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Validation of aerosol and cloud layer structures from the space-borne lidar CALIOP using Seoul National University ground-based lidar

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Abstract

We present first observationally based validations of the space-borne lidar CALIOP onboard CALIPSO satellite using coincidental observations from a ground-based SNU lidar for 3 different types of atmospheric scenes. Both lidar measurements were taken in nearly same airmass in space and time. Total attenuated backscatters at 532 nm from the two instruments show similar aerosol and cloud layer structures (the top and bottom heights) both under cloud-free conditions and in case of multi-aerosol layers underlying semi-transparent cirrus clouds. This result confirms that the CALIPSO science team algorithms of the discrimination of cloud and aerosol as well as of their layer top and base altitudes are sound. Under thick clouds conditions, only information on the cloud top (bottom) height is reliable from CALIOP (ground-based lidar) observations due to strong signal attenuations. However, simultaneous space-borne CALIOP and ground-based SNU lidar measurements complement each other and provide full information on the vertical distribution of aerosols and clouds. Discrepancies between space-borne and ground-based lidar signals are partly explained by the strong spatial and vertical inhomogeneous distributions of clouds at few kilometer horizontal scales.

1 Introduction

Space-borne active remote sensing [e.g. LITE (Lidar In-space Technology Experiment; McCormick et al., 1993), GLAS (Geoscience Laser Altimeter System; Spinhirne et al., 2005) and CALIPSO (Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations; Winker et al., 2004, 2006)] of atmospheric aerosols and clouds is the key to providing global observations that are needed to better understand a variety of aerosol-cloud-radiation-climate feedback processes (e.g. Berthier et al., 2006; Spinhirne et al., 2005). Contrary to the previously launched passive sensors, especially, the recently-launched space-based backscatter lidar Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) onboard CALIPSO provides information on the vertical distri-

ACPD

7, 11207–11222, 2007

bution of aerosols and clouds as well as on their optical and physical properties over the globe with unprecedented spatial resolution (Winker et al., 2006). Validation of CALIOP products via intercomparison with independent measurements is essential to the productions of a high quality dataset (Liu et al., 2006; Winker et al., 2006). An important current activity for CALIPSO is thus to link its measurements with those from ground-based or airborne measurements along the tracks for validations of their science products and further synergetic studies (e.g. input/validation of global-scale modeling).

This study presents first observationally based validations of space-borne lidar CALIOP profiles by comparing measurements collected by ground-based lidar at Seoul National University (SNU; 37.4579° N, 126.9520° E, 116 m above mean sea level), Seoul, South Korea. We perform direct profile-to-profile based comparisons for coincident measurement datasets of the total 532 nm attenuated backscatter signal (the sum of the 532 nm parallel and perpendicular return signals) from both space-based CALIOP and ground-based SNU lidars with focus on the magnitude of the lidar backscatter as well as the detectability of the height and thickness of aerosol and cloud layers. This validation is made for 3 different types of atmospheric scenes: (1) boundary aerosol layer under cloud-free conditions, (2) multi-aerosol layers underlying semi-transparent cirrus clouds, and (3) aerosol layer under thick tropospheric clouds.

2 Overview of the lidar measurements and the validation approach

The payload on the CALIPSO satellite is a lidar system denoted CALIOP and two other instruments (a 3-channel imaging infrared radiometer and a wide field camera). CALIOP is a nadir-pointing instrument which is built around a diode-pumped Nd:YAG laser producing linearly-polarized pulses of light at 1064 and 532 nm (with parallel and perpendicular polarizations; pulse energy 110 mJ) with a pulse repetition rate of 20.25 Hz (Vaughan et al., 2004; Winker et al., 2006). CALIOP data have different spatial resolution for different altitude regimes and wavelengths, i.e., 30 (60) m vertical and 333 (333) m horizontal between –0.5 and 8.2 km above mean sea level (a.m.s.l.), 60 (60) m vertical and 1 (1) km horizontal between 8.2 and 20.2 km a.m.s.l. at 532 nm (1064 nm in parentheses) wavelength. The CALIOP is calibrated by normalizing the return signal between 30 and 34 km a.m.s.l. Detailed descriptions can be found in CALIOP mission website (http://www-calipso.larc.nasa.gov/) and references therein.

