for 9–13 km where the radar and lidar retrievals are most likely to overlap. In this analysis we double the HWZ05 coefficient a of equation (1) to 238 to correct for particle shattering as discussed above. The radar and lidar can both resolve multiple cloud layers, but have different instrument sensitivity considerations. CloudSat is unable to detect all of the high, optically thin ice clouds that are detected by CALIOP. Conversely, CALIOP is unable to penetrate as deeply into optically thick clouds as the CloudSat Cloud Physics Radar

(CPR) [*Mace et al.*, 2009; *Winker et al.*, 2010; *Delanoe and Hogan*, 2010]. The altitude where CALIOP and CloudSat IWC retrievals overlap varies with cloud type, and by latitude. CloudSat IWC retrievals above 9 km are roughly an order of magnitude larger than CALIOP IWC retrievals, but this is not unexpected because the CloudSat detection limit ($\sim$5 mg/m^3) is also an order of magnitude larger than CALIOP ($\sim$0.4 mg/m^3). CloudSat does not measure signal from small cloud ice particles at high latitudes and high altitudes, and so is biased to high IWC in these regions, while screening of CALIOP data to remove HOI and poor extinction retrievals may bias the CALIOP IWC low where HOI and thick clouds are prevalent. The complexity of this comparison warrants a thorough investigation beyond this first look.

[15] The Microwave Limb Sounder (MLS) on the AURA satellite retrieves cloud ice water content along a slant path through the atmosphere at tangent points of 215 hPa (corresponding to 11–12 km) and above. The limb geometry and vertical averaging functions result in a spatial resolution of approximately $300 \times 7 \times 4$ km^3 [*Wu et al.*, 2009]. Figure 3c shows CALIOP IWC re-averaged to the MLS vertical sampling resolution, while Figure 3d shows the MLS V3.3 IWC screened using the 2σ–3σ approach described by *Wu et al.* [2008]. The CALIOP average IWC for an MLS volume includes clear air because MLS does not resolve individual clouds. Note that the bottom layer contour extends to just between 9–10 km due to the $\sim$4 km MLS vertical "bin" size. The agreement between zonally averaged MLS (Figure 3d) and CALIOP IWC is quite good, to about +/−50% of the averaged IWC, with CALIOP a bit higher than MLS above 16 km, and MLS higher between 12–14 km. This good agreement is encouraging, because while MLS and CALIOP both sample the upper troposphere, the measurement and retrieval approaches and instrument viewing geometries are very different.

4. Summary

[16] Based on our initial evaluation, CALIOP is sensitive to IWC at concentrations above roughly 0.4 mg/m^3 during the daytime, and 0.1 mg/m^3 at night. An apparent upper limit on the order of 100 mg/m^3 is due to attenuation of the lidar signal in optically dense clouds. IWC retrievals are difficult to validate precisely because of a lack of global IWC "truth" at comparable spatial and temporal resolution. However, initial comparison with zonally averaged MLS upper tropospheric IWC indicates agreement of about 50%, despite radically different measurement and retrieval approaches and viewing geometries. Relative to *in situ* comparisons from the TC4 case study, CALIOP retrieves lower IWC in the tropics below 12 km, and comparable or higher IWC above 12 km, indicating a possible need for a temperature-dependent IWC parameterization, although further comparisons are needed to be conclusive. Results from the HWZ05 IWC parameterization applied to CALIOP and to CPL 532 nm extinctions for this case suggest that adjustment of the HWZ05 parameterization by roughly a factor of 2 is justifiable, and studies of this type will continue to improve the parameterization. An error analysis, cloud particle phase validation and a more thorough V3.01 IWC evaluation for both the TC4 time period and for other years is ongoing, including comparisons between matched CALIOP V3.01, CloudSat R04 CWC-RVOD and hybrid IWC retrievals. The CALIOP lidar has now been operational since June, 2006, providing more than 5 years of continuous global IWC data. Together with the complementary IWC data from CloudSat and MLS, CALIOP IWC provides significant advances in our abilities to observe and characterize the global distribution of ice mass and ice cloud processes.

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