A COMPARISON OF SPACE-BORNE AND AIRBORNE LIDAR OBSERVATIONS OF COMPLEX, HIGH CLOUD FIELDS DURING CLASIC

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ABSTRACT

Estimates of high-cloud optical depths retrieved from analyses of lidar data acquired during the Cloud and Land Surface Interaction Campaign (CLASIC) by the space-borne Cloud-Aerosol Lidar Infrared Pathfinder Satellite Observations (CALIPSO) lidar and by the Cloud Physics Lidar (CPL) flown on the high-altitude ER-2 aircraft are compared. Differences in the optical depths and in the integrated attenuated backscatter derived by the two instruments are interpreted by considering the large difference in signal-to-noise ratios and possible errors in CALIPSO's calibration during these daytime observations, along with differences in the contributions of multiple scattering to the two instruments and the inferred presence of oriented crystals in the relatively complex cloud fields.

1. INTRODUCTION

Global-scale measurements of the temporal and geospatial variability of the distribution of clouds made by CALIPSO [1] are making major contributions to our understanding of global climate by providing a valuable data set against which to test, improve and validate Global Climate Models (e.g. [2]). However, information of potentially even greater value is being retrieved on the optical properties and ice-water phase of these clouds, but before these data products can be used with confidence they must be validated.

The method of choice for validation of CALIPSO's analyses of high clouds is comparison with analyses of lidar observations made from high-altitude aircraft underflying CALIPSO's orbit. CPL [3] is a three-wave-length elastic backscatter lidar that is typically mounted on NASA's high-altitude ER-2 aircraft, and is thus especially well suited for acquiring the measurements required to validate space-borne lidars (e.g., [4], [5]). Here we compare observations from CALIPSO and the CPL made during CLASIC [6], which was conducted by the US Department of Energy's Atmospheric Radiation Measurement (ARM) program with the primary purpose of studying the influence of land surface processes on cumulus convection. Because the ER-2 was flying the CPL and Cloud Radar System, underflights of the CALIPSO and CloudSat satellites also occurred as part of CLASIC and allowed for potential validation of those satellite instruments.

As CLASIC was focused primarily on daytime processes, this study allows us to examine the potential effects on CALIPSO's performance of the lower signal to noise ratio (SNR) and more difficult signal calibration associated with daytime measurements. In addition, unlike the clouds studied during other validation experiments, which tended to be fairly extensive, optically dense, and occasionally opaque cloud banks, the clouds studied during CLASIC were often more tenuous, less homogeneous and appear to have contained a variety of particle shapes and orientations. Here we examine the influence of these factors, and of the different sensitivities of CALIPSO and the CPL to multiple scattering, on both the signals measured by the two instruments and the optical quantities retrieved by them.

2. INSTRUMENTS

2.1 CALIPSO

CALIPSO flies as part of the Aqua constellation of satellites (A-Train) in a circular, sun-synchronous, polar orbit at an altitude of 705 km with a daytime equatorial crossing time around 13:30 hours local time. It carries three co-aligned, nadir-viewing instruments: CALIOP (Cloud-Aerosol Lidar with Orthogonal Polarization), a two-wavelength (1064 nm and 532 nm), dual-polarization (at 532 nm), elastic-backscatter lidar, an Imaging Infrared Radiometer, and a Wide Field Camera. When combined with an along-track speed of ~7.5 km. sec^{-1}, the laser's firing rate of ~20 sec^{-1} produces one profile every 333 m at each wavelength. In order to improve the SNR and the consequent accuracy of the data products, 15 consecutive, along-track profiles are averaged before particulate extinction and optical depths are retrieved at the finest horizontal resolution of 5 km.

2.2 The Cloud Physics Lidar

The CPL [3] is a state-of-the-art, elastic-backscatter lidar system operating at 1064, 532, and 355 nm, thus providing detailed, multispectral information about cloud and aerosol optical properties. Linear depolarization measured at 1064 nm can be used to determine the thermodynamic phase of clouds. The CPL provides cloud and aerosol backscatter and optical properties products at 1 second (~200 m along-track) horizontal resolution and 30.0 m vertical resolution. The CPL has a field of view (FOV) of 100 microradians (full angle), similar to CALIOP's. However, its much closer proximity to the clouds it studies, ~5 km compared with CALIPSO's ~700 km, produces a footprint on a cloud target that is about two orders of magnitude smaller than CALIPSO's. Therefore, the contribution of multiple scattering to the CPL signals is small relative to the signal noise, and this contribution is very small when compared with that for CALIPSO.

