Comparison of Aerosol and Cloud Structure from CALIPSO, CloudSat and Ground-based Lidar

Sang-Woo Kim, Soon-Chang Yoon

[1]*School of Earth and Environmental Sciences, Seoul National University, Seoul, Korea, kimsw@air.snu.ac.kr*

ABSTRACT

In this study, we present results of the intercomparison of aerosol/cloud top and bottom heights obtained from a space-borne active sensor Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) onboard CALIPSO, and the Cloud Profiling Radar (CPR) onboard CloudSat, and the space-borne passive sensor Moderate Resolution Imaging Spectroradiometer (MODIS) onboard Aqua, and ground-based 2-wavelenght polarization lidar system (532 and 1064 nm) at Seoul National University (SNU), Seoul, South Korea. This result confirms that the CALIPSO science team algorithms for the discrimination of cloud and aerosol as well as for the detection of layer top and base altitude provide reliable information both under cloud-free conditions and in cases of multiple aerosol layers underlying semi-transparent cirrus clouds. Simultaneous space-borne CALIOP, CPR and ground-based SNU lidar (SNU-L) measurements complement each other and can be combined to provide full information on the vertical distribution of aerosols and clouds, especially for thick opaque clouds. The aerosol extinction profiles from both lidars show good agreement for aerosols within the planetary boundary layer under cloud-free conditions and for the night-time CALIOP flight.

1. INTRODUCTION

Recently-launched space-based backscatter lidar Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) onboard CALIPSO provides information on the vertical distribution of aerosols and clouds as well as on their optical and physical properties over the globe with unprecedented spatial resolution (Winker et al., 2007). Validation of CALIOP products via intercomparison with independent measurements is essential to the production of a high quality dataset (Liu et al., 2006, Kim et al., 2008). In this study, we present initial validation results of space-borne lidar CALIOP profiles of aerosols and clouds by comparing space and time coincidental measurements collected by the space-based Cloud Profiling Radar (CPR), and the space-borne passive sensor Moderate Resolution Imaging Spectroradiometer (MODIS), and a ground-based lidar at Seoul National University (SNU; 37.4579 ºN, 126.9520 ºE, 116 meters above mean sea level), Seoul, South Korea, and discuss the strengths and weakness of each instrumental technique. This validation is made for 3 different types of atmospheric scenes: (1) boundary aerosol layer under cloud-free conditions, (2) multiple aerosol layers underlying semi-transparent cirrus clouds, and (3) aerosol layer under thick tropospheric clouds. A comparison of aerosol extinction profile between CALIOP and SNU-L measurements both under cloud-free conditions and in cases of multiple aerosol layers underlying semi-transparent cirrus clouds is also presented.

2. OVERVIEW OF THE MEASUREMENTS AND THE VALIDATION APPROACH

The CALIOP emits polarized light at both 1064 and 532 nm with a pulse energy of 110 mJ and a pulse repetition rate of 20.25 Hz, polarization discrimination in the receiver is only done for the 532 nm channel (Winker et al., 2007). Here we use CALIOP level-1 [version 1.10 (13 June 2006 ~ 05 January 2007) and 1.11 (06 January 2007 ~ 13 March 2007)] and -2 data (version1.10). The ground-based SNU lidar (SNU-L) has also the same two wavelengths as CALIOP (1064 and 532 nm) with the depolarization ratio measurement at 532 nm (Sugimoto et al., 2006; Yoon et al., 2008). SNU-L employs a Nd:YAG laser (pulse energy of 20 mJ; pulse repetition rate of 10 Hz) and an analog detection system. SNU-L makes the vertical profile from surface to 18 km every 15 min (starting at 00, 15, 30, 45 minutes of every hour) with a 6-m vertical resolution. The CPR onboard CloudSat measures the signal backscattered from hydrometeors as a function of the distance at a frequency of 94 GHz (Stephens et al., 2002). These backscattered signals are sampled to produce 125 vertical bins with a range gate spacing of 240 m. The CPR profiles are generated every 1.1 km along-track. The nominal footprint of a single profile is approximately 2.5 km along track and 1.4 km cross track. In the CloudSat standard data products, the level-2 GEOPROF (ver. – Release 4; R04) products providing information on the cloud mask and radar reflectivity were used. CALIPSO flies over the SNU-L site at 04:50 UTC (13:50 local time) during daytime (ascending) and 17:41 UTC (02:41 local time) during night-time (descending). The CALIPSO (also, CloudSat) ground tracks are located within 10 km (approximately 0.1º) from the ground-based lidar station (Kim et al., 2008). To avoid huge sampling volume discrepancies due to different vertical resolution and horizontal footprint size of data between the two lidars, we averaged the closest 18 profiles of CALIOP and used 5-min averaged SNU-L profiles acquired between 04:45 and 04:50 UTC (daytime) or between 17:45 and 17:50 UTC (night-time) are used for comparison.

