RESULTS OF THE CALIPSO LIDAR 532 NM LIDAR RATIO VALIDATION STUDY USING THE AERONET SUN-PHOTOMETER SYSTEM IN THE SOUTH AMERICA CONTINENT.

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ABSTRACT

Using AERONET sunphotometers operating at five different locations in Brazil, a validation methodology was developed to verify the assumed values of the lidar ratio (LR) used by the CALIOP aerosol extinction algorithms. In this study, days were selected and analyzed when the two instrument's measurements were spatially coincident under cloud-free conditions. LR values from our proposed AERONET/CALIOP model (AC model) were determined and showed good agreement with the values assigned by the CALIOP algorithm. Based on the quantitative comparison, a mean percentage difference of $-8\pm64\%$ was achieved when comparing 5-km resolution profiles in a horizontal range of 100 km centered within the CALIPSO's closest approach. Mean percentage differences of $-1.74\pm26\%$ were obtained when comparing only the best matching profiles linked using the HYSPLIT air mass trajectory model. These results confirm the accuracy in the LR assumed a priori by the CALIOP algorithms within the uncertainty range of no more than 30%.

1. INTRODUCTION

One of the main challenges in the field of atmospheric science lies in achieving a more accurate knowledge about aerosol and cloud properties and how their interactions can affect and contribute to climate model predictions. In the last decades, several remote sensing platforms, i.e., space, aircraft and ground-based measurement systems, were developed or improved to conduct studies of aerosol and cloud optical properties on local and also global scales, as well as to provide the scientific basis for understanding the Earth's climate system.

Since 2006 the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite has retrieved vertical profile information of aerosols and clouds, providing important contributions in the atmospheric science studies and also complementing our knowledge of horizontal distributions [1]. The primary instrument aboard CALIPSO satellite, Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP), operates in an elastic backscatter mode, which presents an extra challenge in the retrieval of atmosphere optical properties, since it does not contain all of the information required to fully resolve the lidar equation, and therefore must derive aerosol backscatter and extinction coefficients using assumed values of the so-called extinction-to-backscatter ratio (LR=lidar ratio). Therefore, the development of validation methodologies using ground-based instruments becomes necessary to assess the accuracy of optical properties retrieved from CALIPSO satellite measurements. Since the launch of the CALIPSO, several validations studies have been conducted to assess the CALIOP algorithm performance and its products [2, 3]. Most studies have been conducted in the North Hemispheres, and indicate underestimations of CALIOP AOD values probably due CALIOP's low signal-to-noise ratio, cloud contaminations, or even potentially erroneous assumptions of the aerosol extinction-to-backscatter ratio. In this sense, there is a lack of CALIOP validation studies in the South Hemisphere, specially in South America continent, that is a region directly affected by the South Atlantic Anomaly (SAA) [4]. The SAA radiation effects can introduce large errors in the calibration procedure, which in turn can lead to misclassification or even lack of identification of aerossol layers [5].

In order to assess the accuracy and performance of the CALIOP algorithms we used data from AERONET sunphotometer system installed at five different location in the Brazilian territory. We employed aerosol optical depth (AOD) values from AERONET and CALIOP layer integrated attenuated backscatter coefficient at 532 nm to derive the most likely LR values and compared with those assigned by CALIOP system.

