Quantifying the Amount of Ice in Cold Tropical Cirrus Clouds

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1. INTRODUCTION

How much ice is there in the Tropical Tropopause layer, globally? How does one begin to answer that question? Clouds are currently the largest source of uncertainty in climate models, and the ice water content (IWC) of cold cirrus clouds is needed to understand the total water and radiation budgets of the upper troposphere and lower stratosphere (UT/LS). The Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) satellite, originally a "pathfinder" mission only expected to last for three years, has now been operational for more than eight years. Lidar data from CALIPSO can provide information about how IWC is vertically distributed in the UT/LS, and about inter-annual variability and seasonal changes in cloud ice. However, cloud IWC is difficult to measure accurately with either remote or *in situ* instruments. Generally assumptions must be made about the relationship between the area, volume and density of ice particles with various crystal habits, since direct total water measurements have large uncertainties. Recently there have been numerous aircraft field campaigns providing detailed information about cirrus ice water content from cloud probes. This presentation evaluates some of the assumptions made when creating the Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) global IWC data set, using recently reanalyzed aircraft particle probe measurements of very cold, thin TTL cirrus from the 2006 CR-AVE aircraft field mission.

2. CLOUD ICE WATER CONTENT PARAMETERIZATION

Cloud ice water content is created in the CALIOP data set using a two-step process. As an elastic backscatter lidar, CALIOP measures attenuated backscatter, and extinction is retrieved using the method of Young and Vaughan (2009). Retrieving extinction for thin subvisible cirrus requires the assumption of extinction to backscatter coefficient ratio, currently 25 sr in the CALIOP Version 3 algorithm. Given the retrieved extinctions, Version 3 uses an empirically based power law:

$$IWC = a\sigma^b, \text{ a=119, b=1.22} \qquad (1)$$

This power law is based on a set of *in situ* and remote aircraft-based measurements (Heymsfield et. al., 2005).

Figure 1 illustrates these steps for an overpass of Hurricane Sandy, from total 532 nm backscatter, to extinction and then IWC.

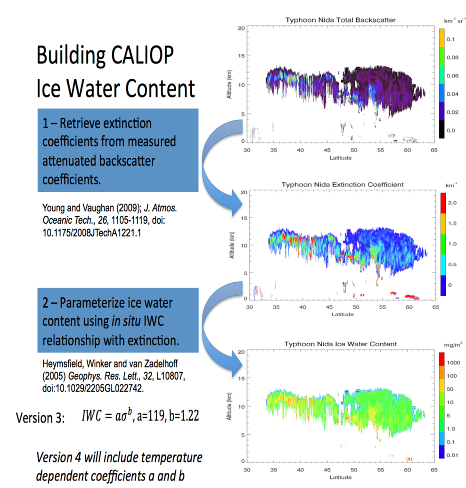


Figure 1: Representation of the CALIOP ice water content parameterization process.

3. ICE PARTICLES IN THE TTL

The TTL is the region where vertical motion transitions between convection and the large-scale Hadley circulation. Ice clouds in the Tropopause Transition Layer (TTL) are difficult to measure remotely because they are optically thin; most are sub-visible. Figure 2 a, b and c show the subtle boundary between the level of neutral buoyancy with maximum convective outflow and the TTL at 14.5 km (in a) or 355 K potential temperature (in b). These plots show data from a representative month (December 2009).