3. RESULTS AND DISCUSSION

Figure 1 show color coded time-height images of the daytime level-1 data at 532 nm acquired by CALIOP and SNU-L, and the vertical profiles of the apparent scattering ratio R_{app} at 532 nm, as well as the level-2 cloud/aerosol layer flag, as calculated at the coincident

© Proceedings of the 8th International Symposium on Tropospheric Profiling, ISBN 978-90-6960-233-2
Delft, The Netherlands, October 2009. Editors, A. Apituley, H.W.J. Russchenberg, W.A.A. Monna

point. The R_{app} calculated from the two instrument measurements of total attenuated backscattering signals at 532 nm show similar aerosol and cloud structures both under cloud-free conditions (Figure 1a) and in case of multi-layered aerosols underlying thin cirrus clouds (Figures 1b and 1c). The top and base heights of cloud and aerosol layers estimated from simultaneous space-borne CALIOP and ground-based SNU-L measurements are generally in agreement within 0.10 km, particularly during night-time. This result confirms that the CALIPSO science team algorithm for the discrimination of cloud and aerosol as well as for the detection of layer top and base altitudes provides reliable information on the height and thickness of aerosol and cloud layers in such atmospheric conditions. The accuracy of the PBL top height under cirrus clouds appears, however, much more limited during daytime. In cases of aerosol layers underlying thick tropospheric clouds (Figure 1d), comparison results illustrate the limitations of space-borne downward-looking and ground-based upward-looking lidar measurements due to strong signal attenuations, and imply that only information on the cloud top (bottom) height is reliable from satellite-based CALIOP (ground-based SNU-L) observations. However, the complementarity between space-borne and ground-based lidar observations can provide complete vertical structures of aerosols and clouds.