The ground-based SNU lidar is also two wavelengths (1064 and 532 nm) with the depolarization ratio measurement at 532 nm, and is operated as part of the Asian dust network (AD-Net; http://www-lidar.nies.go.jp/AD-Net/index.html; Murayama et al., 2001) as well as the Japanese NIES lidar network (http://www-lidar.nies.go.jp; Sugimoto et al., 2006). The SNU lidar employs a Nd:YAG laser (pulse energy 20 mJ; pulse repetition rate –10 Hz) and an analog detection system. The SNU lidar makes the vertical profile from surface to 18 km every 15 min with 6 m vertical resolution. The measurement sequence of SNU lidar is such that it runs 5 min, and then stops working during the next 10 min (i.e., start from 00, 15, 30, 45 min of every h). The background noise of ground-based SNU lidar is estimated by an average of uppermost 100 data points (17.4∼18 km a.m.s.l.) for each single-shot measurement. For the purpose of CALIPSO validation, the SNU lidar has been continuously operated from March, 2006.

The validation of satellite-borne lidar by ground-based lidar system is not straight forward, because the CALIOP has very narrow swaths and carry out measurements over a significant horizontal distance during a short period of time, while the ground-based SNU lidar is localized, the only change being due to atmospheric motions. Add to this that signal attenuation by atmospheric constituents such as aerosols and clouds need to be explicitly taken into account, because ground-based SNU lidar is below aerosols/clouds looking up, but corresponding satellite-based CALIOP is above aerosols/clouds looking down.

Figure 1 represents CALIPSO ground tracks for selected 6 days in this study and the location of ground-based SNU lidar. The SNU lidar deployed in this study is uniquely suited for not only local-emitted urban and long-range transported aerosols and clouds measurements, but also validating CALIOP products because all CALIPSO flights are fortunately located within 10 km (approximately 0.1°) horizontal. CALIPSO flies over the site every 16 days (1-time per day and 1-time per night). This meets the CALIPSO validation guidelines for aerosol and cloud coincidences (Kovacs et al., 2004; Winker et al., 2004) and the recommendation for separation distances to assess ground-based validation strategies for space-borne lidar (Kovacs, 2006). Therefore, we conclude that both lidar measurements in this study were taken in nearly same airmass in space and time. To avoid huge sampling volume discrepancies due to different vertical resolution and horizontal footprint size of data between the two instruments, we averaged the closest 20 profiles of CALIOP, which is corresponding to about 6.66 km horizontal coverage and 1 s sampling duration, as shown in Fig. 1 with closed circles. 5-min averaged SNU lidar profile during the satellite overpass is used for comparison.

3 Results and Discussion

3.1 Case 1: Aerosols under clear sky

Figure 2 shows a plot of 532 nm total attenuated backscatter (β'_{532}) profiles determined by the CALIOP and the SNU lidar during a daytime flight (04:50 UTC; The local time is UTC + 9 h.) on 24 October 2006 under cloud-free conditions. Both β'_{532} profiles are derived from the calibrated, range-corrected, laser energy normalized, background noise subtracted from lidar return signal. The nearest 20 CALIOP-derived β'_{532} profiles (level 1 science product; profile ID: 134 146∼134 165) to the SNU lidar site are averaged (pink dots), and then smoothed (red line) by 300 m from surface to 8.2 km a.m.s.l. and 600 m from 8.2 to 15 km a.m.s.l. vertically. In the absence of clouds, both lidar measurements well detected typical urban planetary boundary layer (PBL) aerosols, although the signal strength of CALIOP is relatively smaller than that of ground-based SNU lidar due to the combined effects of large signal attenuation and spatial inhomogeneity of PBL aerosols along the CALIPSO track. The averages of the closest 10 β'_{532} profiles (profile ID: 134 151∼134 160) showed almost identical (not shown). Compared to the ground-based SNU lidar β'_{532} profile, relatively small variations of the CALIOP-derived β'_{532} above the boundary aerosol layer (> approximately 1.3~8 km a.m.s.l.) can be explained mostly by (*i*) an increased background noise due to sunlight, especially profiling during daytime, as revealed by the scattered dots in Fig. 2, and (*ii*) strong spatial and vertical inhomogeneous distributions of aerosols sampled along the CALIPSO overpasses at few kilometer or few hundred meter horizontal scales. Another potential factor to be considered in Fig. 2 is that the CALIOP signal might have a problem with multiple scattering in a fairly thin elevated aerosol layer, which affects the two lidar systems differently: in general, multiple scattering can be ignored for ground-based lidars, but not for satellite borne instruments, because the approximation that transmitted photons undergo only one scattering event before returning to the receiver is usually not valid for space-borne lidar (Young et al., 2006). This is also well apparent for the returned lidar signal in a clean atmosphere below cirrus clouds (see Fig. 3). A somewhat little enhanced signal between 8 and 12 km a.m.s.l. is found.

