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Validation of CALIPSO space-borne-derived attenuated backscatter coefficient profiles using a ground-based lidar in Athens, Greece

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Abstract. We present initial aerosol validation results of the space-borne lidar CALIOP -onboard the CALIPSO satellite-Level 1 attenuated backscatter coefficient profiles, using coincident observations performed with a ground-based lidar in Athens, Greece (37.9° N, 23.6° E). A multi-wavelength ground-based backscatter/Raman lidar system is operating since 2000 at the National Technical University of Athens (NTUA) in the framework of the European Aerosol Research LIdar NETwork (EARLINET), the first lidar network for tropospheric aerosol studies on a continental scale. Since July 2006, a total of 40 coincidental aerosol ground-based lidar measurements were performed over Athens during CALIPSO overpasses. The ground-based measurements were performed each time CALIPSO overpasses the station location within a maximum distance of 100 km. The duration of the ground–based lidar measurements was approximately two hours, centred on the satellite overpass time. From the analysis of the ground-based/satellite correlative lidar measurements, a mean bias of the order of 22% for daytime measurements and of 8% for nighttime measurements with respect to the CALIPSO profiles was found for altitudes between 3 and 10 km. The mean bias becomes much larger for altitudes lower that 3 km (of the order of 60%) which is attributed to the increase of aerosol horizontal inhomogeneity within the Planetary Boundary Layer, resulting to the observation of possibly different air masses by the two instruments. In cases of aerosol layers underlying Cirrus clouds, comparison results for aerosol tropospheric profiles become worse. This is attributed to the significant multiple scattering effects in Cirrus clouds experienced by CALIPSO which result in an attenuation which is less than that measured by the ground-based lidar.

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1 Introduction

Lidar techniques play an increasing role in future Earth observation strategies. CALIOP (Cloud-Aerosol LIdar with Orthogonal Polarization), onboard the NASA/CNES CALIPSO satellite, provides a first opportunity to study in detail the performance and the scientific value of a space-borne aerosol lidar during a long-term mission. CALIPSO observations provide global, but snapshot-like view of aerosol vertical distributions. However, combined studies with ground-based lidars together with transport modeling techniques will allow full exploitation of this data for a detailed description of the temporal and spatial aerosol distribution and evolution on a global scale (Ansmann, 2006).

Space-borne active remote sensing (e.g. LITE (Lidar Inspace 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, 2007)) of atmospheric aerosols and clouds is the key for providing global vertically resolved observations that are needed to better understand a variety of aerosol-cloud radiation-climate feedback processes (e.g. Spinhirne et al., 2005; Berthier et al., 2006).

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 properties over the globe with unprecedented spatial resolution, since June 2006 (Winker et al., 2006, 2007). Validation of CALIOP products via intercomparison with independent ground-based or airborne lidar measurements is essential to the production of a high quality dataset (Liu et al., 2006; Winker et al., 2006). To our knowledge, a very small number of studies concerning CALIPSO validation exist currently in the literature, especially using ground-based coincident lidar measurements. McGill et al. (2007) have presented initial airborne validation results

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where cloud layer top determinations from CALIPSO are found to be in good agreement with those from the Cloud Physics Lidar (CPL) onboard the NASA ER-2 research aircraft. On the other hand Kim et al. (2008), have presented initial validation results of the space-borne lidar CALIOP data using coincidental observations from a ground-based lidar in Seoul located at the National University (SNU), Seoul, Korea (37.46° N, 126.95° E). Their study was based in a small number of coincident measurements (six selected cases between September 2006 and February 2007, including 3 daytime and 3 night-time observations. The authors found good agreement for the night-time CALIOP data, but relative large discrepancies were found at the height range above PBL for the daytime data, even if absolute difference values are not mentioned. They attributed the discrepancies found to the small signal-to-noise ratio of the CALIOP measurements due to contamination by solar background (McGill et al., 2007). Finally, the EARLINET lidar teams have presented some initial validation results referring to the first year of operation of the CALIOP (Mattis et al., 2007; Mona et al., 2007, 2009).