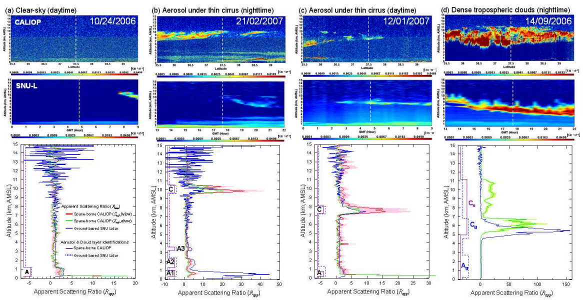

Figure 1. *Vertical profiles of CALIOP-derived (top) and SNU lidar-derived (middle) total attenuated backscatter at 532 nm, and apparent scattering ratios R_{app} at 532 nm (bottom) calculated from the CALIOP (red and green lines) and the SNU lidar (blue line) measurements on (a) October 24, 2006, (b) February 21, 2007, (c) January 12, 2007, and (d) September 14, 2006. Two CALIOP R_{app} profiles were obtained by choosing z_{ref} between 10 and 11 km (green line; z_{ref} _above) and between 5 and 6 km (red line; z_{ref} _below). The vertical resolution of CALIOP data is 30 m (60 m) below 8.2 km (above 8.2 km), whereas the SNU-L resolution is 6 m from surface up to 15 km. The vertical white dashed lines in upper two figures indicate the points of nearest spatial/temporal coincidence between the SNU lidar site and the CALIPSO flight. Because the plot is to be too complicated, the standard deviation (pink shaded envelope) of CALIOP app R_{app} (z_{ref} _below) is only represented in the bottom figures. The violet line and blue dashed line in the bottom figures indicate the top and bottom heights of the aerosol layer, estimated by aerosol and cloud layer identification algorithm (level-2) of CALIPSO science team and SNU algorithm, respectively. The label 'A' and 'C' indicate an aerosol and cloud layer. Subscripts "g" and "s" denote the ground-based and space-borne measurements, respectively.*

Detailed discussions for the cloud vertical structure given in Figure 1d are given Figure 2. The cloud top pressure (hPa) retrieved from the Aqua MODIS measurements over northeast Asia, centered on the ground-based SNU lidar site, on September 14, 2006 are shown in Figure 2a. Along the region of the CloudSat/CALIOP overpass, high clouds (<400 hPa) were mostly overcast, except between the latitudes 31.5N and 32.5N and some areas north of 40N. Figures 2b and 2c show the cross-section of the CPR-derived reflectivity and cloud top/base height (CTH/CBH) information obtained from MODIS, CPR, and CALIOP along the Aqua/CloudSat/CALIPSO track, respectively. According to the cloud vertical structures obtained from the CPR and CALIOP, various types of clouds are present along the track. Scene "A1" illustrates the systematic difference of CTH between CALIOP and CPR/MODIS due to the vertical non-homogeneity of microphysical properties of the clouds. The cirrus cloud between 13 and 14 km in scene "A2" was detected only by the CALIOP. This is because the CPR and CALIOP have different sensitivities for cloud particles due to the use of different wavelengths: ~3.2 mm (94 GHz) and 532 nm, respectively. A lidar signal cannot penetrate thick clouds owing to its strong signal attenuations (Kim et al., 2008), and therefore, the CALIOP could not detect the well-developed thick clouds under cirrus clouds [latitudes from 30.8N to 31.6N in scene "A1"]. In contrast, the CPR detected the complete cloud structure. The limitation of lidar measurements to dense cloud is more clearly revealed in scene "A3". The CTH values obtained from the CPR and CALIOP showed an good agreement with each other, whereas large discrepancies were found between the CBH values provided by the CPR and those obtained by the CALIOP. The CALIOP-derived backscatter signals were completely attenuated by the opaque and thick cloud feature. In contrast, for the relatively thin altostratus, both the CTH and CBH values estimated from the CPR and CALIOP were in good agreement (i.e., scene "A5").

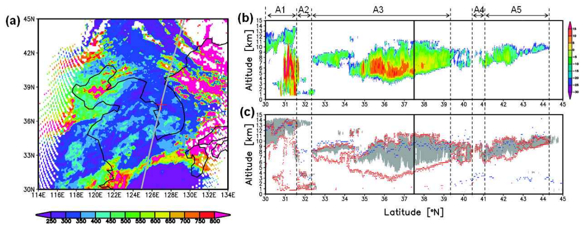

Figure 2. *(a) MODIS-detected cloud top pressure (unit: hPa) on September 14, 2006 (See Figure 1d). Location of the ground-based lidar monitoring station (red crosshair), and the night-time descending node of the CloudSat/CALIPSO orbit (gray solid line) are superimposed. (b) Color-coded latitude-height images of the CPR-derived cloud particle reflectivity (unit: dBZ) and (c) cloud top and bottom heights along the CloudSat/CALIPSO track in (a). Cloud boundary information obtained from the CPR, CALIOP, and MODIS are plotted as red dots, gray shading, and blue dots, respectively. The vertical black solid lines in (b) and (c) indicate the nearest spatial coincidence between the ground-based SNU lidar and the CloudSat/CALIOP flight. Five selected cloud scenes labeled from "A1" to "A5" are given at the top of figure (b) using a vertical dashed line.*

