STRATEGIES FOR IMPROVED CALIPSO AEROSOL OPTICAL DEPTH ESTIMATES

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ABSTRACT

In the spring of 2010, the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) project will be releasing version 3 of its level 2 data products. In this paper we describe several changes to the algorithms and code that yield substantial improvements in CALIPSO's retrieval of aerosol optical depths (AOD). Among these are a retooled cloud-clearing procedure and a new approach to determining the base altitudes of aerosol layers in the planetary boundary layer (PBL). The results derived from these modifications are illustrated using case studies prepared using a late beta version of the level 2 version 3 processing code.

1. INTRODUCTION

One of the primary objectives of the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) mission is to help reduce uncertainties in climate model predictions by acquiring global measurements of the vertical distribution of aerosols [1]. To accomplish this goal, CALIPSO employs a fully automated data analysis system to detect cloud and aerosol layers in the backscattered signal [2]; determine which of these layers are clouds and which are aerosols [3]; estimate aerosol lidar ratio, S_a, via an empirical determination of aerosol type [4]; and finally, based on the combined results of these preliminary analyses, retrieve profiles of aerosol extinction coefficients, which are then integrated to derive estimates of aerosol optical depths (AOD) at 532 nm and 1064 nm [5]. At present, the consensus of various validation studies is that the CALIPSO data analyses are performing well and that the results produced are reliable [e.g., 6–9]. Still, there are times when this is not so, and the CALIPSO retrieval scheme can be savagely battered by an indifferent Mother Nature, who pays no attention whatsoever to the carefully constructed models of the atmosphere upon which the CALIPSO data analyses depend, and instead intermingles clouds and aerosols arbitrarily, according to her own whims. In this paper we describe some (but certainly not all) of the latest innovations incorporated into the CALIPSO software to help us more successfully grapple with these hard cases. With respect to improving AOD accuracies, these enhancements fall into three main categories: (i) more accurate clearing of small-scale clouds embedded in aerosols in the planetary boundary layer (PBL); (ii) significant refinements of the probability distribution functions (PDFs) used to distinguish between aerosols and clouds; and (iii) implementation of a new procedure for layer base determination for PBL aerosols. An in-depth assessment of items (i) and (iii) will be given in the sections that follow. The PDF improvements mentioned in item (ii) are described in detail in a companion paper published in these same proceedings [10], and hence will be addressed only briefly here.

2. CLOUD-CLEARING CORRECTIONS

Since its inception, the CALIPSO layer detection algorithm has included a procedure devoted specifically to detecting small scale clouds in the PBL. The primary motive for including this special, high-resolution cloud search is to remove the high-intensity backscatter data identified as cloud, and thus permit extended spatial averaging of the surrounding data, which in the PBL is presumed to contain aerosols. Based on prelaunch software testing using synthetic data sets, the initial implementation of this cloud-clearing procedure was expected to work as designed. However, shortly after version 2 of the CALIPSO data products was released, data users began commenting on the unexpectedly frequent occurrence of weakly scattering cumulus clouds being reported in the 5-km layer products. An investigation by the algorithm and software development teams found that while the high-resolution cloud detection was being performed correctly, and that the layer boundaries being reported in the CALIPSO 1/3-km and 1-km cloud layer products were accurate. However, the procedure subsequently used for cloud-clearing and reaveraging the surrounding data was incomplete. The layer detection algorithm operates on attenuated scattering ratios, and for this realization of the data the cloud clearing was being done properly, as evidenced by the correctness of the results at 1/3-km and 1-km. The cloud-aerosol discrimination (CAD) algorithm, on the other hand, uses the attenuated backscatter coefficients, and, because these data were not being used in the layer detection routine, they were not being cloud cleared. Both the cause and the cure for this malady are illustrated in Figure 1. The upper panel of this figure shows the 532 nm attenuated backscatter coefficients acquired on August 4 2007 during a daytime overpass along the eastern seaboard of North America. Occasional small scale clouds (e.g., cumulus humilis and/or cumulus mediocris) are seen to be embedded in an extensive layer of urban pollution that rises to a maximum altitude of approximately 4.5-km.

