CALIPSO AT FOUR: RESULTS AND PROGRESS

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ABSTRACT

Aerosols and clouds play important roles in Earth's climate system, but limitations in our ability to observe them globally limit our understanding of the climate system and our ability to model it. The CALIPSO satellite was developed to provide new capabilities to observe aerosol and cloud from space. CALIPSO carries the first polarization-sensitive lidar to fly in space, which has now provided a four-year record of global aerosol and cloud profiles. This paper briefly summarizes the status of the CALIPSO mission, describes some of the results from CALIPSO, and presents highlights of recent improvements in data products.

1. INTRODUCTION

Aerosols and clouds have important impacts on the Earth's climate through their roles in the global radiation budget and the hydrologic cycle. But limitations in our ability to observe aerosols and clouds globally are responsible in part for the current uncertainties in modeling the global climate system and predicting climate change. The CALIPSO satellite was developed jointly by NASA and the French space agency CNES to provide new capabilities to observe aerosol and cloud from space [1]. CALIPSO carries CALIOP, the first polarization-sensitive lidar to fly in space, along with passive infrared and visible sensors. CALIPSO data are freely available through the NASA Langley Atmospheric Sciences Data Center (http://eosweb.larc.nasa.gov).

2. MISSION STATUS

Launched in April 2006, CALIPSO flies as part of the A-train satellite constellation and has now produced a four-year record of global aerosol and cloud profiles. CALIOP has two Nd:YAG lasers - a primary and a backup - which emit linearly polarized pulses at 1064 nm and 532 nm. Details of the instrument can be found in [2] and [3]. Each laser is contained in its own pressurized canister, filled with roughly one atmosphere of dry air. The primary laser operated from June 2006 through February 2009, accumulating 1.6 billion shots on-orbit. The primary laser canister had a slow leak, which caused the pressure to decrease to the point where laser operation became erratic and the laser was shut down in mid-February 2009. Until this point laser energy was quite stable, as can be seen in Figure 1, and no adjustments to the laser pulse energy were required. Science operations resumed in mid-March 2009 using the backup laser. The backup laser has performed well since then with pulse energy decreasing just 7% over the first year of operation. This performance is similar to that of the primary laser (Figure 2) and no adjustments to the backup laser have been required to date. Pressure in the backup laser canister has been holding better than expected. With no known hardware issues, CALIPSO was recently approved to continue operations through 2011 and has sufficient propellant to remain in the A-train formation until at least 2015.

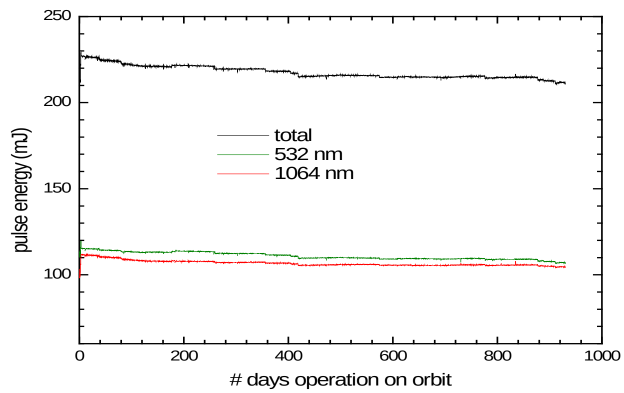

Fig. 1. Energy trend over the life of the primary laser.

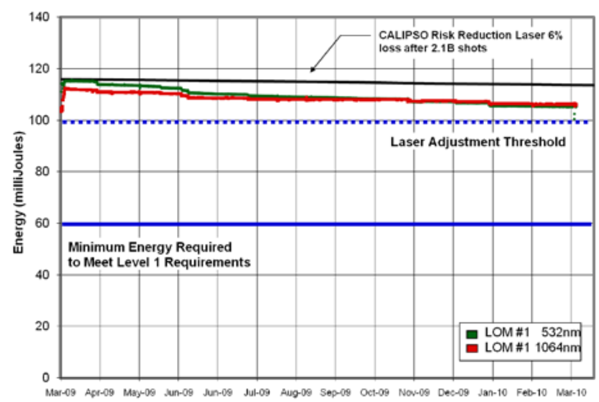

Fig. 2. Energy trend of CALIOP backup laser compared with first year of operation of the primary laser.