Meantime, the CALIOP aerosol/cloud layer height product (green line in Fig. 1), which is estimated by an adaptive threshold (Vaughan et al., 2004), well indicates both the top (~1.20 km a.m.s.l.) and bottom (~ 0.18 km a.m.s.l.) heights of boundary aerosol layer. This result is well corresponding with ground-based SNU lidar retrievals (1.28 km a.m.s.l. top and 0.18 km a.m.s.l. bottom), which is based on detecting the maximum gradient in the returned lidar backscattering intensity. Note that level 2 CALIOP aerosol layer products with 5 km horizontal and 60 m vertical resolutions are used in this case.

3.2 Case 2: Aerosols under thin cirrus

Figure 3 shows comparisons of β'_{532} profiles on the conditions of aerosol layer(s) underlying the semi-transparent cirrus clouds. We choose 3 different atmospheric scenes with different lidar return signal strengths as well as different layer altitudes of cirrus clouds, although the thickness of cloud layers looks similar. Contrary to aerosol layer products, in this case, the 6 profiles of the top and bottom heights of clouds products (CALIOP level 2 data 1 km horizontal grid data) were used, because 333 m horizontal resolution cloud layer level 2 product is limited up to 8.2 km altitude. Cloud/aerosol discrimination is performed using the magnitude and spectral variation of the lidar backscatter (Liu et al., 2004).

On 25 November 2006 (ascending node; CALIOP profile ID: 134 026~134 045; Fig. 3a), the strongest β'_{532} was detected from a transmissive cirrus centered around 11.2 km a.m.s.l. and a relatively weak peak was observed below approximately 1.3 km a.m.s.l., corresponding to the top of urban aerosol mixing height in Seoul metropolitan area. The thickness of cirrus layer was estimated as 580 m by the CALIPSO science team algorithm (level 2). The signal attenuation of ground-based SNU lidar was quite low due to relatively low aerosol loadings in PBL and fairly clear in free troposphere. The comparison identified that the top and base boundaries of upper tropospheric semi-transparent cirrus clouds and its β'_{532} were in excellent agreement between two lidars.

A thicker (~900 m), but having lower signal strength than Fig. 3a, cirrus cloud was observed on 21 February 2007 (descending node; CALIOP profile ID: 86 609~86 628; Fig. 3b). Three distinct aerosol layers (labeled 'A1' to 'A3') existed below cirrus cloud layer. Both lidars showed good agreements for aerosol layers, 'A1' and 'A2'. However, the signals for the bottom aerosol layer 'A3' from CALIOP, and inversely, for the cirrus cloud layer 'C' from ground-based SNU lidar were strongly attenuated. This result illustrates not only the limitations of space-borne downward-looking and ground-based upward-looking lidar measurements due to return signal attenuations, but also the complementarity between space-borne and ground-based lidar observations for providing complete vertical structures of aerosols and clouds. This will be further discussed hereafter in the case of thick clouds.

