VALIDATING CIRRUS CLOUD OPTICAL PROPERTIES RETRIEVED BY CALIPSO

Mark Vaughan[1], Ralph Kuehn[2], Stuart Young[3], Matthew McGill[4], Zhaoyan Liu[5], Yongxiang Hu[1]

[1] *NASA Langley Research Center (LaRC), Mail Stop 475, Hampton VA 23681 USA mark.a.vaughan@nasa.gov*
[2] *Science Systems & Applications Inc., LaRC Mail Stop 475, Hampton VA 23681 USA ralph.e.kuehn@nasa.gov*
[3] *Centre for Australian Weather and Climate Research, Aspendale, VIC, Australia stuart.young@csiro.au*
[4] *Goddard Space Flight Center, Bldg 33, Rm A410, Greenbelt MD 20771 USA matthew.j.mcgill@nasa.gov*
[5] *National Institute of Aeronautics, LaRC Mail Stop 475, Hampton VA 23681 USA zhaoyan.liu-1@nasa.gov*

ABSTRACT

The spatial and optical characteristics of transparent cirrus clouds measured by CALIPSO are compared to measurements made by the Cloud Physics Lidar (CPL). We examine statistical ensembles of both intrinsic and extrinsic properties, with a particular emphasis on the 532 nm lidar ratio distributions retrieved by the two instruments. Despite differences in the seasonal and geographic data acquisition statistics between the two data sets, the mean values for the two distributions are essentially identical. CALIPSO's fully automated retrieval scheme yields a lidar ratio of 23 ± 9 sr; the value derived from the CPL measurements is 25 ± 10 sr. Similarly, despite disparities in single shot signal-to-noise ratios, the 532 nm optical depth distributions also compare well, with CALIPSO measurements of transparent clouds averaging 0.42 ± 0.37, versus a mean of 0.38 ± 0.29 for CPL.

1. INTRODUCTION

Launched on April 26, 2006, the Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) mission [1] now routinely delivers continuous, global measurements of the Earth's atmosphere. Unlike the passive sensors aboard previous space-based Earth observing systems, the two-wavelength, polarization sensitive backscatter lidar aboard CALIPSO measures range-resolved profiles of the atmosphere, thus providing climate researchers with the first-ever long-term assessment of the vertical structure, composition, and distribution of clouds and aerosols. However, validating the data acquired by space-based lidar faces formidable challenges introduced by the constantly changing nature and spatial scales of the measurement targets, combined with the very high speed at which CALIPSO traverses the sample volume (~7 km sec^{-1}) and the relatively low sampling rate of the lidar (20.16 Hz). Given these conditions, the traditional validation approach of comparing coincident measurements is generally sub-optimal, because, even for aircraft under flights, the exact coincidence lasts for only a tiny fraction of a second. Beyond that time, the validity of the comparisons is wholly dependent on the assumption of spatial and temporal stability of the atmospheric scene being measured. An alternate technique, and the one adopted for use in this work, is to use a statistical approach in which direct, one-to-one comparisons are eschewed in favor of comparisons made between probability distribution functions (PDFs) derived from extended time series. For the statistical approach, the actual coincidence in time and space between the two sets of measurements is less important; what is important is that the quantity and quality of the measurements gathered by both/all instruments is sufficient to accurately characterize the physical parameters of interest.

Irrespective of the approach employed, the Cloud Physics Lidar (CPL [2]) is the current tool of choice for validating CALIPSO measurements of high, thin cirrus. Like CALIPSO, CPL is a polarization sensitive, back-scatter lidar operating wavelengths of 532 nm and 1064 nm. Furthermore, because CPL is typically mounted in a nadir pointing configuration aboard NASA's high altitude ER2 aircraft, it too can measure clouds and aerosols throughout the entire vertical extent of the troposphere. CPL data has previously been used successfully in traditional validation campaigns supporting both CALIPSO [3] and the Geoscience Laser Altimeter Satellite (GLAS [4]). CPL's utility with respect to the statistical approach derives from its long history of participating in extended duration field measurement campaigns. Table 1 summarizes the dates and locations for all field campaigns during which CPL flew aboard the ER2. To conduct the current study, we compiled statistics from all flights, excluding only those for which the data was compromised due to an instrument malfunction. The sole exception to this statement is the SAFARI campaign. Because the receiver optics required for depolarization measurements had not yet been installed, the SAFARI configuration of CPL could not provide the complete inventory of measurements desirable for validating CALIPSO measurements of cirrus clouds.