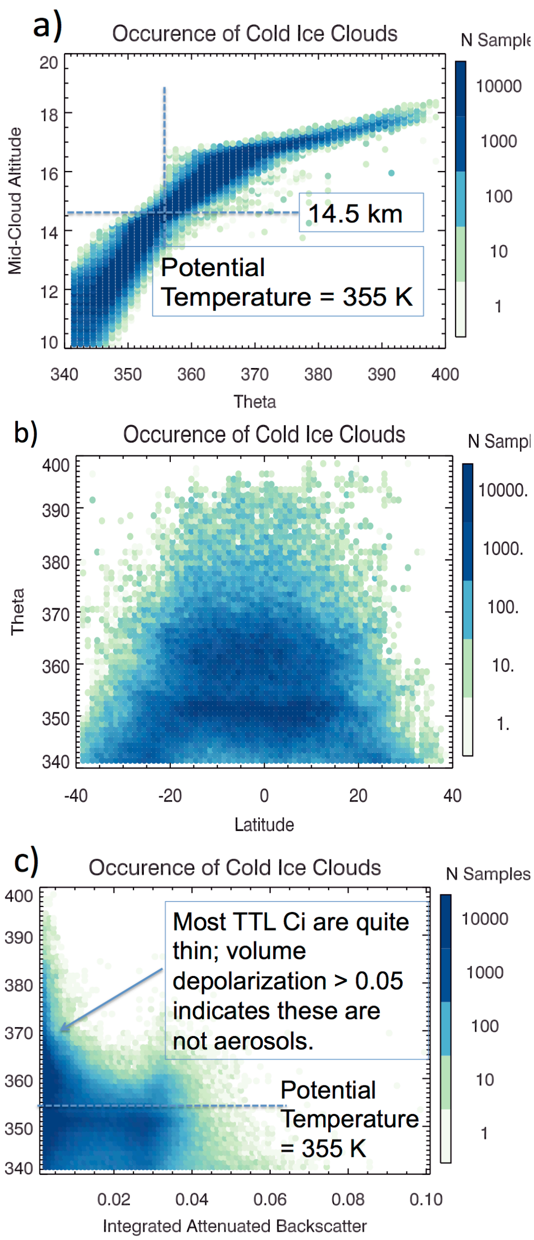


Figure 2,a-c: Occurrence of Cold Ice Clouds during December 2009. Shown are a) Potential temperature (theta) vs. mid-cloud altitude, b) Zonal cloud occurrence profile (theta y-axis), c) Integrated attenuated backscatter in the tropics as a function of altitude (theta).

As shown in 2c, most TTL cirrus are quite thin. Volume depolarization greater than 0.05 indicates that these layers are not sulfate aerosols. Figures 3a and 3b show the distribution of ice water path, depolarization and backscatter color ratio for TTL Ci. The statistics are noisy because the sub-visible Ci are thin. Nonetheless, they provide information about this critical region when averaged appropriately.

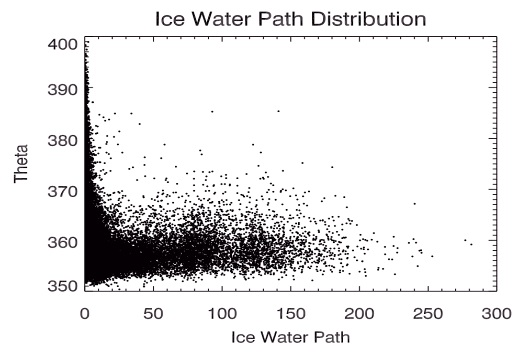


Figure 3a: Cloud ice water path as a function of theta

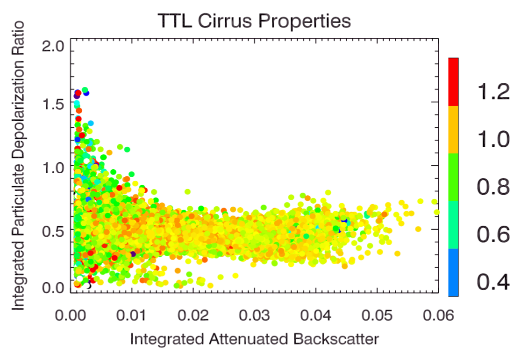


Figure 3b: Cloud depolarization as a function of integrated backscatter, colored by the 1064/532 nm color ratio (color scale).

Figures 4a and 4b show the mean integrated attenuated backscatter (IAB) and relative uncertainty for IAB and optical depth in very cold TTL clouds. Below -75 the uncertainty is dominated by the difficulty of detecting thin layers accurately. Note that we define "cold" clouds as having mid-layer temperature < -55^{o}C, but when selected dynamically (theta > 355 K) the cloud mid-layer temperature < -65^{o}C.