In case of 12 January 2007 (ascending node; CALIOP profile ID: 134 182~134 201; Fig. 3c), ground-based SNU lidar signal was relatively bigger than that of CALIOP for both cloud and aerosol layers. CALIOP Cloud and aerosol layer heights were identified as 7.22~8.06 km a.m.s.l. (labeled 'C') and 0.21~0.78 km a.m.s.l. (labeled 'A'), respectively. However, the ground-based SNU lidar showed a slightly different: 7.20~9.06 km a.m.s.l. (cloud) and 0.18∼1.36 km a.m.s.l. (aerosol). The SNU lidar-derived β'_{532} was enhanced above both aerosol layer 'A' (0.78∼1.36 km a.m.s.l.) and cirrus cloud layer 'C' (8.06∼9.06 km a.m.s.l.). Based on the PBL aerosol mixing heights at Seoul from other figures shown in this study, we assume that the ground-based SNU lidar measurements of aerosol signals from surface to about 1.4 km is correct. The signal discrepancy between 8.06 and 9.06 km can be explained by mis-matching of sampled airmass due to the spatial inhomogeneity of cirrus clouds and associated prevailing wind directions. CALIPSO flew over the site from southeast to northwest, in this case, whereas prevailing wind was a westerly during the CALIPSO flight (not shown).

Overall, all cases presented in Figs. 2 and 3 proof that the CALIPSO science team algorithms of the discrimination of cloud and aerosol as well as its layer top and base altitudes perform well. Meantime, compared to CALIOP signal during nighttime (e.g. 4∼8 km in Fig. 2b), the noise in daytime CALIOP profiles (e.g. 1.3∼8 km in Fig. 2a) were more distinct because of the intense solar light.

3.3 Case 3: Aerosols under thick clouds

Comparisons of vertical profiles of β'_{532} on the condition of aerosol layer underlying thick clouds in upper and middle troposphere are presented in Fig. 4. Under this condition, there were strong signal attenuations. On 24 September 2006 (descending node; CALIOP profile ID: 86 106∼86 125; Fig. 4a), CALIOP identifies two-layered cloud structures (Cs): thin cirrus clouds from 7.1 to 11.2 km and middle-tropospheric thick clouds (e.g., stratocumulus) from 4.9 to 7.1 km. The signal strength of upper cirrus cloud layer is similar to that given in Fig. 3. The top and base heights of cloud layer estimated from the ground-based SNU lidar (Cg) is 4.7 and 6.9 km, with a peak around 5.5 km. As we mentioned above, this is related with the limits of atmospheric remote sensing by using the lidar techniques. Laser emitted from the CALIOP doesn't penetrate the whole cloud layer downward, and inversely, the thick cloud layer blocks the upward penetration of the laser from the ground-based SNU lidar. Add to this that strong spatial and vertical inhomogeneous distributions of clouds at few kilometer horizontal scales are also strong candidates of discrepancy, as shown by Fig. 5. During the CALIPSO overpass, the strongest β'_{532} from middle-tropospheric thick clouds was observed over the ground-based lidar site (β'_{532} profiles from 9 to 11 in Fig. 5). Although the signal from the ground-based lidar cannot penetrate this thick cloud layer, noticeable changes of both middle-tropospheric thick cloud and thin cirrus clouds were apparent along the CALIPSO track. This result suggests paying strong attention to data analysis under cloudy conditions. The gap of cloud base heights between two lidar measurements was also consistently apparent in Fig. 5.

Similar to Fig. 4a, the CALIOP profile on 30 September 2006 (descending node; CALIOP profile ID: 86 142~86 161; Fig. 4b) showed two thin cloud layers from 8.6~9.0 km (C_s^1) and 6.8~7.6 km (C_s^2), respectively. But, the cloud layer boundaries were estimated as 4.8 and 6.2 km by the ground-based lidar (C_g^1). Dramatic aerosol layers in PBL (Ag), as shown enlarged in the bottom right inside of Figs. 4a and 4b, observed by the ground-based SNU lidar are not visible in CALIOP profile. These results indicate the limitations of space-borne downward-looking and ground-based upward-looking lidar measurements, and imply that only information on the cloud top (bottom) height is reliable from satellite-based CALIOP (ground-based SNU lidar) observations under the presence of thick clouds. As we mentioned in Sect. 3.2, however, simultaneous space-borne and ground-based lidar observations complement each other to provide full information on the height and thickness of aerosol and cloud layers.