Validating the full catalog of data products produced by CALIPSO is a daunting undertaking, and lies well beyond the scope of this work. Instead we focus on a critical subset of retrievals: the estimated optical depths and the corresponding lidar ratios retrievals for transparent cirrus clouds. These two data products represent the culmination of a complex, fully automated analysis sequence, which begins with signal calibration, and subsequently includes layer detection, cloud-aerosol discrimination, and an assessment of cloud ice-water phase. For the final data products to be correct, every preceding step in the analysis chain must also be correct. Therefore, validating the optical depths and lidar ratios for transparent cirrus implicitly (albeit not comprehensively) verifies the correctness of substantially all of the upstream results in the CALIPSO data processing scheme.

Table 1: CPL field campaigns used to derive validation statistics. The number of samples given represents the number of transmissive cirrus measured during each mission. Note several CPL missions are excluded from this list, including SAFARI and three separate Aura Validation Experiments (AVE), which took place between October 2004 and January of 2006. During the AVE missions CPL was mounted aboard the WB57 aircraft rather than on the ER2. In addition to unexpected instrument integration problems that significantly degraded the backscatter signal, the AVE data collection protocol, which frequently called for the aircraft to "porpoise" repeatedly throughout the vertical extent of a cloud, is incompatible with the straight and level flight paths required for reliable CALIPSO validation.

Mission	Date	Range	Samples
CRYSTAL-FACE	July 2002	14° N – 29° N	5289
TX-2002	November – December, 2002	26° N – 38° N	7179
THORPEX-Pacific	February – March, 2003	16° N – 40° N	7573
GLAS Cal-Val	October 2003	33° N – 47° N	8313
THORPEX-Atlantic	November – December, 2003	32° N – 53° N	10150
CC-VEX	July – August, 2006	23° N – 40° N	10417
CLASIC	June 2007	28° N – 40° N	8146
TC4	July – August, 2007	3° N – 39° N	16735

2. DATA SELECTION

Statistical validation requires that we establish some degree of spatial and temporal correspondence between the data sets being compared. Although CALIPSO has now acquired a global set of backscatter measurements more-or-less continuously since June 7, 2006, for practical reasons[1], the analysis presented here is restricted to data acquired between June 15 and December 31, 2006. This time period covers the summer, fall, and early winter seasons, which are all well sampled by CPL. To further ensure consistency with CPL, the CALIPSO data are restricted to those measurements acquired between -3° S and 53° N, thereby encompassing a range of latitudes identical to that spanned by the CPL data set.

The retrieval of optical depths and lidar ratios becomes increasingly problematic as the backscatter intensity and/or optical depth of the layer decrease. For this study, we have applied a somewhat arbitrarily selected lower bound of 0.0025 sr^{-1} for integrated attenuated backscatter (γ'), and an upper limit of 0.85 for the layer two-way transmittance (T^2). These limits, which correspond to a nominal optical depth of ~0.08, are largely determined by instrument signal-to-noise ratios (SNR). The lower bounds chosen here are governed by CALIPSO detection sensitivities, and thus reduce the size of the CPL data set. For example, CPL routinely detected transparent cirrus between the equator and 3° S. However, these clouds were all extremely thin ($\gamma' <$ 0.0025 sr^{-1}), and hence were removed from consideration. At the upper end of the optical depth spectrum, the largest attenuation (i.e., smallest T^2) reliably measured by CPL was 0.015. Those measurements for which T^2 < 0.015 were therefore excluded from both data sets. No upper limit was imposed on γ'.

3. DATA ANALYSIS METHODS

Retrievals of cloud optical properties depend fundamentally on the layer detection scheme(s) used to determine cloud boundaries. Both CALIPSO and CPL use variants of the threshold technique. To overcome the SNR limitations imposed by operation from a space-based platform, CALIPSO uses a selective, iterated boundary location (SIBYL) algorithm that detects layers at a number of different spatial resolutions, corresponding to greater or lesser amounts of horizontal averaging [5]. Consequently, what might appear to be a single layer is, due to inhomogeneities in the backscatter intensity, often detected as a multi-layer ensemble containing vertically adjacent fragments detected at several different averaging intervals. In these cases, the stronger portions will be detected at finer spatial resolutions (e.g., averaging over 5-km horizontally), while the weakest portions will only be detected at a very coarse resolution (e.g., an 80-km horizontal average). These vertically adjacent ensembles often consist of amalgams of dissimilar layer types, with the canonical example being broken clouds embedded in aerosol layers. To avoid inadvertent mixing of dissimilar layers, the CALIPSO data used in this study is restricted to isolated layers only. Vertically adjacent layers are excluded, so that,