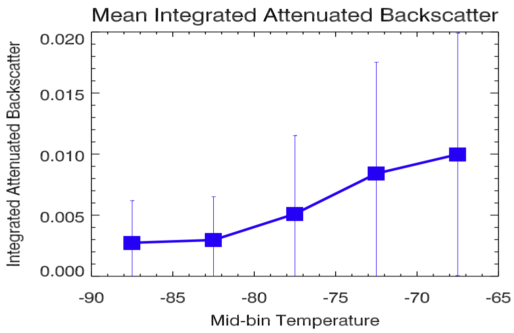


Figure 4a is a plot of integrated backscatter as a function of mid-cloud temperature, showing that clouds become thinner at cold temperatures in the TTL.

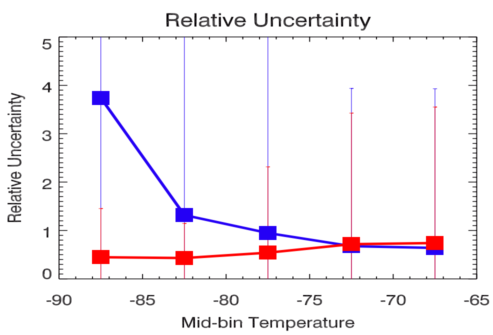
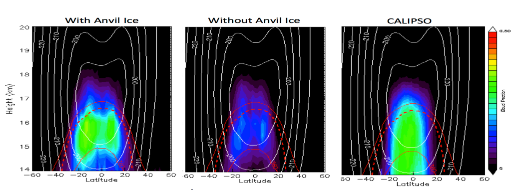


Figure 4b shows the relative uncertainty for optical depth (red) and integrated backscatter (blue).

4. CONVECTIVE INFLUENCE ON LOWER STRATOSPHERIC WATER VAPOR

A model test, CALIOP space-based lidar and *in situ* aircraft observations all demonstrate that convective transport of water vapor and ice to the Tropical Tropopause Layer (TTL) and lowermost stratosphere is a significant process. Figure 5 shows results from a simple cloud model that is added to a global domain-filling forward trajectory model (Schoeberl and Dessler, 2012) to test the impact of convectively lofted cloud ice and water vapor on the TTL and lowermost stratosphere. Results suggest that the anvil ice is needed to match CALIOP observations.



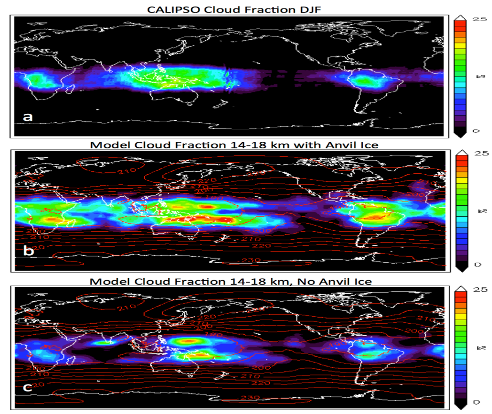


Figure 5: From Schoeberl et al., 2014, shows the global distribution of CALIOP clouds for DJF 2008-9. The trajectory model is compared to the measurements, with and without MERRA anvil ice added to a simple cloud model.

CALIOP ice water content for winter 2008-9 shown in Figure 6 as an example of how much ice mass there is at high altitudes.

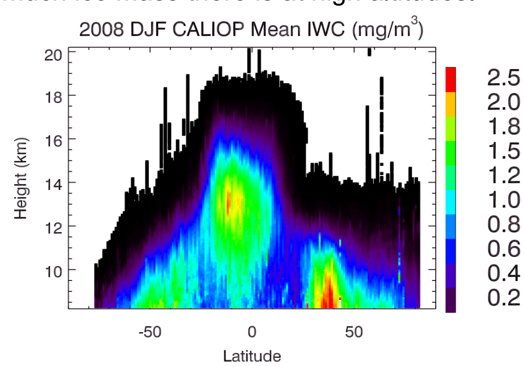


Figure 6: CALIOP zonally averaged ice water content during DJF 2008-9. Some of the apparent "noise" is due to less frequent overpasses at low latitudes.