3. GLOBAL CLOUD AND AEROSOL OBSERVATIONS

The heating effect of absorbing aerosol is increased when the aerosol is located over a bright surface. Consequently, the relative locations of overlapping cloud and absorbing aerosol layers strongly affect the amount of sunlight absorbed. Figure 3 shows seasonal mean aerosol optical depth retrieved from CALIOP for aerosol located above cloud. The optical depth of aerosol located above cloud can be significant in regions characterized by strong sources of mineral dust, smoke from biomass burning, or pollution. These above-cloud aerosols were previously unobserved and their effects have been either estimated or neglected in observation-based assessments of aerosol radiative forcing. Chand et al. [4] have used CALIOP observations to estimate the radiative impacts of smoke located above low cloud in the southeast Atlantic off the coast of Africa. They find that the warming effect of the smoke is strongly sensitive to the albedo and to the coverage of the underlying cloud, highlighting the need for measuring cloud and aerosol in the same column.

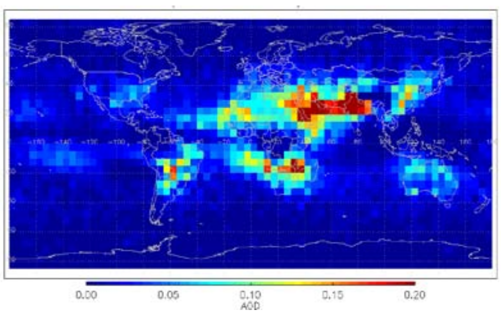

Fig. 3. Mean optical depth of aerosol located above clouds, Sept-Nov 2007.

Observation of aerosol near cloud edges has also proven to be problematic. Retrievals from passive sensors have shown correlations between AOD and cloud fraction, but it has been suspected the correlations are at least partly due to cloud contributions to the clear-sky radiation field. CALIOP observations are now beginning to provide insight into some of these issues, as sunlight scattered by clouds does not contribute to lidar aerosol retrievals. The results shown in Figure 4 were constructed by compositing CALIOP Level 1 backscatter profiles as a function of distance from marine boundary layer clouds [5]. A significant increase in aerosol backscattering can be seen within

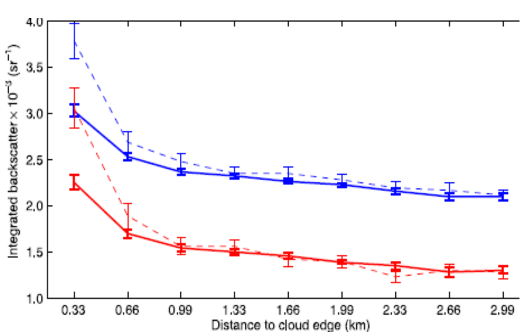

Fig. 4. CALIOP integrated attenuated backscatter as a function of distance from cloud edges [5].

about 1 km of cloud edge, indicating that at least some of the AOD enhancement observed near cloud edges is real.

The various cloud climatologies derived from passive satellite sensors differ substantially in the vertical distribution of clouds. While differences in cloud properties between the available satellite cloud climatologies are generally smaller than the spread for model-predicted clouds, the differences in the observations need to be resolved if the observations are to provide useful constraints on model performance. Complementary cloud observations from CALIPSO and CloudSat have been used to produce a merged CALIPSO-CloudSat cloud dataset providing the first real 3-D climatology of global cloud occurrence [6]. Further, a CALIOP instrument simulator has been developed to aid in comparing CALIOP observations with predictions from global models (Figure 5) [7]. The World Climate Research Program (WCRP) has recommended that the simulator be used by all global modeling groups participating in the IPCC 5th assessment, facilitating comparisons with CALIOP cloud observations as well as model intercomparisons.

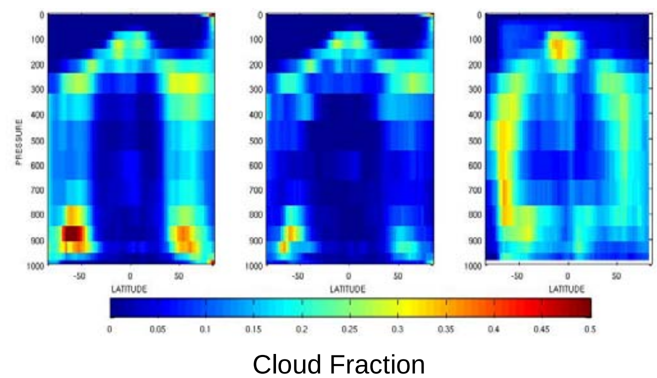

Fig. 5. Zonal mean cloud occurrence for Jan-Mar 2007. Left: LMDz GCM; Center: LMDz output using the CALIPSO simulator; Right: CALIOP observations [7].