The differences between the CTH values acquired by the passive sensor (i.e., MODIS) and by the active sensors (i.e., CALIOP and CPR) were significant in this case. MODIS failed to detect the CTH of high-altitude thin cirrus clouds (e.g., scene “A2”) and optically very thin cloud layers (e.g., scene “A4”), while the CTH was detected by the CALIOP. MODIS measurements of the CTH of dense clouds are also have difficulties (e.g., scene “A3”); the operational MODIS products overestimate the CTH by approximately 0.5–1 km (latitudes from 32.3N to 34.5N), but they underestimate the CTH by approximately 1–2 km from 35.2N to 39.3N. This discrepancy may stem from several factors: a relatively large pixel (5 km×5 km resolution) of the MODIS cloud product, uncertainty in the conversion of MODIS CTP to CTH by using ECMWF profiles, uncertainty in the clear-sky radiance estimates under overcast conditions, and the inhomogeneous distribution of clouds along the satellite track.

Figure 3 shows the intercomparison of the vertical profiles of the CPR-measured cloud reflectivity [dBZ] and the CALIOP-derived and ground-based SNU lidar-derived total attenuated backscatter signals at 532 nm wavelength (β'_{532}: the sum of the 532 nm parallel and perpendicular return signals) [$km^{-1}sr^{-1}$], which were selected for the profiles of the nearest coincidence between the ground-based SNU lidar station and the Aqua/CloudSat/CALIPSO flight on September 14, 2006 (see the vertical solid line in Figure 2 around 37.46°N). As described in Section 2, the three profiles of level-1 CALIOP and two profiles of level-2 CPR closest to the ground-based SNU lidar station along the satellite tracks were averaged. Cloud layer identification results from these instruments are given in the right-hand side of the figure. It is observed that the CTHs obtained from the space-based down-looking radar and lidar showed a good agreement (within 0.1 km), but the MODIS-derived CTH (9.7 km) was underestimated by approximately 1.8 km. The CTH derived from the up-looking SNU lidar was approximately 6.8 km because the lidar signals were strongly attenuated by cloud particles. The aerosols in the planetary boundary layer may also contribute to the lidar signal attenuation (not shown). Contrast to the CTH retrievals, the CBH determined from the three active sensors showed relatively large differences in this case: CPR (4.31 km), CALIOP (4.93 km), and SNU-Lidar (4.47 km). These discrepancies in the CBH values can be attributed to several factors. Firstly, as discussed above, the signal attenuation of the nadir-pointing CALIOP should be considered. There are no signal attenuations in the case of CTH measurements by down-looking space-based CPR and CALIOP; however, the CALIOP signal experiences considerable attenuation as it propagates through dense clouds. Secondly, the inhomogeneity in the horizontal and vertical cloud distributions along the track and differences in the CPR/CALIOP sampling volumes resulting from different fields of view (FOVs) and horizontal footprints (i.e., coverage) may contribute to the disagreement in the CBH values, although we considered a supreme sampling volume matching requirements in time and space in order to minimize this effect. In addition, the CPR/CALIOP carries out measurements over a significant horizontal distance during a short period of time, while ground-based SNU lidar is