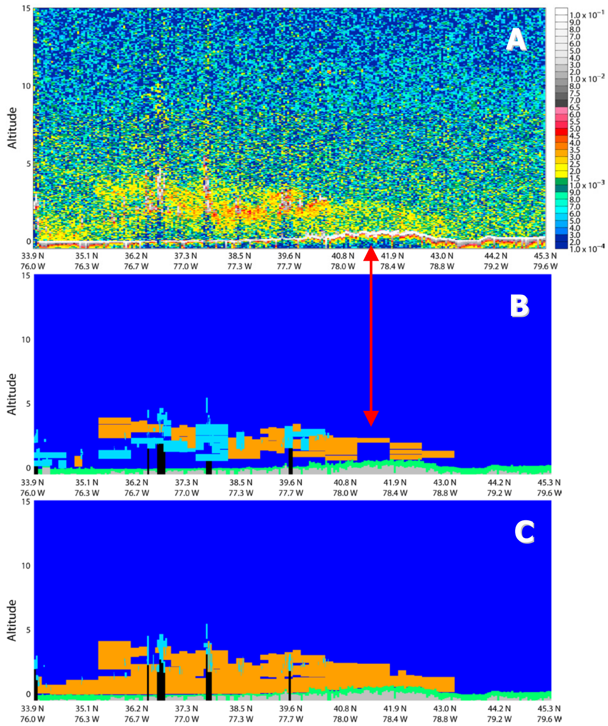

Figure 1: (a) CALIPSO 532 nm attenuated backscatter coefficients acquired during a daytime overpass along the eastern seaboard of the United States, with all data averaged to 60-m vertically and 5-km horizontally; (b) vertical feature mask, showing the locations of all clouds (pale blue), aerosols (orange), and surface data (green) reported in the version 2.01 CALIPSO level 2 data products; regions where no features were detected are rendered in dark blue (clear sky), pale gray (subsurface), and black (signal totally attenuated); (c) vertical feature mask for the version 3 CALIOP data products.

Figure 1(b) shows the layer detection and CAD results reported in the version 2.01 data products for this scene. Given the low SNR of the CALIPSO daytime data, layer top detection seems to be adequate (though certainly not perfect). Layer base determination and layer classification are, on the other hand, clearly suboptimal. The reason for the poor CAD performance can be traced directly to the software defect described earlier. As seen in Figure 1(c), which displays the results from the version 3 processing, aerosol layers misclassified as cloud in the version 2.01 analysis were all cloud-contaminated to some degree. However, as demonstrated by the layer at ~2.5-km and ~36.0° N, the mere presence of small scale clouds is not sufficient to skew the classification scheme. What is required is that, in the mean, the total backscatter contribution from embedded clouds overwhelms the backscatter contribution of the surrounding aerosols. In these cases, the bulk optical properties of the feature detected at the coarser resolution more closely resemble clouds than aerosols, and hence the CAD algorithm recognizes them as clouds.

3. PBL AEROSOL BASE ALTITUDES

As pointed out above, the layer base determination in Figure 1(b) is also clearly suboptimal. When examining an aerosol layer that, by inspection of Figure 1(a), is clearly in contact with the Earth's surface, the CALIPSO layer detection algorithm instead reports the lowest base altitudes as being up to 2-km above the surface. To some extent, this sort of behavior was anticipated prior to launch. Based on the authors' prior experience with data from the Lidar In-Space Technology Experiment, erroneous estimates of base altitude were known to occur most often in highly absorbing, optically thick aerosol layers measured during daylight over bright surfaces; i.e., exactly the circumstances encountered in this example. As illustrated in Figure 2, the rapid attenuation of the signal within the layer, combined with relatively weak backscattering (high lidar ratio) and very high noise levels can cause the signal to fall below the detection limit before the full extent of the layer is measured.

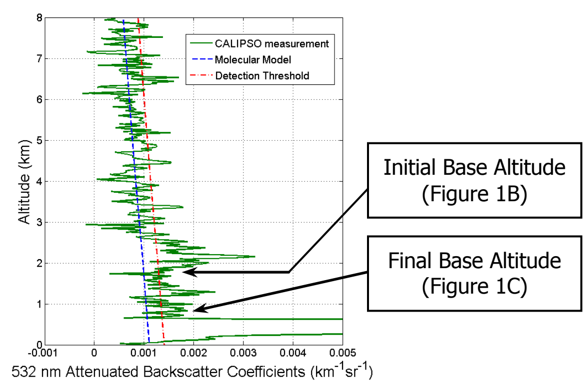

Figure 2: profile data averaged to a horizontal resolution of 20-km, taken from Figure 1(a) at ~41.3° N (red arrow); as seen in Figure 1(b), an aerosol layer is detected between ~2.5-km and ~1.9-km, where the backscatter coefficients rise continuously above the detection threshold.

To minimize the occurrence of premature base determination, a very simple new procedure has been incorporated into version 3 of the CALIPSO level 2 analyses. As was done in all previous versions, following execution of the layer detection algorithm, all features within a scene are assigned an initial classification by the CAD algorithm. (Note that, in multi-layer scenes, this initial classification can later change, as a result of attenuation corrections applied to the data within lower layers to compensate for the extinction incurred in overlying layers. The final classification of any layer occurs immediately before an extinction solution is attempted.) In the version 2 processing, the next and final step in the analysis was to launch the extinction and optical properties retrievals. In the version 3 processing, an intermediate step is inserted: the initial classification is now followed by an assessment of the lowest layers within each column. If the lowest layer is an aerosol and

(a) the layer is not opaque (i.e., the surface was detected below);

(b) the initial layer base is within some minimum distance of the surface (2.5-km for the version 3 processing); and

(c) the 532 nm integrated attenuated backscatter in the region between the initial base altitude and the top of the surface echo is positive

then the estimate of the layer base altitude is revised downward to a point three range bins (~90 m) above the top of the surface spike. The extinction and optical properties retrievals are conducted immediately after the conclusion of the base readjustment procedure. An example of the algorithm's performance on a single profile is given in Figure 2, where the arrows indicate the approximate altitudes of the initial and final altitudes of the aerosol layer shown in Figure 1(a).