While polar stratospheric clouds (PSCs) were not one of the primary measurement objectives of CALIPSO, daily coverage of Antarctica to 82S throughout Antarctic winter and spring is providing a wealth of new insights into the distribution, composition, and formation mechanisms of PSCs. The CALIOP data have much higher vertical and spatial resolution than those used to derive previous PSC climatologies. The continuous along-track coverage throughout polar night greatly reduces the sampling biases of earlier occultation and limb-viewing data sets. As illustrated in Figure 6, CALIOP measurements have generated the first unbiased estimates of the time evolution of the geographical extent of Antarctic PSCs as a function of altitude [8].

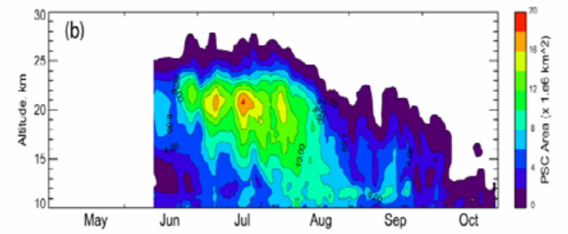

Fig. 6. Daily PSC areal coverage as a function of altitude for the 2006 Antarctic season [8].

4. DATA PRODUCT IMPROVEMENTS

CALIOP Version 3 data products, released in spring 2010, contain numerous improvements to the Level 2 data products. Uncertainty estimates are now provided for most retrieved parameters, the Cloud-Aerosol Discrimination algorithm has been improved (making use of depolarization signals for the first time [9]), and a completely new algorithm for discrimination of cloud ice-water phase has been developed [10]. The new algorithm discriminates clouds composed of randomly oriented crystals from those containing horizontally oriented ice crystals (Figure 7), which were often identified as water clouds by the Version 2 algorithm.

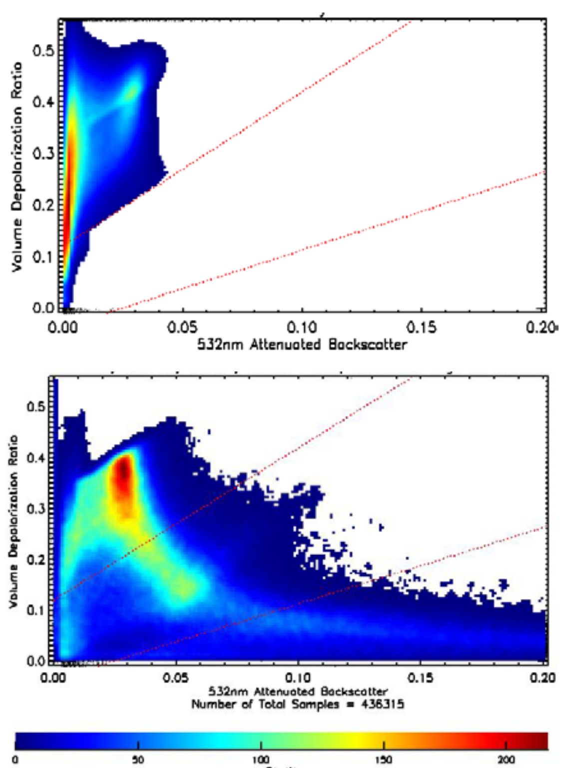

Fig. 7. Distribution of cloud types in depolarization-backscatter space, Jan 2007. Upper: randomly-oriented ice clouds. Lower: horizontally oriented ice clouds.