4 Summary and Conclusion

In this study, we validated space-borne lidar CALIOP profiles using coincidental observations from a ground-based lidar at Seoul National University for 3 different types of atmospheric scenes. Both lidar measurements were taken in nearly same airmass in space and time. Total attenuated backscatters at 532 nm from the two instruments showed similar aerosol and cloud structures both under cloud-free conditions and in case of multi-layered aerosols underlying thin cirrus clouds. This result confirms that the CALIPSO science team algorithms of the discrimination of cloud and aerosol as well as its layer top and base altitudes are sound. In case of aerosol layer underlying thick tropospheric clouds, comparison results illustrated 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 lidar) observations. However, the complementarity between space-borne and ground-based lidar observations provides complete vertical structures of aerosols and clouds. Discrepancies between space-borne and ground-based lidar signals are partly explained by the strong spatial and vertical inhomogeneous distributions of clouds at few kilometer horizontal scales.

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References

Berthier, S., Chazette, P., Couvert, P., Pelon, J., Dulac, F., Thieuleux, F., Moulin, C., and Pain, T.: Desert dust aerosol columnar properties over ocean and continental Africa from Lidar in-Space Technology Experiment (LITE) and Meteosat synergy, J. Geophys. Res., 111, D21202, doi:10.1029/2005JD006999, 2006.

Kovacs, T. A., McCormick, M. P., Trepte, C. R., Winker, D. M., Garnier, A., and Pelon, J.: Coordination of quid pro quo ground-based measurements of cloud and aerosol optical properties for validation of the CALIPSO mission, Proc. SPIE Int. Soc. Opt. Eng., 5653, 281–289, 2004.

Kovacs, T.: Comparing MODIS and AERONET aerosol optical depth at varying separation distances to assess ground-based validation strategies for spaceborne lidar, J. Geophys. Res., 111, D24203, doi:10.1029/2006JD007349, 2006.

Liu, Z., Vaughan, M., Winker, D., Hostetler, C. A., Poole, L. R., Hlavka, D. L., Hart, W. D., and McGill, M. J.: Use of probability distribution functions for discriminating between cloud and aerosol in lidar backscatter data, J. Geophys. Res., 109, D15202, doi:10.1029/2004JD004732, 2004.

Liu, Z., Hu, Y., Vaughan, M., Reagan, J., Hostetler, C., Winker, D., Hunt, W., Powell, K., and Trepte, C.: Validation Of Calipso Lidar (CALIOP) Calibration. ILRC 2006, Nara, Japan, 2006.

McCormick, M. P., Winker, D. M., Browell, E. V., Coakley, J. A., Gardner, C. S., Hoff, R. M., Kent, G. S., Melfi, S. H., Menzies, R. T., Platt, C. M. R., Randall, D. A., and Reagan, J. A.: Scientific investigations planned for the Lidar In-space Technology Experiment (LITE), Bull. Amer. Meteorol. Soc., 74, 2, 205–214, 1993.

Murayma T., Sugimoto, N., Uno, K., Hagiwara, N., Liu, Z., Matsui, I., Sakai, T., Shibata, T., Arao, K., Sohn, B.J., Won, J.-G., and Yoon, S.-C.: Ground-based network observation of Asian dust events of April 1998 in East Asia, J. Geophys. Res., 106, D16, 18 345–18 360, 2001.

Spinhirne, J. D., Palm, S. P., Hart, W. D., Hlavka, D. L., and Welton, E. J.: Cloud and aerosol measurements from GLAS: Overview and initial results, Geophys. Res. Lett., 32, L22S03, doi:10.1029/2005GL023507, 2005.

Sugimoto, N., Shimizu, A. Matsui, I., Dong, X., Zhou, J., Bai, X., Zhou, J., Lee, C.-H., Yoon, S.-C. Okamoto, H., and Uno, I.: Network Observations of Asian Dust and Air Pollution Aerosols Using Two-Wavelength Polarization Lidars, ILRC 2006, Nara, Japan, 2006.