[1] The initial release of the CALIPSO layer products was restricted to the spatial properties of layers, and thus did not report layer optical depths. The version 2.0 processing, released on January 28, 2008, remedies this omission; however, as of this writing, the revised processing has only been completed through December, 2006.

irrespective of the amount of averaging required for detection, all layers analyzed herein are bounded everywhere both above and below by "clear air" only. Enforcing this condition yields a CALIPSO data set similar in nature to the one extracted from the CPL measurements. Because the CPL layer detection scheme operates on single profiles only, vertically adjacent layers are not detected.

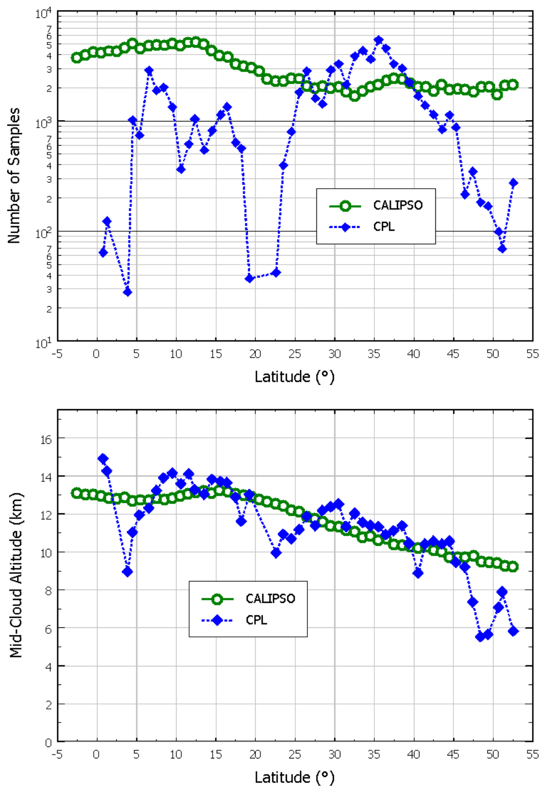

Figure 1: (upper panel) number of samples acquired by each instrument as a function of latitude; (lower panel) mean mid-cloud altitude as a function of latitude. CALIPSO data are shown using green circles; CPL uses blue diamonds. (b) Mid-cloud altitudes measured by CALIPSO (green circles) and CPL (blue diamonds).

For transparent layers, both CALIPSO and CPL use the same method to estimate layer optical depths. This long-known and well-documented technique computes the two-way transmittance of a layer by measuring the signal attenuation that occurs between the clear air overlying the layer and the clear air immediately beneath the layer. An estimate of the layer lidar ratio can subsequently be obtained by using the optical depth derived from the attenuation measurement as a constraint in the solution of the two-component lidar equation [6]. Solutions derived using this kind of constrained retrieval are clearly identified in the CPL data products. Within the CALIPSO data products, isolated transparent layers can be unambiguously identified using the extinction quality assessment flag reported in the CALIPSO Level 2 5-km Layer Products. A flag value of 1 identifies those layers for which a constrained retrieval was both possible and successful.

4. LAYER PROPERTIES COMPARISONS

When attempting a statistical validation for some measurement or retrieval, sample size matters. After filtering according to the strategies outlined above, the CALIPSO thin cloud data set contained 169,881 successful retrievals versus 73,802 for CPL. The spatial distributions of these measurements are shown in Figure 1. The upper panel shows the number of samples acquired by each instrument as a function of latitude. The shape of the CPL curve is dictated by the locations of the various field campaigns, which took place primarily over the continental United States. The CALIPSO curve is indicative of the relative frequency of occurrence of thin clouds; it remains essentially flat between 53° N and ~22° N, and increases in the tropics. The lower panel of Figure 1 shows the mean mid-cloud altitudes detected by each instrument. Within those regions where CPL acquired a large number of samples (e.g., between 25° N and 45° N), the correspondence between the two curves is surprisingly close.