3. MEASUREMENTS

The remote sensing portion of the CLASIC mission was based out of Ellington Field, Johnson Space Center in Houston, Texas from June 8-30, 2007. Although 11 flights were conducted in total, with a vast majority heading to the Oklahoma region, CALIPSO underflights were only conducted on the days of June 12, 21 and 28. The validation procedure directed the NASA ER-2 aircraft to fly CALIPSO's predicted ground track for 30 to 40 minutes centered on the predicted overpass time. The cross-track mismatch between the satellite and the aircraft ground tracks during the three CALIPSO coincident flights was excellent, averaging 54 meters and ranging from 10 to 94 meters. However, because of the large difference in relative speed, the 4-degrees-latitude coincident segment was covered by CALIPSO in ~70 seconds (at ~7.5 km/s) compared with 40 minutes by the ER-2 (at ~200 m/s). This time difference led to a cloud drift in the coincident segment that increased with time/distance from the exact coincident point. For this study, we compromised between having enough data points and minimizing the cloud drift by restricting analysis to within 10 minutes of the exact coincidence. For 21 June, then, the wind vector relative to CALIPSO's ground track would have caused cloud to drift distances of up to 2.4 km along track and 5.6 km across track for locations at the extreme ends of the ~240-km analyzed data segment.

4. ANALYSIS METHODS

The analysis of CALIPSO lidar data is a multi-stage process that is performed on horizontal scales increasing from 0.3 km to 80 km in order to improve the SNR and enable the detection of more tenuous backscatter targets. Full details of all algorithms have been published recently in a Special Collection of *J. Atmos. Oceanic Technol.*. Those most relevant to the current work concern calibration [7], feature detection [8], cloud-phase discrimination [9], and extinction retrieval [10]. Of particular relevance is the discussion of the increased difficulty and possible reduction in accuracy involved in daytime signal calibration in [11]. Here we focus on the Level 2 Integrated Attenuated Backscatter (IAB) and the Cloud Optical Depth (COD) data products, which are reported at 5-km horizontal resolution.

As CPL is also a multi-channel backscatter lidar, its data analysis algorithms (e.g., [12][13]) are not very different from those employed by CALIPSO. Furthermore, CPL provides data products that are similar to CALIPSO's, but at a higher spatial resolution, and with better SNR and significantly less influence from multiple scattering. These facts make the CPL data an ideal benchmark to use in assessing the quality and correctness of the CALIPSO data.

CPL cloud backscatter and extinction profiles and cloud layer OD data are produced at a standard horizontal resolution of 200 m. In order to compare data from CALIPSO and the CPL, for each CALIPSO profile, a CPL profile was identified that had the smallest physical separation from the CALIPSO profile within the ± 10 minute window. Then all CPL data within 2.5 km either side of the closest profile were averaged for comparison with the CALIPSO 5-km data.

Also, CALIPSO's lower SNR requires more spatial averaging before layer detection is attempted with the result that clouds that were detected as a single layer by CALIPSO were often detected as multiple layers by the CPL. Therefore, all the COD and IAB data for all individual layers within a specified altitude band were summed to permit a more valid comparison.

5. RESULTS

Data acquired by CALIPSO and the CPL on 21 June 2007 are plotted in Figure 1. The latitude at temporal coincidence was 32.769° with time differences between the instruments at the ends of the plots being ± 10 mins. The attenuated backscatter curtain files, plotted in (a) and (b) at the native resolution of each instrument, show some interesting differences. The lower SNR of the CALIPSO data is obvious and has the effect of almost hiding the thin upper layer (A), easily seen in the CPL data, to the degree that it is not reported in the CALIPSO data products.

There are also differences in the measured cloud structure, e.g. region (B), that may be caused by cloud drift during the interval between the measurements by the two instruments. However, a much more significant difference is the greater apparent detected “area” (i.e. height by along-track distance) in the CALIPSO data, especially in the stronger lower cloud to the north of latitude ~32.2°. Not only is the signal visible deeper into the cloud, especially in regions (C), but the CALIPSO backscatter is stronger. We attribute the deeper penetration by CALIPSO’s signal to the higher level of multiple scattering, which reduces the effective cloud attenuation.

The stronger CALIPSO signal and the step increase in the 7 km – 14 km integral is also seen in the IAB plots in (c). Before the increase, the ratio of CALIPSO’s to CPL’s 532-nm IABs is 1.6 with a standard error of 0.5 (11 points). To the north of 32.2°, in the denser cloud, the ratio more than doubles to 3.8±0.3 (37 points). Although it is possible that CALIPSO’s daytime calibration is less than perfect [11], calibration changes occur much more gradually than seen here (and the calibration factors for both instruments were essentially constant during this period), so we suggest that the changes in the signals are due to changes in the cloud microphysics. Indeed, CALIPSO’s Cloud Phase Algorithms show a much higher preponderance of horizontally-oriented ice (HOI) crystals in the denser cloud, which, when combined with CALIPSO’s June 2007 nadir viewing angle of 0.3°, could have permitted CALIPSO to detect enhanced backscatter from specular reflections from the HOI crystals. (Note that, with a nadir angle closer to 2°, the CPL signals are less likely to show HOI effects.) By contrast, the 532-nm IAB ratio for a layer between 9 km and 15 km on June 28, not containing HOI, was 0.98±0.10 (43 points).

Finally, the 532-nm cloud optical depths over the 7 km - 14 km layer are compared in (d). The mean OD is 3.2±0.1 (48 points) for CALIPSO and 2.3±0.1 for the CPL. By contrast, the corresponding ODs for the 9 km - 15 km layer on June 28 were almost identical at 0.35±0.03 (43 points) and 0.36±0.02.