Measurements of cloud microphysical parameters in the TTL are few. Figure 7 shows flight tracks from the CR-AVE mission out of Costa Rica in JF 2006.

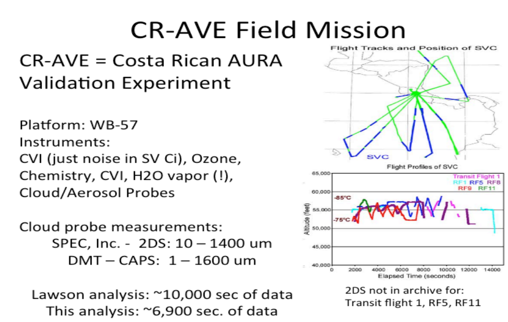


Figure 7: Flight tracks from CR-AVE

A SPEC, Inc. optical array probe (2D-S) measured the particle size distributions, extinctions and IWC in the TTL and lowermost stratosphere from the WB-57. IWC measurements are shown in Figure 8.

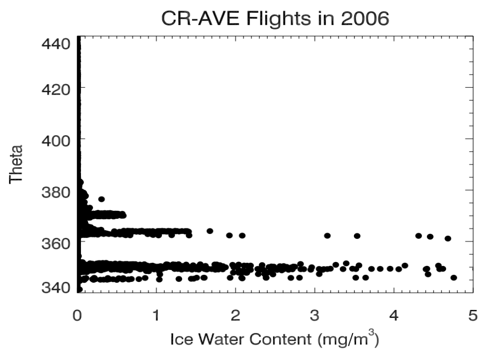


Figure 8: CR-AVE 2D-S IWC composite

Figure 9 shows a corresponding CALIOP climatology of vertically-resolved cloud frequency (fraction of 60m bins with IWC > 0.01 mg/m^3.

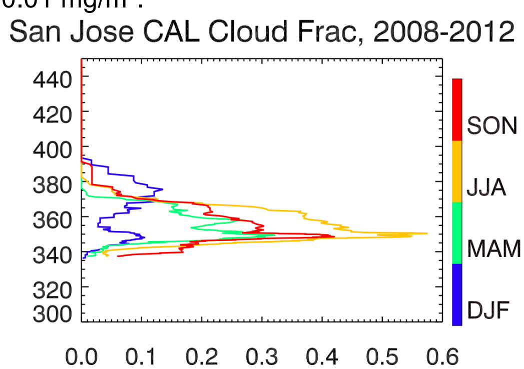


Figure 9: Cloud frequency, San Jose, Costa Rica, DJF 2008-2012.

An interesting result from CR-AVE is that there is that the largest particles occur above 380 K and appear to have nucleated heterogeneously (Jensen, et al., 2008).

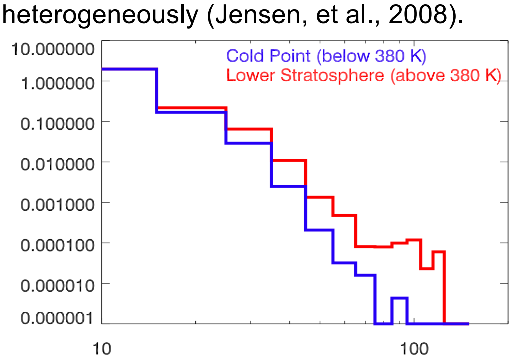


Figure 10: Average particle size distribution in the TTL measured by the 2D-S

The size distributions from the 2D-S in Figure 10 agree well with the observations of de Reus et al., 2009, from Darwin during SCOUT. Typical CPI images of these particles are shown in Figure 11.