Vaughan, M., Young, S., Winker, D., Powell, K., Omar, A., Liu, Z., Hu, Y., and Hostetler, C.: Fully automated analysis of space-based lidar data: an overview of the CALIPSO retrieval algorithms and data products, Proc. SPIE, 5575, pp. 16–30, 2004.

Winker, D. M., Hunt, W. H. and Hostetler, C. A.: Status and Performance of the CALIOP Lidar. Proc. SPIE, 5575, pp. 8–15, 2004.

Winker, D. M., Pelon, J., and McCormick, M. P.: Initial Results from CALIPSO. ILRC 2006, Nara, Japan, 2006.

Young, S. A., Winker, D. M., Vaughan, M. A., and Powell, K. A.: Treatment Of Multiple-scattering Effects In Extinction Retrievals In Complex Atmospheric Scenes Probed By CALIPSO. ILRC 2006, Nara, Japan, 2006.

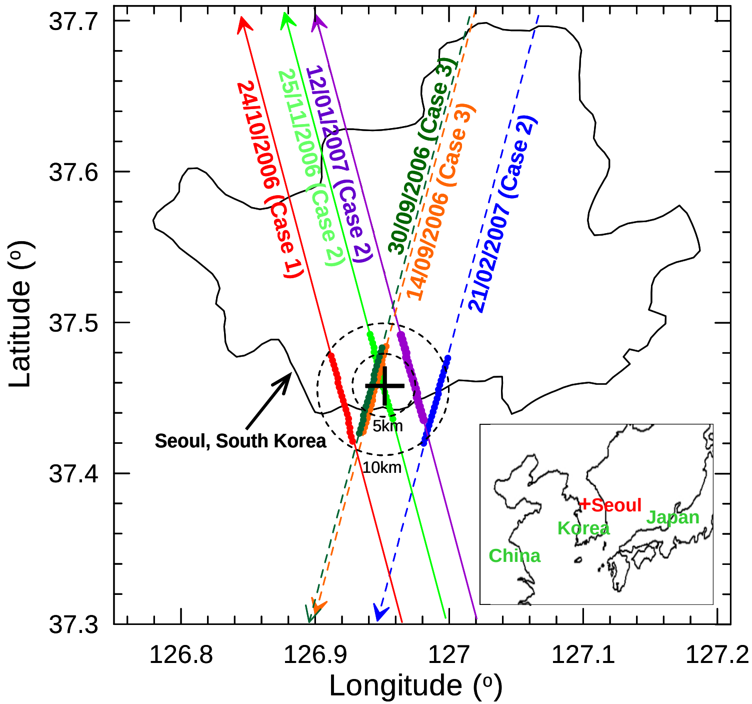

Fig. 1. Ground-based lidar monitoring station at Seoul National University (SNU, crosshair), Seoul, South Korea and CALIPSO orbit ground tracks for 6 days utilized in this study. The solid and dashed lines represent daytime ascending and nighttime descending nodes of CALIPSO orbit, respectively. The 20 CALIOP-derived profiles closest to the SNU site have been selected for comparison (closed circles). The inner (5 km) and outer (10 km) dashed circles represent the horizontal distance from the ground-based SNU lidar site. Refer to the discussion section for details the different types of cases.

ACPD
7, 11207–11222, 2007

Validation of CALIOP aerosol and cloud layer structures

S.-W. Kim et al.