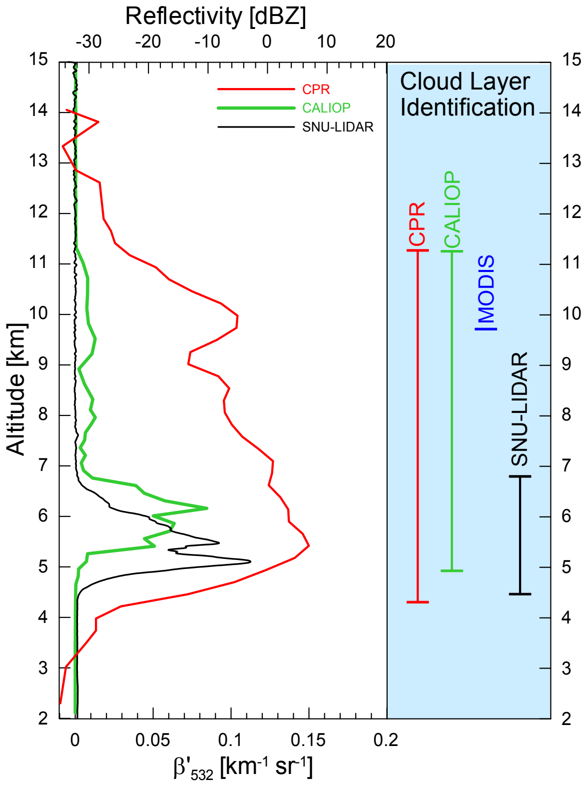

Figure 3. *Vertical profiles of the CPR-derived cloud particle reflectivity (red), CALIOP-derived (green) and ground-based SNU lidar (black) derived total attenuated backscatter signal at 532-nm wavelength, which were selected for the profiles of the nearest coincidence between the ground-based SNU lidar and the Aqua/CloudSat/CALIPSO flight on September 14, 2006 (approximately 17:41 UTC; 02:41 local time). In formation on cloud top and bottom height obtained from each platform are given on the right-hand side of the figure.*

localized and changes in the measurements are caused only by the atmospheric motions resulting from prevailing winds. It is worth mentioning that multiple scattering in the clouds during the space-borne radar measurements probably limits the accuracy of the estimated CBH; however, this multiple scattering is not crucial in this study and is important only for CPR applications like the collection of rainfall and snowfall retrievals.

The vertical profiles of the cloud reflectivity obtained by CPR and the CALIOP-derived β'_{532} values for coincident measurements between the ground-based SNU lidar and the Aqua/CloudSat/CALIPSO are provided in Figure 4; these profiles satisfactorily illustrate the two-layered cloud structure: an upper transmissive cloud layer centered at around 10.5 km and dense cloud layer centered at around 6~7 km. Compared to the lidar signal during night-time (e.g., Figure 2), it should be noted that the daytime CALIOP and SNU-Lidar profiles are more noisy because of solar radiation (Kim *et al*. 2008); the noise probably limits the accuracy of the CALIOP/SNU-Lidar algorithm in the detection of the CTH and CBH. The top and bottom boundaries of the semi-transparent upper cloud determined from the

CPR and CALIOP are in good agreement within 0.09 km and 0.02 km, respectively. Similar to the case given in Figure 2, the MODIS-derived CTH was detected at 9.68 km. This is identical to the CBH of upper cloud layer measured by CPR and CALIOP, but is underestimated by about 1.3 km compared to CTHs from CPR and CALIOP measurements. The CTH of the lower thick layer estimated by the CPR (8.02 km) differed from that obtained by the CALIOP (7.61 km) by 0.4 km, but the differences in the CBH for this cloud layer was 1.56 km due to the CALIOP signal attenuation. The CBHs retrieved from the CPR (5.38 km) and ground-based SNU-Lidar (5.60 km) show good agreement.

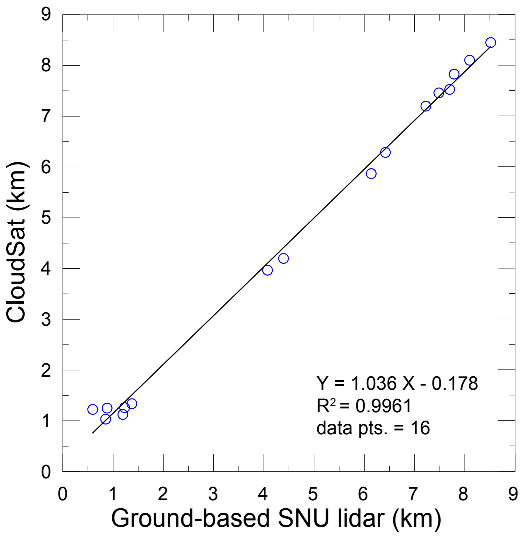

Figure 4. *Scatterplot of cloud base height for the CloudSat relative to the ground-based lidar.*