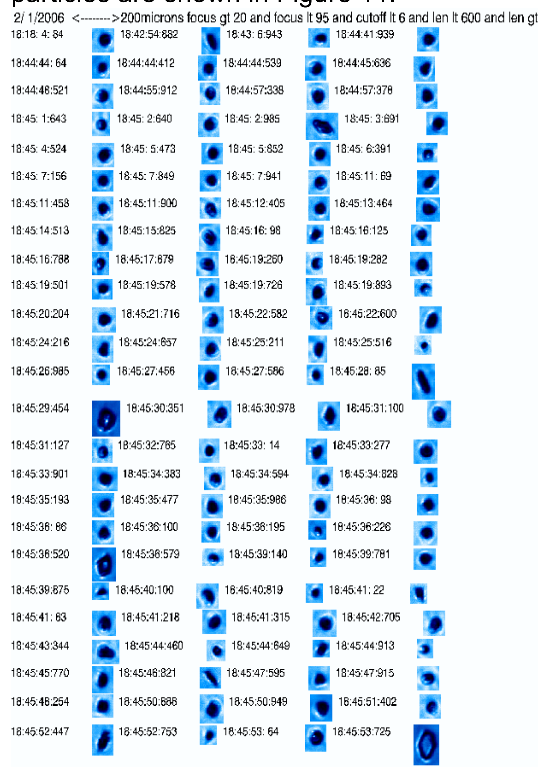


Figure 11: SPEC CPI images of ice particles just above 380 K during CR-AVE.

5. EVALUATING EXTINCTION COEFFICIENTS

A set of extinction coefficients measured using aircraft particle probes (details in Heymsfield et. al., 2014) has been compiled, and statistics of the distribution are shown in Figure 12, in blue. The mean extinction clearly decreases at colder temperatures, as will the associated ice water content. CALIOP data is shown in black for all of the data, and in red for extinction solutions that are calculated using a transmittance method (Young and Vaughan, 2009), hereafter called "constrained". Figure 12 shows that the constrained extinctions are not representative of the ensemble of CALIOP extinctions within each temperature range, and that at cold temperatures the CALIOP constrained extinction mean is larger than the corresponding mean for the probe data, because the criteria for using the transmittance method in the Version 3 data set selects relatively optically thick layers.

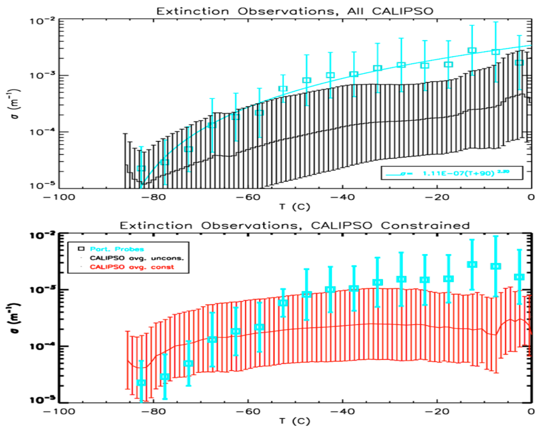


Figure 12: In situ measured extinction coefficients (blue) compared with CALIOP retrieved extinctions - all (black) and only solutions calculated using transmittance measurements - constrained (red).

Figure 13 shows that for temperatures colder than -55 deg C, constrained solutions are 20% or less of the data. The bulk of the cold Ci cloud layers are assigned the a priori lidar ratio of 25 sr. Referring back to the mean CALIOP extinctions in Figure 12, one can infer that the a priori extinction solution is too low.