CALIPSO was launched in April 2006, and since June 2006 when CALIOP started measurements, the ground-based stations of the European Aerosol Research Lidar Network perform coincident correlative measurements for CALIPSO validation studies. EARLINET was established in 2000 to derive a comprehensive, quantitative, and statistically significant data base for the aerosol distribution on the European scale (Bösenberg et al., 2003). At present, EARLINET consists of 25 partners, including backscatter lidar stations, 16 combined backscatter/Raman lidar stations and 8 multi-wavelength Raman lidar stations which are used to retrieve the aerosol microphysical properties (Mattis et al., 2007). EARLINET follows a specific measurement strategy for CALIPSO validation, according to which, each station performs measurements each time CALIPSO overpasses the station location within a maximum distance of 100 km and 2 h (so-called “case 1” measurements). Additional measurements are performed at the lidar station which is closest to the actually overpass site (“case 2”). If a multi-wavelength Raman lidar station is overpassed, then also the next closest multiwavelenght station performs measurements as well (“case 3”) (Mattis et al., 2007). In this study we present initial validation results of the space-borne lidar CALIOP aerosol retrievals, using 40 coincident “case 1” measurements performed in Athens, Greece, with NTUA’s multi-wavelength ground-based Raman lidar. For this study, Level 1 CALIPSO data are used referring to attenuated backscatter profiles. In Sect. 2 we describe the ground-based and the space-borne instrumentation used along with the validation approach followed. Results and conclusions are presented in Sects. 3 and 4, respectively.

2 Instrumentation and methods

2.1 Description of the ground-based lidar system of NTUA

The NTUA compact 6-wavelength Raman lidar system is based on a pulsed Nd:YAG laser emitting simultaneously at 355 nm, 532 nm and 1064 nm. The respective emitted output energies per pulse are 75 mJ, 130 mJ and 140 mJ, with a 10 Hz repetition rate. The optical receiver is a Cassegrainian reflecting telescope with a primary mirror of 300 mm diameter and of focal length f=600 mm, directly coupled through an optical fiber to the lidar signal multi-channel detection box. The elastically backscattered lidar signals (at 355, 532 and 1064 nm), as well as those generated by stimulated Raman scattering by atmospheric N_2 and H_2O (at 387, 607 and 407 nm, respectively) are simultaneously recorded by photomultipliers (PMTs) and an avalanche photodiode system (APD), after the spectral separation of the returned lidar signals (Mamouri et al., 2007; Papayannis et al., 2007). The PMT detectors used are operated both in the analog and photon-counting mode and the spatial raw resolution of the detected signals is 15 m.

NTUA’s lidar is used to perform continuous measurements for the retrieval of the aerosol optical properties over Athens inside the Planetary Boundary Layer (PBL) and the lower free troposphere. The lidar signals detected at 355, 387, 532, 607 and 1064 nm are used to derive the aerosol backscatter (at 355, 532 and 1064 nm) and the extinction (at 355 and 532 nm) coefficient profiles (Ansmann et al., 1992), while the 407 nm channel is used to derived the water vapor mixing ratio profiles (Whiteman et al., 1992). NTUA lidar was successfully intercompared with the other EARLINET groups, showing on the average an agreement better than 5% for heights above 2 km in the backscatter coefficient (Matthias et al., 2004). The simultaneous measurement of the elastic backscatter signal of the emitted laser wavelengths, λ_L=355/532 nm, and the nitrogen (N_2) inelastic Raman backscatter signal at λ_R=387/607 nm allows the determination of the extinction and backscatter coefficients at 355 and 532 nm, independently of each other and thus, of the lidar ratio according to the Raman lidar method (Ansmann et al., 1992). With the present experimental setup, 355 and 532 nm Raman lidar applications are limited to nighttime because the weak inelastic backscatter signals can be detected only in the absence of the strong daylight background. The bandwidth of the interference filters that are used for the Raman signals’ detection are 0.84 nm, 3.26 nm and 1.06 nm for the wavelengths 387, 407, and 607 nm, respectively.

For the final calculation of the aerosol extinction at 355 nm and 532 nm, we first, calculate the derivative of the logarithm of the ratio between the atmospheric number density and the range-corrected lidar-received power and then we assume the value of the wavelength dependence k between the extinction coefficients for the pairs 355/387 nm and 532/607 nm. For aerosol particles with diameters comparable to the measurement wavelength, k=1 is appropriate (Ansmann et al., 1992). Thus, the error in the derived aerosol extinction profile at 355 nm due to uncertainty in k is less than 10% (Ferrare et al., 1998).