We conclude that attempts at validating retrievals made using satellite-borne lidars, like CALIPSO, with airborne lidars, like the CPL, need to consider effects resulting from a combination of differences in instrument measurement geometry (including viewing angles), cloud microphysics and the different contributions of multiple scattering to the signals. However, such comparisons can also provide information on the cloud microphysics.

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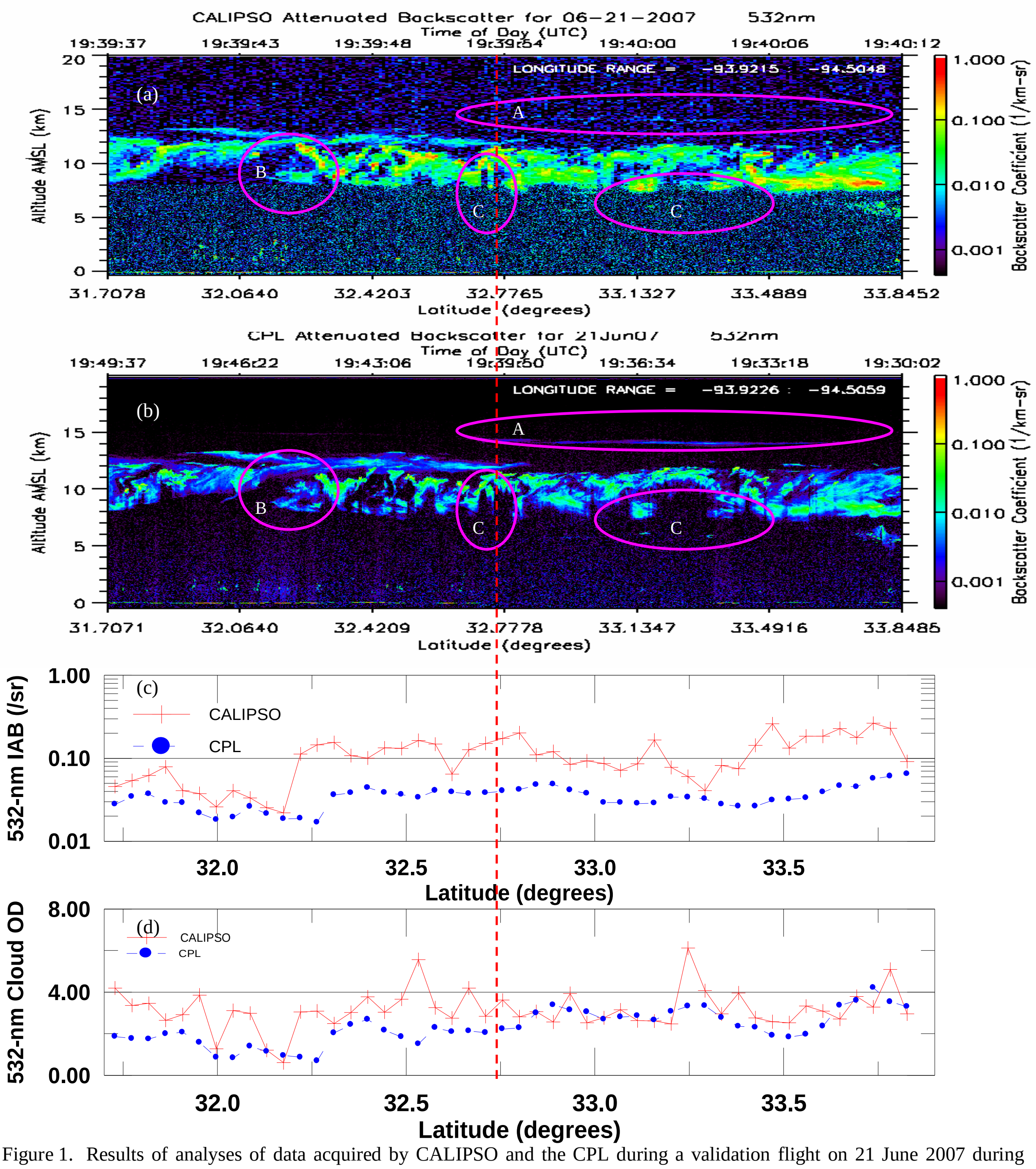

Figure 1. Results of analyses of data acquired by CALIPSO and the CPL during a validation flight on 21 June 2007 during CLASIC. The ground tracks coincided exactly at latitude 32.77° (red dashed line). (a) CALIPSO 532-nm Attenuated Backscatter (units: $(km.sr)^{-1}$), (b) CPL 532-nm Attenuated Backscatter (units: $(km.sr)^{-1}$), (c) 532-nm Integrated Attenuated Backscatter over column (7 km - 14 km) measured by CALIPSO and the CPL (units: sr^{-1}), (d) 532-nm Cloud Optical Depth measured by CALIPSO and the CPL between 7 km and 14 km. (CALIPSO data are version 3 beta.)