2. VALIDATION METHODOLOGY

Initially, the validation methodology needed to decide the location and time period to collect ground-based data correlated to CALIPSO satellite measurements. We select a dataset measurement period of 2006 to 2009 for five operational AERONET locations, namely: *Rio Branco*, *Alta Floresta*, *Cuiabá*, *Campo Grande* and *São Paulo*. The COVERLAI/MCSA algorithms (CALIPSO Overpass Locator Algorithm/Multi-instrumental Coincidence Selection Algorithm) was developed to select the date, time and the closest approach distance for all the chosen sites, as well as all coincident measurements between CALIOP and the ground-based system. COVERLAI uses as initial input the latitude and longitude values of the CALIPSO ground-track coordinates and also the latitude and longitude values for each site location to selected the dataset of the CALIPSO's best closest approach. MCSA uses CALIOP and AERONET informations to select all coincident measurements within a specific temporal interval. Both processes are based on previous validation studies of spaceborne lidar using ground-based instruments [6]. Taking into account comparisons between ground-based instruments and spaceborne lidar showing that good correlations ($r > 0.9$) occurs for time and space offsets less than 3 hours and 60 km, and acceptable correlations ($r > 0.8$) occurs for offsets less than 6 hours and 120 km [6], the COVERLAI algorithm was set up to select only those days which CALIPSO satellite overpasses the five locations within a horizontal range distance of $\Delta D \leq 100$ km. Subsequently, the MCSA algorithm selects all the coincident measurements carried on by CALIOP and the AERONET in a temporal matching windows up to 6 hours centered in the closest approach of CALIPSO. For the matching dataset the Number Layers Found (NLF) products were analysed for each 5-km resolution profiles, using the CALIOP Level 2 Cloud Layer products, within the total spatial range of 100 km centered in the closest distance between CALIOP ground-track and AERONET site (i.e., 20 consecutives profiles) in order to check the number of cloud-layers found, and consequently, to be assured that all data were under cloud-free condictions at the time of the closest approach. Those profiles with NLF equal to zero were flagged as cloud-free measurements. Since the objective of this validation study is focused on aerosol LR values, all aerosol layers in the same spatial range flagged as cloud-free conditions were selected using the 5-km resolution Level 2 Aerosol Layer products, and verified the cloud-aerosol discrimination (CAD) score [7]. We selected only those aerosol profiles flagged with CAD equal to -50 to -100, where the larger the magnitude of the CAD score the higher is the confidence in the classification, ensuring the selection of reliable aerosol profiles. Once these steps have been completed, we used both 5-km resolution aerosol layer and profile products to calculate the so-called "backscatter centroid", as given in the equation 1, where x_i is the total attenuated backscatter signal at 532 nm associated to the altitude Z_i:

$$C = \frac{\sum_{i=1}^{N} x_i \, Z_i}{\sum_{i=1}^{N} x_i} \qquad (1)$$

The "backscatter centroid" values were employed as input data in the air mass trajectories computed using the HYSPLIT model. Since the mesoscale variation and short lifetime in the troposphere should be taken into account, the HYSPLIT trajectory modeling is used to determine if and when the air mass parcels along the CALIPSO ground-track region are actually measured at the AERONET site, as can be seen in figure 1, where HYSPLIT air mass trajectories were plotted for 14 July of 2009 at the Alta Floresta AERONET site. The backward-trajectories started at the CALIPSO ground-track coordinates, relative to the CALIPSO's closest approach, e.g., the 17:41 UTC and evolved backwards in the time scale. This means that the aerosol parcels detected by the AERONET sun-photometer about 15:00 UTC have been transported and arrived in the CALIPSO overpass region about 3 hours later, at the precise altitude of the centroids of each aerosol detected layer. In this case, the AERONET AOD values used in the equation 3 in posterior analysis should be the AOD values retrieved around 15:00 UTC.

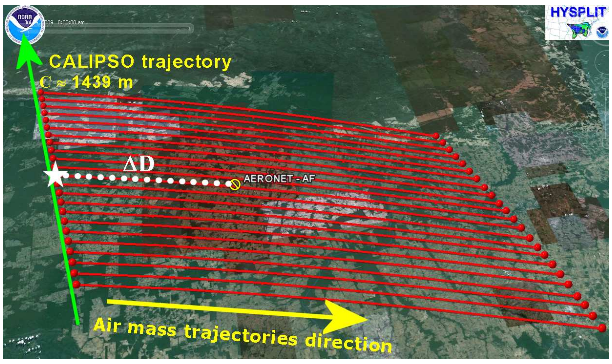

Figure 1: HYSPLIT backward trajectories in the region of the Alta Floresta AERONET site for 14 July of 2009.