4. RESULTS

The primary motivation for incorporating the aerosol base extender algorithm into the version 3 processing is to improve the quality of the CALIPSO AOD retrievals. This is because the CALIPSO data products only report extinction profiles – and hence, only calculate optical depths – in those regions where features are detected. Especially during daytime operations, the SNR achieved by the current signal averaging levels, which extends to a maximum of 80-km horizontally, is inadequate for deriving reliable extinction profiles in the so-called "clear air" regions where no layers are detected. Thus the AODs reported by CALIPSO depend critically on an accurate determination of layer boundaries, combined with the ability to accurately differentiate between clouds and aerosol and to correctly recognize different aerosol species.

To quantify the improvements that the aerosol base extension procedure makes in the CALIPSO optical depth retrievals, we conducted two types of studies. The first of these was a straightforward exercise in data product validation. Since acquiring its first lidar measurements in June, 2006, the CALIPSO validation program has relied heavily on coincident measurements made by the airborne high spectral resolution lidar (HSRL) developed by researchers at NASA's Langley Research Center (LaRC) [11]. HSRL makes separate measurements of total and molecular backscatter, and thus provides direct measurements of AOD and lidar ratio without any requirement for assumptions about the nature of the aerosol being observed. The story is different for CALIPSO: with very few exceptions, CALIPSO cannot make direct measurements of aerosol optical depth. Instead, estimates of optical depth are derived using a model-based lidar ratio selected on the basis of measured spatial and optical properties of each layer [4]. HSRL underflights of CALIPSO thus provide the high quality validation measurements that are essential for assessing the performance of the CALIPSO retrieval algorithms.

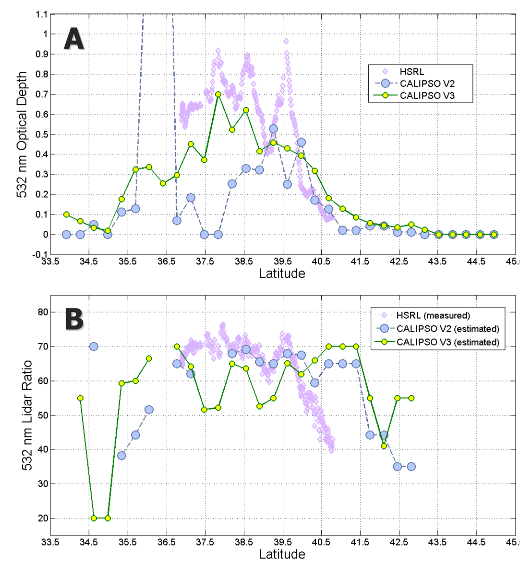

Figure 3: (a) comparisons of CALIPSO version 2 and version 3 AOD retrievals with coincident measurements made by the NASA Langley's airborne HSRL system; when no aerosol is detected within a column, the AOD is zero; (b) as in (a), but for lidar ratios. All measurements/estimates in both panels are for data acquired at 532 nm. To facilitate direct comparisons, the CALIPSO version 3 data are averaged to the same 40-km horizontal resolution that was used in the version 2 data products.

For the August 4 2007 data shown in Figure 1, the LaRC HSRL acquired a full complement of validation measurements along the CALIPSO track. Figure 3 compares the HSRL measurements of AOD (upper panel) and lidar ratio (lower panel) with the estimated quantities reported in CALIPSO's version 2 and version 3 data products. The effects of the base extension procedure are readily seen in Figure 3(a), where the AOD from CALIPSO's version 3 products is uniformly and substantially larger and closer to the HSRL measurement than in the previous version. That this effect is due largely, if not entirely to the extra vertical extent included in the extinction retrieval is, paradoxically, reinforced by the disparity in lidar ratio estimates between CALIPSO versions 2 and 3. In the optically dense parts of the aerosol layer, the lidar ratio estimates in version 3 are lower than their version 2 counterparts by as much as 10 sr. This lowering of lidar ratios is due to increased depolarization in the aerosol closest to the surface. This change in bulk layer properties is subsequently reflected in a change in aerosol type assignment. Layers that were identified as smoke or pollution (S_a = 70 sr) in version 2 are reclassified as pollution mixed with dust (S_a = 55 sr) in the version 3 analysis.

