MULTI-SENSOR CIRRUS OPTICAL DEPTH ESTIMATES FROM CALIPSO

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ABSTRACT

Global measurements of cirrus optical depth are critical to assessing their radiative impacts and need to be validated. Comparisons of retrievals from different instruments and techniques can be very informative regarding the different sources of uncertainty. In this paper, we compare cirrus cloud optical depth estimates retrieved by the active (lidar) and passive (radiometer) remote sensing instruments aboard the CALIPSO satellite.

1. INTRODUCTION

The CALIPSO mission [1], launched in 2006, carries the CALIOP (Cloud and Aerosol Lidar with Orthogonal Polarization) lidar operating at two wavelengths (532 and 1064 nm), the 3-channel Imaging Infrared Radiometer (IIR) operating in the 8-12 µm thermal infrared spectral range, and the Wide Field Camera (WFC) operating in the visible domain. The three instruments are assembled in a staring and near nadir looking configuration. The cross-track swaths of the passive instruments are centered on the lidar track where observations from the three instruments are almost perfectly temporally and spatially collocated, allowing detailed comparison studies. In this paper we first briefly review the measurements and methods used by CALIOP (section 2) and IIR (section 3) to estimate cirrus cloud optical depths. We then compare the optical depth retrievals in the visible spectrum (532 nm) from the CALIOP lidar to those in the thermal infrared (12.05 µm) from the IIR.

2. CALIOP CIRRUS OPTICAL DEPTH

2.1 Calibration

CALIOP signal to noise ratio at 532 nm is higher during nighttime than during daytime, leading to two different strategies to calibrate the instruments. For nighttime operations, the 532 nm parallel channel is calibrated at high altitude (30-34 km) where the atmosphere is largely free of clouds and aerosols, and where the expected calibrated backscatter signal can be computed using an atmospheric model [2]. The presence of stratospheric aerosols in the calibration region in the tropics introduces a low bias into the calibration factors of about 5%. For daytime operations, the calibration is performed in cloud free regions between 8 and 12 km. The daytime calibration algorithm has been revised for Version 3 CALIOP products [3], producing calibration coefficients that scale the daytime clear air scattering ratios to match what has been measured at the same latitude at night.

2.2 Cirrus layers detection

The Level 1 calibrated 532 nm total attenuated backscatter profiles are used to detect scattering layers [4], which are further classified as clouds or aerosols [5]. Cloud layers are classified as water, randomly-oriented ice, or horizontally-oriented ice clouds [6]. Cloud layer properties are reported in the Level 2 5-km Cloud Layer products with a horizontal resolution of 5, 20 or 80 km defined by the amount of averaging required to detect the layers.

2.3 Cirrus optical depth

For each ice cloud layer, one of the fundamental optical properties measured by CALIOP is the layer integrated attenuated backscatter, or IAB, defined as:

$$IAB = \int_{z_{top}}^{z_{base}} \beta_c(r) \cdot T_c^2(r).dr \qquad (1)$$

In Eq. 1, z_{top} and z_{base} are the top and base altitudes of the layer, and $\beta_c(r)$ and $T_c^2(r)$ are, respectively, the cloud backscatter coefficient and two-way transmittance. The relationship between the cirrus optical depth, τ_c, and the integrated attenuated backscatter is given by the following equation [7]:

$$IAB = \frac{1-e^{-2\eta\tau_c}}{2\eta S_c} \qquad (2)$$

In Eq. 2, η is the multiple scattering factor, indicating the contribution from multiple scattering to the backscatter signal, which is set here to 0.6 for cirrus clouds. S_c is the cirrus cloud lidar ratio, defined as the ratio of the extinction to the backscatter coefficients, which are the two main unknowns of the lidar equation. The product $\eta\tau_c$ is the "apparent" optical depth associated to the layer 2-way-transmittance, T_c^2, such as:

$$T_c^{\,2} = e^{-2\eta\tau_c} \quad (3)$$

CALIOP cirrus visible optical depths are retrieved using one of two different and totally independent techniques. The first one is the so-called "constrained" technique, in which the layer 2-way transmittance can be measured if clear air is found both above and below the layer [8]. This technique allows a direct determination of the layer "apparent" optical depth, and ultimately of the cloud optical depth after correction for the multiple scattering factor, η. This technique can be applied when the signal to noise ratio is large enough, for optical depths typically greater than 0.3 and mostly during nighttime. It does not require any assumption about the lidar ratio. On the contrary, S_c can be retrieved using Eq.2 from IAB and the layer 2-way transmittance, as will be shown in section 4.

When the first technique cannot be applied, the layer optical depth is retrieved from Eq.2 using an initial lidar ratio, S_c and the factor, η. The initial lidar ratio can be increased or reduced to prevent extinction retrievals from diverging. For semi-transparent cirrus clouds, most of the retrievals are "unconstrained", with final lidar ratios identical to the initial ones, which in the CALIPSO Version 3 data products are set to 25 sr for cirrus clouds. It is to be noted that some cirrus are classified as opaque, meaning that the layer has totally attenuated the signal, preventing the algorithm from detecting the true layer base. The retrieved cloud optical depth corresponds to the upper part of the layer. Only non-opaque cloud layers will be considered in the following. However, lidar ratio estimates can be retrieved from measurements of opaque clouds, since $e^{-2\eta\tau_c}$ approaches zero as τ_c gets large.