EGU

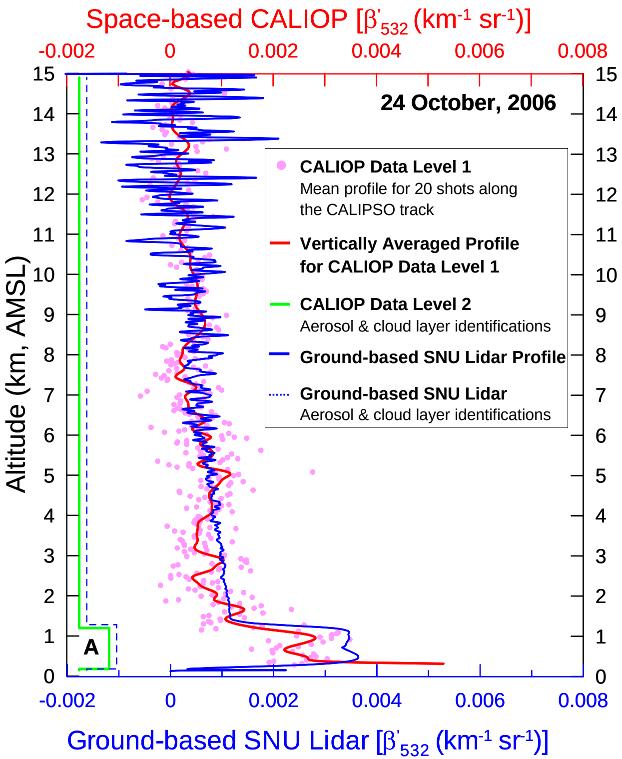

Fig. 2. Vertical profiles of total attenuated backscatter at 532 nm wavelength under cloud-free conditions were obtained from space-borne CALIOP (04:50 UTC) and ground-based SNU lidar (04:45~04:50 UTC, blue line) on 24 October 2006. The pink dots and red line are the average of CALIOP-derived 20 instantaneous profiles and its smoothed profile by 300 m vertically (600 m above 8.2 km). The green line and blue dashed line 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' indicates an aerosol layer.

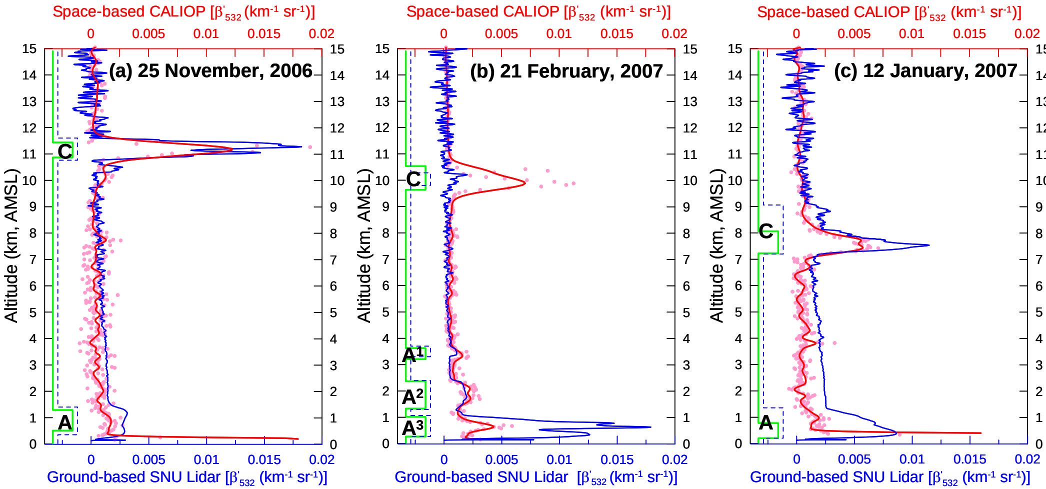

Fig. 3. Same as Fig. 2, except for the presence of a transmissive high-altitude cirrus cloud and aerosol layer in lower troposphere on 25 November 2006 (04:50 UTC), 21 February 2007 (17:41 UTC) and 12 January 2007 (04:50 UTC). The label 'A' and 'C' indicate the aerosol and cloud layers, respectively.