The reason for using the trajectory model is to constrain the direction of the air masses and improve the correlation between optical properties (i.e., AOD and LR) measured by CALIOP and AERONET sun-photometer. The application of trajectories analysis might constrain the dataset and decrease the available number of correlative measurements, however, it does strengthen the results obtained from comparisons of the optical properties measured by both systems, giving in some degree of confidence that similar air parcels are being probed by the AERONET and CALIOP.

The next step, using the merged data set produced satisfying all the imposed constraints, was to calculate the layer integrated attenuated backscatter coefficient at 532 nm, γ'_{532}, for each twenty consecutive 5-km horizontal resolution profiles using a relation between the layer optical depth and its LR [8], as can be seen in equation 2

$$\gamma'_{caliop,532} = \frac{1 - T^2_{caliop}}{2\, S_{caliop}} = \frac{1 - exp(-2\, \tau_{caliop})}{2\, S_{caliop}} \qquad (2)$$

where T_{caliop} and and S_{caliop} is the CALIOP's two-way transmittance and the LR, respectively. The results from equation 2 were used to calculate the "appropriate" value of S_{ac} (AERONET/CALIOP lidar ratio) based in the AOD values retrieved from AERONET sun-photometer, according to following equation:

$$S_{AC} = \frac{1 - exp(-2\, \tau_{aeronet})}{2\, \gamma'_{caliop,532}} \qquad (3)$$

The AERONET AOD were interpolated at 532 nm using aerosol optical depth values at 440, 500 and 675 nm. Since the CALIOP algorithm is based on an aerosol model to choose the appropriate LR values [9], the final lidar ratios retrieved by CALIOP were compared to the S_{AC} calculated by the AERONET/CALIOP Model proposed in order to determine the performance of aerosol type classification and LR selection in the Brazilian territory, giving an idea of how well the CALIPSO algorithms is processing those data measurements acquired within the South Atlantic Anomaly region (SAA).

3. RESULTS AND DISCUSSION

Using the COVERLAI and MCSA algorithms to determined all the CALIPSO daytime overpass within a horizontal distance up to 100 km from the five AERONET sites and selected the coincident measurements between both systems in a temporal window up to 6 hours centered within the satellite's closest approach interval, a total of 237 correlative measurements were sorted out. After calculating the "backscatter centroids" of the aerosol-layer and using it as initial altitude to generate forward or backward HYSPLIT air mass trajectories, we selected only those days when CALIOP and AERONET sun-photometer seems to have probed the same aerosol air mass parcels under cloud-free conditions (figure 1), giving then a total of 75 days to be analysed. Such a rigorous procedure contributes to a considerable decrease in the correlative measurements dataset, although, it will increase the probability that both satellite and ground-based systems are detecting the same aerosol mass parcels in the atmosphere and therefore increase the reliability of the correlative measurements. Finally, the LR values from the so-called AC model were calculated using the AOD and the layer integrated attenuated backscatter coefficient at 532 nm retrieved from AERONET and CALIOP systems, respectively (equation 3). Figure 2 shows the CALIOP final LR ($S_{caliop,532}$) and the AC model LR (S_{AC}) distributions based on the 75 selected days. The high frequency of fixed LR values, 20 sr (clean marine aerosol type), 35 sr (clean continental), 40 sr (dust), 55 and 65 sr (polluted dust) and 70 for smoke and polluted continental, are expected since CALIOP retrieval algorithms use fixed LR values based on the cluster analysis of a multiyear AERONET dataset to determine characteristic aerosol types [9]. Whereas the LR values retrieved by the AC model show a continuous distribution spanning all those values, peaks in the distribution can be seen, especially around 35, 45, 55, 65 and 70 sr [10]. These peaks in S_{AC} values show a good agreement with the LR retrieved by CALIOP since their uncertainties can change up to 30%. The mean percentage difference between CALIOP LR and AC model is -8 $\pm$ 64%. The high value in the standard deviation reveals a large dispersion of the retrieved LR values. Such difference can be due the disparity between the AOD values measured in the atmospheric column by the AERONET sun-photometer and the respective values for each aerosol layer retrieved by CALIOP. In some cases these disagreements can be a consequence of the atmospheric variability during the time of the CALIPSO closest approach and the time period which the air masses were transported to the AERONET station region. It is also important to note that in these analysis we used a single τ value measured by the AERONET system applied to each 20 consecutive 5-km resolution aerosol profile, which indicate that in some cases there is a possiblity of both systems are not measuring the same air mass parcels. In addition, in the inversion method applied to obtain CALIOP's AOD and LR, an average value is considered over the whole atmospheric column, in other words, the LR is considered as a single value for the total column. It is only valid for a well mixed atmophere and in many cases might not be true when a two or more aerosol layer types are distinct in the profiles. The same approach described previously was used to calculate the values of S_{AC} for one single 5-km resolution profile, which were then compared to the values assigned by the CALIOP system. In this analysis, profiles are chosen only among those which the air masses trajectories obtained from HYSPLIT model links the AERONET measurements sites and the CALIPSO ground-track region, indicating a great probability that both systems have measured the same aerosol mass parcels in the atmosphere. The best matching profiles are presented in figure 1 signed with ★ and a dotted line in white color. Figure 3 shows the LR probability distribution functions for the S_{AC} and the final LR retrieved by the CALIOP aerosol model for the best matching profiles in each day of correlative measurements. Applying the same reasoning of the previous analysis it can be seen a high frequency of fixed LR values of 40, 55 and 70 sr retrieved by the CALIOP algorithm. The AC model shows a broader distribution spanning from all LR values with some predominant peaks for