3. IIR CIRRUS OPTICAL DEPTH

3.1 Calibration

The IIR instrument consists of three window channel spectral bands centered at 8.65, 10.6 and 12.05 µm that have medium spectral resolution, respectively 0.9 µm, 0.6 µm and 1µm. The IIR operates at uncooled temperature with on-board calibration. It has been designed to meet the high sensitivity performance required to derive the calibrated radiances in all channels with a radiometric noise better than 0.3 K (1 sigma) for brightness temperatures greater than 210 K as observed for most cirrus clouds. Comparisons with MODIS/Aqua collocated similar observations [9] have been done continuously since launch, showing an excellent stability with a differential trend between instruments smaller than 0.1 K.

3.2 Effective emissivity

The Level 1 calibrated and geo-located IIR radiances are registered on a reference grid centered on the CALIOP ground track, with 1 km horizontal resolution over a 69-km swath. The IIR Level 2 code [10] and track products are organized around the vertical information reported at 5-km resolution in the CALIOP 5-km Layer products. A scene classification algorithm selects suitable scenes for effective emissivity retrievals. The IIR analysis is conducted on the uppermost single or multi-layer cloud identified by the CALIOP operational algorithm. Its effective emissivity, ε_{eff}, is retrieved from the observations for each IIR channel as:

$$\varepsilon_{eff} = \frac{R_m - R_{ref}}{R_{Tcloud} - R_{ref}} \quad (4)$$

In Eq 4, R_m is the calibrated radiance. R_{Tcloud} is the opaque cloud radiance at the top of the atmosphere (TOA), i.e. the radiance of a blackbody source located at the lidar altitude of thermodynamic temperature T_{cloud} retrieved from ancillary meteorological data (Global Modeling Assimilation Office GEOS5 model). R_{ref} is the TOA reference radiance which would be observed in the absence of the studied cloud. Three types of reference scenes are selected, which are identified unambiguously from the lidar product: clear air and low (<7 km) or high altitude (>7km) opaque clouds, based on the CALIOP opacity flag. R_{ref} is determined either from observations in neighboring pixels or from computations. Real-time radiance computations use the FASRAD radiative transfer model [11] adapted to the IIR spectral functions, GEOS5 atmospheric profiles including surface temperatures, and surface emissivities computed for the IIR channels based on the IGBP (International Geosphere Biosphere Program) surface types, with snow/ice coverage daily updates from the National Snow and Ice Data Center.

3.3 Cirrus optical depth

The cloud effective emissivity retrieved in each IIR channel includes the contribution from both absorption and scattering. The associated cloud effective optical depth, OD_{eff}, is derived as:

$$OD_{eff} = -\ln(1-\varepsilon_{eff}) \quad (5)$$

The IIR effective optical depth retrieved at 12.05 µm represents essentially an absorption optical depth. It has been shown to be a good proxy for about half of the cloud optical depth, depending on the atmospheric conditions and ice crystal sizes, allowing direct comparisons with CALIOP visible optical depth [10].

4. CALIOP AND IIR COMPARISONS

4.1 Data screening

The data set is screened to identify those atmospheric columns containing only a single layer non-opaque cirrus cloud. Single layer clouds are preferred for a more reliable determination of the opaque cloud radiance (R_{Tcloud} in Eq. 4) in the IIR analysis. Also, retrievals over ocean and over land are considered separately, as the IIR sources of uncertainty are smaller over water, where the surface parameters are known with better confidence than over land. We select tropospheric clouds of centroid altitude higher than 7 km and classified as randomly-oriented ice clouds in the CALIOP product. Each ensemble of selected clouds (over water or land) is further sorted according to the CALIOP extinction retrieval technique (constrained or unconstrained). In addition, day and night are analyzed separately, to evaluate the influence of the smaller CALIOP signal to noise ratio during the day. The IIR retrievals are expected to be of similar quality for these 4 last categories.

CALIOP cirrus optical depths are reported in the Level 2 5-km Cloud Layer product. By design, each CALIOP 5-km segment is perfectly collocated with 5 successive 1-km IIR track pixels. IIR retrievals are averaged over each 5-km segment for comparison with CALIOP.