On the other hand, comparisons of aerosol extinction profiles retrieved from CALIOP and SNU-L are shown in Figure 5. The comparison under cloud-free conditions (24 Oct.2006, left) illustrates that both lidars show good agreement in the upper part of the PBL (0.7 ~ 1.2 km) with mean difference of about 0.02 km^{-1}. Compared to the ground-based SNU-L, CALIOP shows unexpected peaks of aerosol extinctions above the PBL. This may be due to small signal-to-noise ratio (SNR) during daytime. Under semi-transparent cirrus cloud conditions, the CALIOP-derived aerosol extinction coefficients are about 5~10 times greater than those from SNU-L for daytime observations on 25 Nov. 2006 (middle left) and 12 Jan. 2007 (middle right). The aerosol extinction profile obtained during the night-time CALIOP flight under semi-transparent cirrus cloud conditions (right) shows good agreement both in aerosol extinction coefficients and in the layer top and bottom structures. This can be explained by the better night-time signal-to-noise ratio (SNR) of CALIOP.

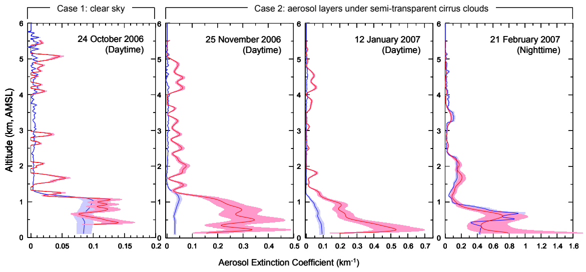

Figure 5. *Comparison of aerosol extinction profiles between CALIOP (red line) and ground-based SNU lidar (blue line) for cloud-free conditions (left) and aerosol layers under semi-transparent cirrus clouds (right three figures. The shaded envelopes represent the range of aerosol extinction coefficient originating from the lidar ratio uncertainty.*

ACKNOWLEDGEMENTS

This study was supported by the Korea Meteorological Administration R&D programs under the grant CATER 2006-4104 and the BK 21 Program of the SEES/SNU. We acknowledge the technical support provided by Dr. Sugimoto for the operation of ground-based SNU lidar.

REFERENCES

[1] Kim, S.-W., Berthier, S., Raut, J.-C., Chazette, P., Dulac, F., & Yoon, S.-C., 2008: Validation of Aerosol and Cloud Layer Structures from the Space-borne Lidar CALIOP Using a Ground-based Lidar in Seoul, Korea, *Atmospheric Chemistry and Physics,* ***8***, 3705–3720.

[2] Liu, Z., et al., 2006: Validation of Calipso Lidar (CALIOP) Calibration. ILRC 2006, Nara, Japan..

[3] Sugimoto, N., et al., 2006: Network Observations of Asian Dust and Air Pollution Aerosols Using Two-Wavelength Polarization Lidars. 23rd International Laser Radar Conference, Nara, Japan, 851-854 (2006).

[4] Winker, D. M., Hunt, W. H., & McGill, M. J., 2007: Initial performance assessment of CALIOP. *Geophysical Research Letters*, L19803, doi:10.1029/2007GL030135.

[5] Yoon, S.-C., et al.,2008: Ground-based Mie-Scattering Lidar Measurements of Aerosol Extinction Profiles During ABC-EAREX2005: Comparisons of Instruments and Inversion Algorithms. *J. of the meteor. soc. of Japan* ***86***, 377-396.

[6] Stephens, G. L., et al., 2002: The CloudSat Mission and the A-Train: A new dimension of space-based observations of clouds and precipitation. *Bulletin of American Meteorological Society* ***83***, 1771-1790.