ACPD
7, 11207–11222, 2007

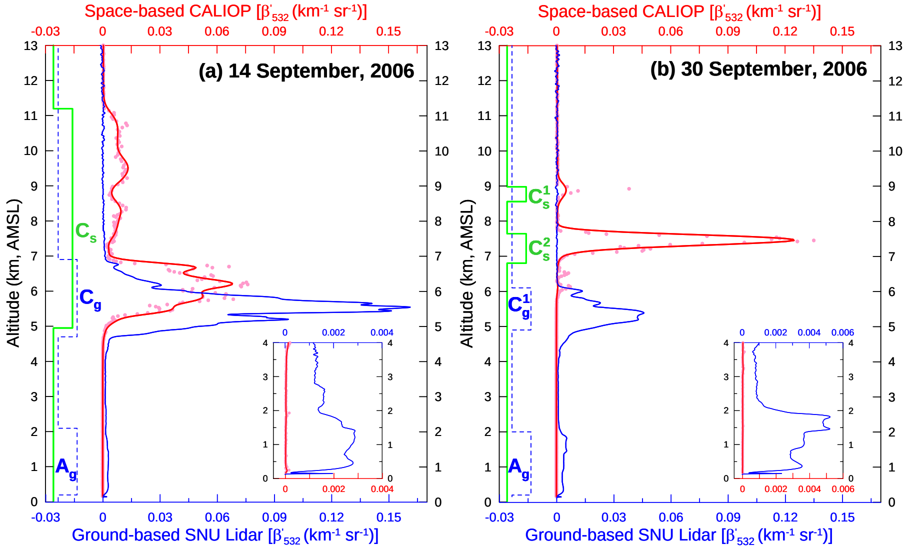

Fig. 4. Same as Fig. 2, except for the presence of middle and high altitude thick cloud and aerosol layer in lower troposphere on 14 September 2006 (17:41 UTC) and 30 September 2006 (17:41 UTC). An enlarged figure of vertical profiles below 4 km for better viewing of boundary layer aerosol is given in the bottom right inside of the figure. Subscripts "g" and "s" denote the ground-based and space-borne measurements, respectively.

ACPD

7, 11207–11222, 2007

Title Page
Abstract
Introduction
Conclusions
References
Tables
Figures
◀◀
▶▶
◀
▶
Back
Close
Full Screen / Esc
Printer-friendly Version
Interactive Discussion

EGU

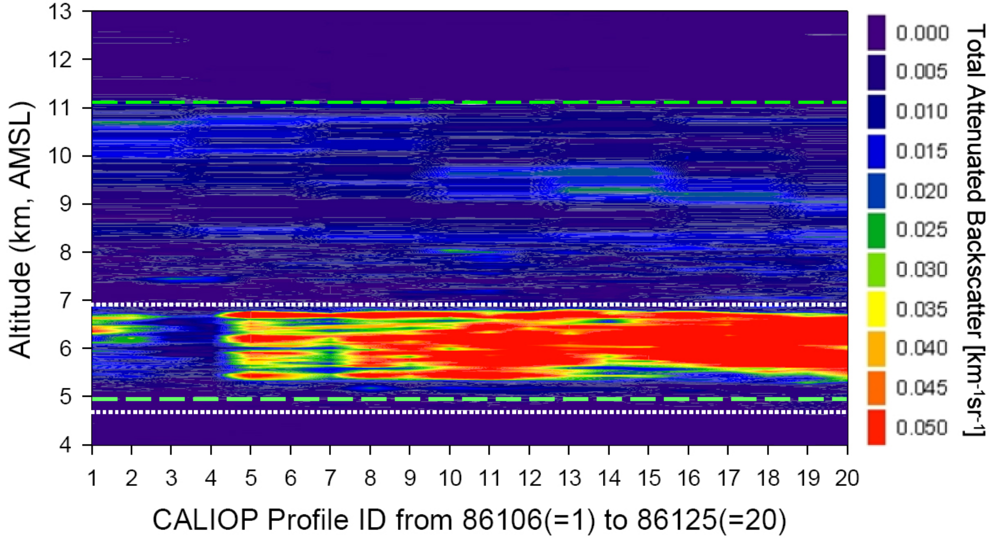

Fig. 5. The closest 20 profiles of CALIOP-derived total attenuated backscatter at 532 nm to the ground-based SNU lidar site on 14 September 2006. Dashed and long dashed lines represent the top and base of cloud heights determined by ground-based SNU lidar and CALIOP, respectively.