The profile products have been restructured, with a number of additional retrieved parameters and flags to help describe and interpret the data. The aerosol profile product is now reported on a 5-km horizontal grid and includes profiles of retrieved backscatter and extinction, at both wavelengths, and profiles of 532 nm particulate depolarization. Results from Version 3 test datasets are shown in Figure 8. High depolarization values are seen over the Sahara, where desert dust is dominant, and low elsewhere. Large color ratios ($\beta_{a,1064}/\beta_{a,532}$), indicative of large particles, are seen over the Sahara. But large color ratios are also seen between 10S and 20S, particularly at low altitudes. Smoke is the dominant aerosol in this region. Because the 532 nm signal is attenuated more rapidly than the 1064 nm signal, color ratios tend to increase toward the surface when the smoke is dense enough to cause significant 532 nm attenuation.

Recent work combining CloudSat and CALIOP measurements points toward the utility of lidar ocean surface returns to improve retrievals of column aerosol

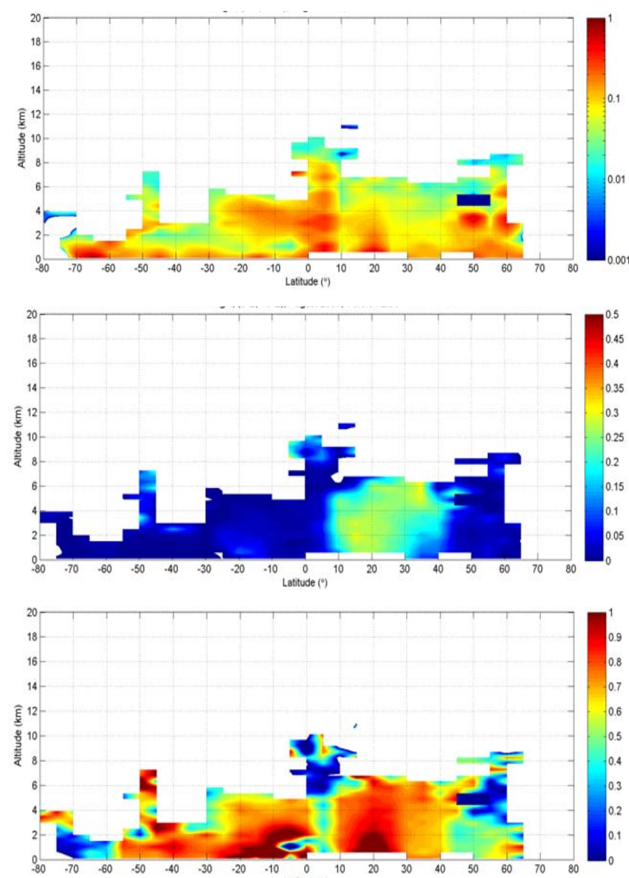

Fig. 8. Aerosol profile statistics for Aug 2007 between 5E and 10E longitude on a 5-degree latitude grid. Top: average aerosol extinction; middle: median aerosol depolarization; bottom: median aerosol color ratio.

optical depth and extinction profiles [11]. CloudSat is used to measure ocean surface reflectance and CALIOP surface returns are then used to estimate column 2-way transmittance. This provides a constraint on extinction retrievals and is being pursued as a means of improving the accuracy of aerosol retrievals over the global oceans.

5. CONCLUSIONS

The CALIPSO mission represents a successful cooperative effort between NASA and CNES and has provided the first continuous, multi-year global dataset of lidar aerosol and cloud profiles. But utilization by the scientific community is just beginning and many more advances are expected.

CALIOP active profiling in conjunction with A-Train and CALIPSO passive observations are opening new fields of investigation into the role of aerosol and clouds in the climate system. Quantitative assessments of passive sensor performance using CALIOP observations have led to improvements in operational retrievals and a variety of synergistic retrievals of aerosol and cloud properties have been explored. The international community is still learning how to use this new dataset, but CALIPSO observations have already provided new insights into characteristics of aerosol and cloud which are critical to understanding their role in the climate system.

More advances in remote sensing of cloud and aerosol are expected in the near future. The Aerosol Polarimetry Sensor, on the Glory satellite, is scheduled to join the A-Train in 2010. Measurements of polarized spectral radiances from APS with coincident CALIOP profiles will provide opportunities to explore new retrieval approaches. Two satellite missions carrying advanced lidars are under development by the European Space Agency: the Atmospheric Dynamics Mission, with the ALADIN Doppler wind lidar, and EarthCare, with the ATLID HSRL. These missions are expected to continue the record of aerosol and cloud profiles begun by CALIPSO, leading to the long-term record of global cloud and aerosol measurements needed to monitor climate trends.

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