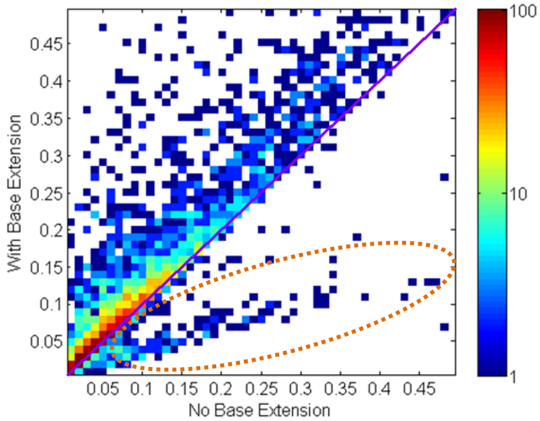

Figure 4: changes in aerosol optical depth resulting from application of the base extender algorithm. Those samples enclosed by the dashed orange line represent layers whose aerosol type changed as a result of the base extension, and thus the 'extended' extinction solution was derived using a lower lidar ratio than the 'not extended' solution.

That aerosol type identification might change as a result of the base extension algorithm is not unexpected, as new and different data are now being included in the layer-integrated properties used by the aerosol typing scheme. However, a change in type identification usually results in a change to the lidar ratio assigned to a layer, and if the reduction in the lidar ratio is large, the AOD estimate for the extended layer may actually be lower than it would have been for the original, unextended layer. This might happen, for example, if a layer initially classified as smoke (S_a = 70 sr) were reclassified as marine (S_a = 20 sr). To assess the occurrence frequency of this phenomenon, we analyzed two full days of data (2007-01-01 and 2007-08-27) first with the base extender enabled and then with it disabled. A comparison of the two sets of results is shown in Figure 4. For this data, layers were extended an average of 0.54-km. As expected, when there was no change in aerosol type, the median optical depth of the extended layers rose by ~22%. Similarly, those occasions when the AOD of the extended layer was smaller than that of the original layer were heavily dominated by cases where the initial lidar ratio was drastically reduced by the reclassification process.

Addition of the base extender procedure is expected to have a significant positive impact on the AOD estimates reported in version 3 of the CALIPSO data products. In a more comprehensive test that used four full months of data, the initial base altitude was extended for 8.7% of all aerosol layers detected.

REFERENCES

[1] Winker, D. M., et al., 2009: Overview of the CALIPSO Mission and CALIOP Data Processing Algorithms, *J. Atmos. Oceanic Technol.*, **26**, 2310–2323.

[2] Vaughan, M. A., et al., 2009: Fully Automated Detection of Cloud and Aerosol Layers in the CALIPSO Lidar Measurements, *J. Atmos. Oceanic Technol.*, **26**, 2034–2050.

[3] Liu, Z., et al., 2009: The CALIPSO Lidar Cloud and Aerosol Discrimination: Version 2 Algorithm and Initial Assessment of Performance, *J. Atmos. Oceanic Technol.*, **26**, 1198–1213.

[4] Omar, A., et al., 2009: The CALIPSO Automated Aerosol Classification and Lidar Ratio Selection Algorithm, *J. Atmos. Oceanic Technol.*, **26**, 1994–2014.

[5] Young, S. A. and M. A. Vaughan, 2009: The retrieval of profiles of particulate extinction from Cloud Aerosol Lidar Infrared Pathfinder Satellite Observations (CALIPSO) data: Algorithm description, *J. Atmos. Oceanic Technol.*, **26**, 1105–1119.

[6] McGill, M. J. et al., 2007: Airborne validation of spatial properties measured by the CALIPSO lidar, *J. Geophys. Res.*, **112**, D20201.

[7] Mielonen, T. et al., 2009: Comparison of CALIOP level 2 aerosol subtypes to aerosol types derived from AERONET inversion data, *Geophys. Res. Lett.*, **36**, L18804.

[8] Mioche, G. et al., 2009: Validation of the CALIPSO/CALIOP Extinction Coefficients from In Situ Observations in Mid-latitude Cirrus Clouds during CIRCLE-2 Experiment, *J. Geophys. Res.*, in press.

[9] Mona, L. et al, 2009: One year of CNR-IMAA multi-wavelength Raman lidar measurements in coincidence with CALIPSO overpasses: Level 1 products comparison, *Atmos. Chem. Phys.*, **9**, 7213–7228.

[10] Liu, Z. et al., 2010: The CALIPSO Cloud and Aerosol Discrimination: Version 3 Algorithm and Test Results, *current proceedings*

[11] Hair, J. et al., 2008: Airborne High Spectral Resolution Lidar for profiling aerosol optical properties, *Appl. Opt.*, **47**, 6734–6752.