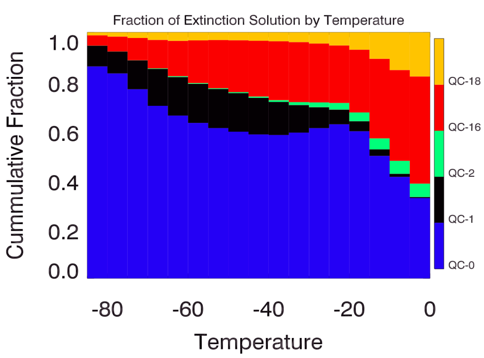


Figure 13: CALIOP distribution of extinction solution types as a function of temperature. Most cold Ci clouds are transparent to CALIOP and are optically thin (blue). These will be assigned an a priori value of the lidar ratio to solve for σ.

Figures 14 a and b show median integrated backscatter and extinctions as a function of temperature. The green line on Figure 14b is the result of increasing the default lidar ratio from 25 to 32 sr.

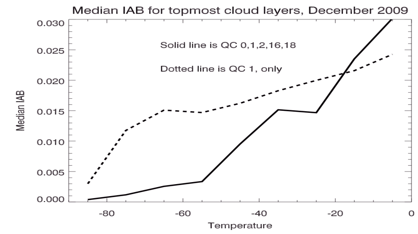


Figure 14a: IAB as a function of mid-cloud temperature.

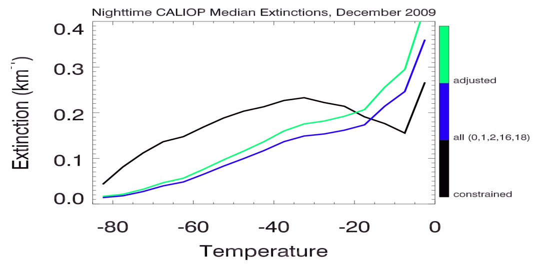


Figure 14b: As 14a, but for extinction.

6. COMPARISON WITH THE IMAGING INFRARED RADIOMETER (IIR)

A matched set of CALIOP and IIR data from December, 2009 (as in Parts I and II) is used for comparison between CALIPSO IIR and CALIOP retrievals of cloud layer optical depth, effective diameter and ice water path. The layers were selected to optimize the IIR retrievals with these characteristics: single (topmost) transparent (to CALIOP) cloud layers of IIR scene types 21, 30 and 24 (see Garnier 2013) with measured reference radiances. These layers were then further classified as: Cold: centroid temperatures < -55 deg C (30k samples); TTL: cloud bases > 14.5 km (6k samples)

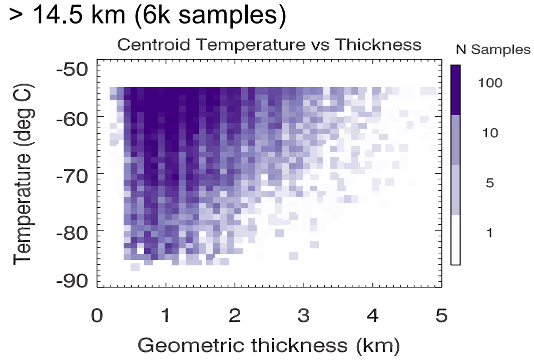


Figure 15a: Occurrence of layer geometric thickness as a function of temperature for "cold" ice clouds.

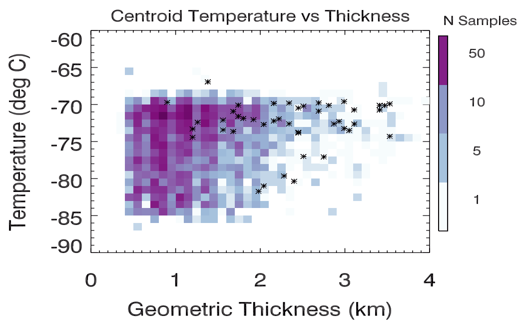
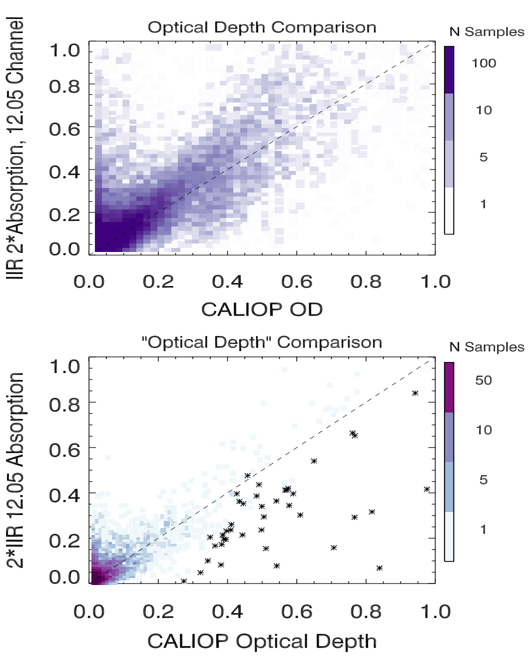