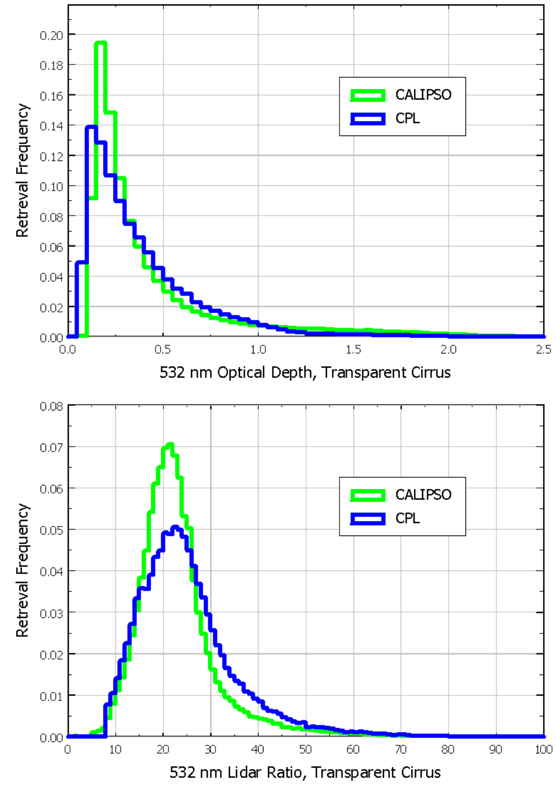

Figure 2: (upper panel) optical depths and (lower panel) lidar ratios measured by CALIPSO (green line) and CPL (blue line).

Figure 2 presents histograms showing the distributions of optical depth (upper panel) and lidar ratio (lower panel) for all transparent cirrus clouds measured by each instrument. Given the spatial and temporal disparities in the input data, the agreement between the two sets of measurements is quite good. CALIPSO retrieves a mean optical depth of 0.42 ± 0.37. The corresponding value measured by CPL is 0.38 ± 0.29. The larger spread in values associated with the CALIPSO retrieval is as expected, both because the CPL SNR is higher and because CALIPSO measures a wider variety of cirrus types. (CPL participates in narrowly focused field missions, with specific measurement objectives; CALIPSO, on the other hand, simply measures whatever happens to be within its field of view.) However, because optical depth is an extrinsic property, one that depends on the concentration of particles present, the closeness of the agreement between CALIPSO and CPL may at first be somewhat surprising. The explanation lies in the fact that both instruments are backscatter lidars, and for these instruments the signal is effectively extinguished at ~3 optical depths. The data being compared here thus does not represent an assessment of the full, natural distribution of cirrus cloud optical depths. We are instead comparing two measurements of the distribution of those cirrus clouds that appear transparent when measured by a backscatter lidar. Considered in this more restrictive (and correct) sense, agreement between the two sets of measurements is to be expected, and we consider the close correspondence between CALIPSO and CPL to be quite gratifying.

The CALIPSO and CPL measurements of lidar ratio also agree well. CALIPSO retrieves a value of 23 ± 9 sr, versus 25 ± 10 sr for CPL. Because lidar ratio is an intrinsic property, depending only on the type of particles present, close agreement should be expected. There are, however, important differences in the way multiple scattering effects the signals from the two instruments, and to obtain an acceptable comparison, these must be properly taken into account. Lidar ratios for both CALIPSO and CPL are derived by solving a two component lidar equation that parameterizes multiple scattering contributions via a multiplicative factor that modifies the particulate optical depth (e.g., as in [5]). In any retrieval, the value of this multiple scattering factor depends not only on the target being measured, but also to a significant degree on the viewing geometry of the lidar itself. Multiple scattering effects are negligible in the CPL signals, so that $\eta \approx 1$. The CALIPSO analysis uses a value of $\eta = 0.6$, which has been derived from extensive model calculations subsequently augmented by numerical experiments. The agreement between the CALIPSO and CPL lidar ratio retrievals gives credence to CALIPSO's assessment of η for cirrus clouds.

5. CONCLUSIONS

In this initial foray into the realm of statistical validation, we have compared the first seven months of CALIPSO measurements of 532 nm optical depth and lidar ratio for transparent cirrus clouds to the extended time history compiled by CPL. Although disparate in time, and only partially matched in space, the two instruments retrieve nearly identical values for both parameters. The close match of the CALIPSO retrievals with those derived from the long-established CPL dataset represents a substantial step toward validating the end-to-end performance of the CALIPSO data analysis system.

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