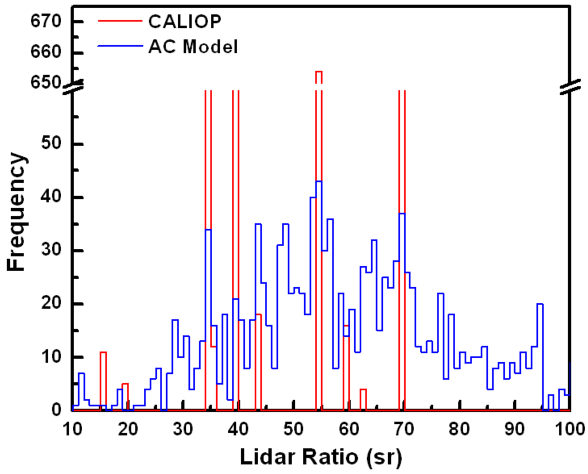

Figure 2: Lidar ratio distributions retrieved by CALIOP system and the AC model. The distribution in red color was retrieved by CALIPSO aerosol model and the blue one used AERONET AOD values and the γ'_{532} from CALIOP system.

aerosol dust, around 40 sr, polluted dust aerosol, around 55 sr, and biomass burning or polluted continental aerosol with LR value of 70 sr. The LR distribution for the best matching profiles provides a mean percentage difference between S retrieved by the CALIOP algorithm and S_{AC} of -1.74 $\pm$ 26%. Such result can be an indication of the CALIOP calibration accuracy within the SSA region and the good performance of the CALIOP's automated LR selection algorithm.

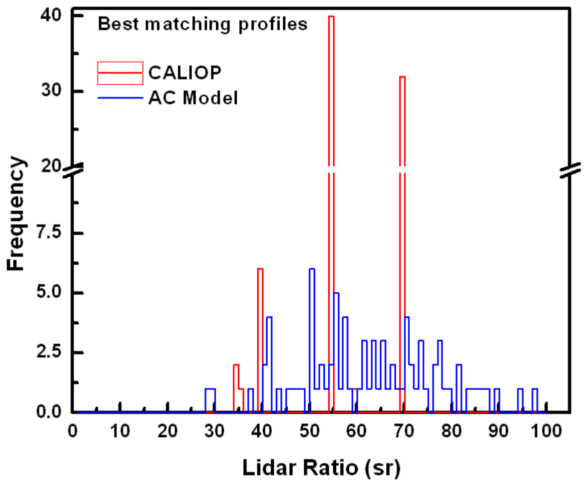

Figure 3: Lidar ratio distributions retrieved by CALIOP system and the AC model for the best matching profile of each measurement day. The distribution in red color was retrieved by CALIPSO aerosol model and the blue one used AERONET AOD values and the γ'_{532} from CALIOP system.