Figure 15b: As for 15a, but TTL layers only.

In the month of December, 2009 there were only 44 Ci layers with constrained CALIOP retrievals in the TTL. These data points are labeled with crosses on Figures 15b, 16b and 17b. In a similar way to the aircraft data comparison for extinctions, CALIOP optical depth is in general lower than the equivalent IIR optical depth because the unconstrained "a priori" retrievals are too small for these optically thin clouds. But the constrained optical depths appear to be much higher than the IIR, suggesting that the smaller particles to be found at cold temperatures are affecting one or both CALIPSO Version 3 extinction and optical depth retrievals. More work is currently being performed to sort this out.

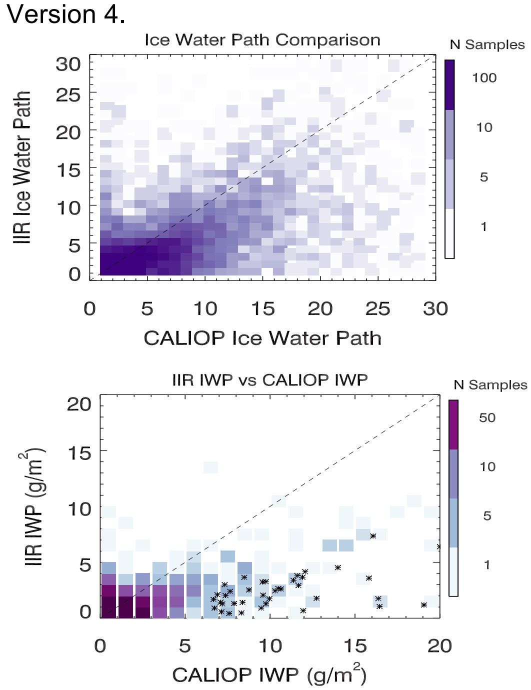


*Figures 16a and 16b: 2*IIR 12.05 μm optical depth compared with the CALIOP optical depth (layer integrated extinction) for "cold" and "TTL" ice clouds, respectively.*

We evaluated effective diameter as it is defined in Mitchell (2010):

$$D_{eff} = (3/\rho_{ice})(IWC/\sigma) \quad (2)$$

In this case we are using integrated quantities for the cloud layers, so the ratio is ice water path (IWP) to optical depth. CALIOP effective diameters are larger than those from the IIR, which may indicate that the Version 3 IWC parameterization is too large for colder temperatures. New analysis in Heymsfield et al., 2014 suggests updated IWC parameterizations that are currently being evaluated for possible use in CALIOP Version 4.



Figures 17a and 17b: IIR vs. CALIOP cloud IWP for "cold" and "TTL" ice clouds.

Figures 17 a and b show the comparison between the IIR and CALIOP ice water path for cold and TTL Ci clouds. CALIOP IWP is slightly higher, even while having mainly lower optical depths, so the differences apparently cancel each other somewhat. The CALIPSO team is currently evaluating updated extinction retrievals and IWC parameterizations for the new Version 4 Level 2 product.

The CALIPSO CALIOP and IIR Version 3 products are available at:
NASA LaRC: (http://eosweb.larc.nasa.gov/)
ICARE: (http://www.icare.univ-lille1.fr/)

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