Air density and the molecular extinction coefficient profiles are calculated from the Rayleigh scattering coefficients (Bucholz, 1995) and actual radiosonde data of temperature and pressure, if available, or from a standard atmosphere model (US Standard Atmosphere, 1976) adjusted to measured ground-level temperature and pressure values. The calibration height is set in a height region with negligible particle load considered as an aerosol-free region. These clean air conditions normally prevail in the upper troposphere (8000–15 000 m). For daytime aerosol observations, only the elastic backscatter signals at 355, 532, and 1064 nm can be used. Under the assumptions about the relation between the aerosol extinction and backscatter coefficients (lidar ratio) and about the value of the backscatter coefficient at the calibration range, the lidar equation for the backscatter coefficient at the emitted wavelengths can be solved following the Klett-Fernald retrieval methods (Klett, 1981, 1985; Fernald et al., 1972; Fernald, 1984). We have to emphasize here that the backscatter solution with this method is very sensitive to the lidar ratio value, especially in cases with high aerosol optical depths.

The lidar data handling procedures that we routinely use at NTUA for the application of Fernald-Klett and Raman retrieval methods were successfully tested by two algorithm intercomparisons that took place during EARLINET (Böckmann et al., 2004; Pappalardo et al., 2004) and include error estimates for all participating groups. According to these studies the mean deviation from the solution in the determination of the backscatter coefficient with the Klett method was around 2.5% at 355 nm and 1.2% at 532 nm, while the mean deviations from the solution for extinction and backscatter calculations at 355 nm with the Raman method was around 20% and 20%, respectively and at 532 nm was around 25% and 15%, respectively for both coefficients. For the height range 2000–4000 m, the overall estimated error in the measurements is up to 15% for the extinction coefficient and up to 30% for the backscattering coefficients and the lidar ratio for both wavelengths.

Finally, we have to mention that the transmitted laser beam overlaps completely with the receiver's field of view, usually at heights around 1400 m for 355 nm and 1000 m for 532 nm and 1064 nm, because of the different geometry with which the three wavelengths are emitted in the atmosphere. A detailed description of the incomplete overlap issues of the NTUA lidar system is described by Chourdakis et al. (2002). The incomplete overlap between the laser beam and the receiver field of view significantly affects lidar observations of particle optical properties in the near-field range. At NTUA we apply an overlap correction on the basis of a simple technique proposed by Wandinger and Ansmann (2002), down to the height where the overlap function is equal to 0.5. This correction allows extending the profile in most cases down to 500 m a.s.l. However, to avoid the introduction of overlap uncertainties in ground-based profiles in this study, we are using profiles only for the complete overlap height region (above 1000 m at 532 nm).

2.2 Description of the space-borne CALIOP lidar system

The Cloud–Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO) mission (http://www-calipso.larc.nasa.gov/) is a collaborative effort between the NASA Langley Research Center (LaRC), the Centre National d'Etudes Spatiales (CNES), The Hampton University (HU), the Institut Pierre-Simon Laplace (IPSL), and Ball Aerospace and Technologies Corporation (BATC). It aims to study the global radiative effects of aerosols and clouds on climate. CALIPSO is an Earth Science observation mission that was launched on 28 April 2006. It flies at a nominal orbital altitude of 705 km and an inclination of 98° as part of a constellation of Earth-observing satellites including Aqua, PARASOL, and Aura – collectively known as the "A-train" (Hostetler et al., 2001; Stephens et al., 2003). The CALIPSO mission includes active lidar and passive sensors to obtain unique data on aerosol and cloud vertical structure, cloud particle phase and classification of the aerosol size.

The CALIPSO payload consists of three co-aligned, near-nadir viewing instruments: a 2-wavelength polarization-sensitive lidar, an imaging infrared radiometer (IIR), and a high-resolution wide field camera (WFC). CALIOP is an elastically backscattered lidar operating at 532 and 1064 nm, equipped with a depolarization channel at 532 nm that provides high-resolution vertical profiles of aerosols and clouds (Winker et al., 2007; Hunt et al., 2009). It includes two Q-switched lasers operating at 20.16 Hz with a pulse length of about 20 ns. Each laser generates nominally 220 mJ per pulse at 1064 nm, which is frequency-doubled to produce about 110 mJ of pulse energy at 532 and 1064 nm. Beam expanders reduce the angular divergence of the transmitted laser beam to produce a beam diameter of 70 m at the Earth's surface (corresponding to a nominal laser beam divergence of 100 μrad) (Hostetler et al., 2006; Hunt et al., 2009).