4. CONCLUSION

In this first validation study in South America region we have used about 4 years of CALIPSO and AERONET measurements to compare LR values retrieved by the CALIOP algorithms and the AC proposed model. The usage of constraints imposed in this validation methodology reduced the coincident dataset, however, increased the degree of confidence that both systems were probing the same aerosol mass parcels, and therefore, improved the accuracy in the assessment of the CALIOP algorithms performance. The mean percentage difference of -1.74 $\pm$ 26% for the best matching profiles linked by the HYSPLIT air masses trajectories shows a consistent agreement between both systems even though separated spatially and temporally.

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REFERENCES

1. Winker, D. M., Vaughan, M. A., Omar, A., Hu, Y., Powell, K. A., Liu, Z., Hunt, W. H., Young, S. A., 2009: Overview of the CALIPSO mission and CALIOP data processing algorithms, *Journal of Atmospheric and Oceanic Technology*, **26**, pp. 2310-2322.
2. Bréon, F-M., Vermeulen, A., Descloitres, J., 2011: An evaluation of satellite aerosol products against sunphotometer measurements, *Remote Sensing of Environment*, **115**, pp. 31023111.
3. Kittaka, C., Winker, D. M., Vaughan, M. A., Omar, A., Remer, L. A., 2011: Intercomparison of column aerosol optical depths from CALIPSO and MODIS-Aqua, *Atmospheric Measurement Techniques*, **4**, pp. 131-141.
4. Hunt, W. H., Winker, D. M., Vaughan, M. A., Powell, K. A., Lucker, P. L., Weimer, C., 2009: CALIPSO Lidar Description and Performance Assessment, *Journal of Atmospheric and Oceanic Technology*, **26**, pp. 1214-1228.
5. Powell, K. A., Hostetler, C. A., Liu, Z., Vaughan, M. A., Kuehn, R. E., Hunt, W. H., Liu, K., Trepte, C. R., Rogers, R. R., Young, S. A., Winker, D. M., 2009: CALIPSO Lidar Description and Performance Assessment, *Journal of Atmospheric and Oceanic Technology*, **26**, pp. 1214-1228.
6. Anderson, T. L., Charlson, R. J., Winker, D. M., Ogren, J. A., Holmén, K., 2003: Mesoscale variations of tropospheric aerosols, *Journal of the Atmospheric Sciences*, **60**, pp. 119-136.
7. Liu, Z., Vaughan, M. A., Winker, D. M., Kittaka, C., Getzewich, B. J., Kuehn, R. E., Omar, A. H., Powell, K. A., Trepte, C. R., Hostetler, C. A., 2009: The CALIPSO Lidar cloud and aerosol discrimination: Version 2 algorithm and initial assessment of performance, *Journal of Atmospheric and Oceanic Technology*, **26**, pp. 1198-1213.
8. Platt, C. M. R., 1973: Lidar and radiometer observations of cirrus clouds, *Journal of the Atmospheric Sciences*, **30**, pp. 1191-1204.
9. Omar, A. H., Winker, D. M., Kittaka, C., Vaughan, M. A., Liu, Z., Hu, Y., Trepte, C. R., Rogers, R. R., Ferrare, R. A., Lee, K., Kuehn, R. E., Hostetler, C. A., 2009: The CALIPSO automated aerosol classification and Lidar Ratio Selection Algorithm, *Journal of Atmospheric and Oceanic Technology*, **26**, pp. 1994-2014.
10. Landulfo, E., Papayannis, A., Torres, A. S., Uehara, S. T., Pozzetti, L. M. V., de Matos, C. A., Sawamura, P., Nakaema, W. M., de Jesus, W. C., 2008: A four-year Lidar-sun photometer aerosol study at São Paulo, Brazil, *Journal of Atmospheric and Oceanic Technology*, **25**, pp. 1463-1468.