4.2 Results

Figure 1 shows 2D histograms of CALIOP optical depth, τ_c, versus IIR effective optical depth, OD_{eff}, in January 2011 over ocean at night (top row) and during daytime (bottom row), and for scenes containing a single layer semi-transparent cirrus cloud only over ocean. The left-hand column corresponds to the "unconstrained" retrievals obtained by using an initial lidar ratio unchanged during the solution process. The right-hand column shows results obtained when the constrained technique has been used. The color code gives the decimal logarithm of the number of points in each bin. An excellent agreement is found between IIR and CALIOP constrained retrievals, for both nighttime and daytime, even though there are fewer daytime points. However, the IIR-to-CALIOP ratio tends to be larger than expected for unconstrained retrievals, more obviously during daytime, likely due to the larger range in optical depth. These results suggest an inconsistency between Version 3 CALIOP unconstrained and constrained retrievals, likely due to the initial lidar ratio used in the former. In addition, statistical analyses of the lidar ratios derived from opaque layers and constrained retrievals since the CALIOP launch (see Table 1) show a mean retrieved lidar ratio in the

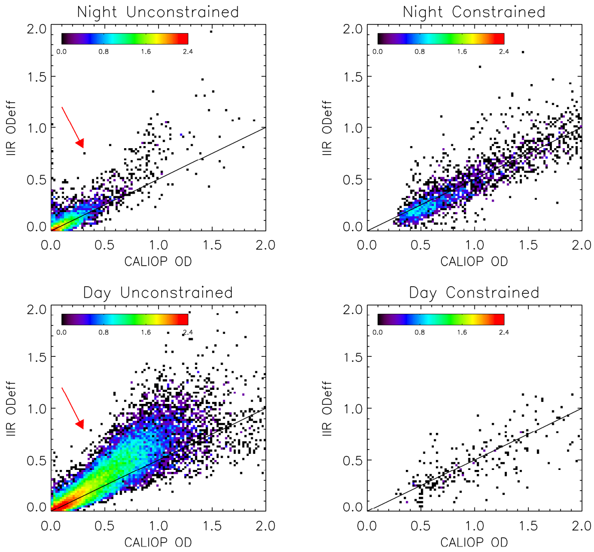

Figure 1. 2D histograms of CALIOP optical depths and IIR OD_{eff} of single layer semi-transparent cirrus over water in January 2011 at all latitudes from the version 3 products. The black solid lines represent the expected relationship.

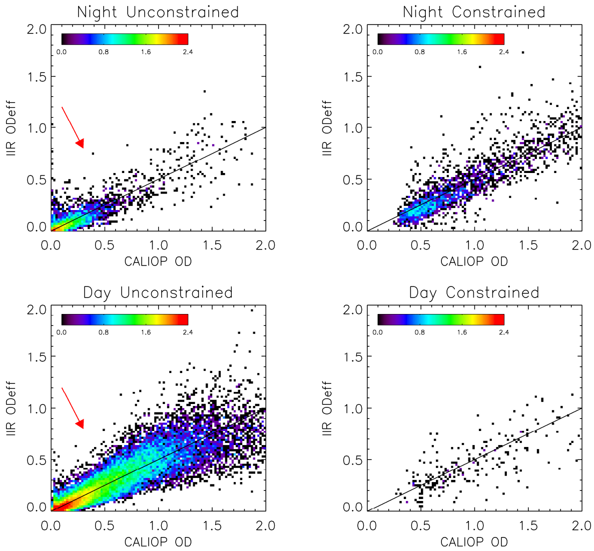

Figure 2. Same as Fig.1, but for a revised initial lidar ratio (unconstrained retrievals).

neighborhood of 20% larger than the initial lidar ratio used in the Version 3 algorithm. These results have been confirmed by authors in [12] using the SODA algorithm and IIR data to retrieve mean cirrus cloud lidar ratios of 33 ± 5 sr. Figure 2 shows comparisons between IIR and CALIOP optical depths obtained in the same conditions as in Figure 1 but with CALIOP unconstrained retrievals performed with an initial lidar ratio of 29.9 sr. We see that unconstrained retrievals produce higher optical depths than for Version 3 products (Fig. 1), whereas "constrained" retrievals are unchanged, as expected. CALIOP and IIR compare similarly for CALIOP "unconstrained" and "constrained" retrievals, with a CALIOP to IIR ratio close to the expected value of about 2. An excellent agreement between the 3 independent retrieval techniques used in the CALIPSO mission is found.

Table 1: 532 nm cirrus clouds lidar ratio estimates retrieved from CALIOP measurements between 2006-06-13 and 2011-12-31 inclusive

	Night Constrained	Day Constrained	Night Opaque	Day Opaque
min	5.3	6.1	5.0	5.0
max	250.0	249.9	249.9	250.0
median	30.8	29.6	28.6	29.7
mean	32.2	31.1	29.0	30.8
st dev	10.1	10.6	8.8	11.8
count	3,598,155	261,069	4,983,983	5,666,891

5. CONCLUSIONS

Optical depths of single-layer semi-transparent cirrus cloud over ocean, well retrieved by both the CALIOP lidar at 532 nm and the IIR infrared radiometer, have been compared. An excellent agreement between both CALIOP retrieval techniques is found when a lidar ratio derived from the statistical analysis of several years of CALIOP data is chosen to initialize CALIOP unconstrained retrievals. This value is about 20% larger than the initial lidar ratio used in the Version 3 algorithm. Furthermore, CALIOP visible optical depths compare as expected with IIR effective optical depths at 12.05 μm. Overall, these findings constitute a significant step toward the validation of the cirrus optical depths retrieved by the CALIPSO mission.

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