CALIPSO produces Level 1 and Level 2 science data products (http://www-calipso.larc.nasa.gov/products/CALIPSO_DPC_Rev2x4.pdf). The Level 1 data include lidar calibrated and geo-located profiles with associated browse imagery while the level 2 products include a cloud layer product with horizontal resolutions of 1/3 km, 1 km and 5 km (cloud height, thickness, backscatter, extinction, ice/water phase, emissivity, and ice particle size), an aerosol layer product at 5 km resolution (height, thickness, optical depth, and integrated attenuated backscatter) and an aerosol profile product with a horizontal resolution of 40 km and vertical resolution of 120 m (backscatter, extinction, and depolarization ratio). We mention here that LITE data were reported with a better vertical resolution of 15 m than ones of the CALIOP.

The Level 1 V2 (Version 2.01) attenuated backscatter profile products are used for the validation presented in this paper. Level 2 aerosol products relative to aerosol extinction profiles are not discussed here, since the lidar ratio assumption of CALIPSO algorithm for the calculation of backscatter and extinction profiles introduces an additional uncertainty that complicates the validation. Additionally, the backscatter and extinction coefficients reported in the Level 2, (version 2.01) release of the CALIPSO profile products are still unvalidated, thus are beta-quality data products. As such, they still contain a number of errors and/or inconsistencies. According to CALIPSO team, these products contain no data quality information, and hence cannot be used as stand-alone products.

2.3 Description of the validation approach

For the calculation of the attenuated backscatter coefficient from the ground-based lidar measurements in this study, the procedure suggested by Mona et al. (2007, 2009) to convert backscatter coefficients into "CALIPSO-like" attenuated backscatter is followed. A summary of the methodology is given in the following:

The total backscatter coefficient $\beta_{\text{tot}}(z)$ provided by CALIPSO is defined at each altitude z as (Hostetler et al., 2006):

$$\beta_{\text{tot}}(z) = \beta_{\text{par}}(z) + \beta_{\text{mol}}(z) \quad (1)$$

where, $\beta_{\text{mol}}(z)$ is the molecular backscatter coefficient and $\beta_{\text{par}}(z)$ is the particle backscatter coefficient.

The particle transmission term $T^2_{\text{par}}(z)$ of the lidar equation (Ansmann et al., 1992) can be obtained from the profile of the particle extinction coefficient $a_{\text{par}}(z)$:

$$T^2_{\text{par}}(z) = \exp(-2\int_z^{z_s} a_{\text{par}}(z)dz) \quad (2)$$

Finally, the attenuated backscatter coefficient, $\beta'_{\text{tot}}(z)$, is defined as:

$$\beta'_{\text{tot}}(z) = \beta_{\text{tot}}(z)T^2_{\text{par}}(z)T^2_{\text{mol}}(z)T^2_{\text{O}_3}(z) \quad (3)$$

For a downward-looking lidar as CALIOP, the attenuated backscatter coefficient is the lidar range-corrected signal normalized by a system dependent constant. To retrieve attenuated backscatter profile from NTUA's ground-based measurements, it has to be taken into account that NTUA and CALIOP transmission terms are different, because the first system is upward-looking while the second is a downward-looking lidar. However, following the above described procedure of Mona et al. (2007, 2009), the differences between the final calculated parameters due to upward and downward field of views are removed since the aerosol transmission term is calculated as a function of the aerosol extinction profile. Therefore, starting from the ground-based measurements and following this approach, the downward and upward derived attenuated backscatter coefficients are comparable without any assumptions.

Since the extinction coefficient profile has to be known, the proposed methodology by Mona et al. (2007, 2009), can be applied only for Raman ground-based lidars. Thus, for the validation purposes of this paper, only the attenuated backscatter coefficients at 532 nm (where a Raman channel is in operation) are used, since no Raman channel is operating at 1064 nm. Additionally, the extinction information needed for the transmission calculation, limits the correlative dataset only to nighttime measurements, when a Raman measurement can be performed. To overcome this limitation and since the daytime ground-based measurements of NTUA are always following nighttime measurements of the previous CALIPSO coincidental measurement (with approx. 11 h of difference), the mean lidar ratio measured for nighttime is used to convert daytime backscatter to extinction values. The influence of the extrapolation of the night time lidar ratio measurements to the daytime retrievals can be significant during cases of high atmospheric variability during the time period between the two coincident with the satellite overpasses ground based measurements. However, the finally selected dataset of 40 in the total of 87 coincident ground-based measurements that will be presented in this paper has been carefully selected, excluding days with high atmospheric variability and strong aerosol layering changes during the day (and additionally days with presence of low clouds). In our final dataset of 40 selected coincident measurements, only 12 cases are referring to daytime measurements. Daytime attenuated backscatter retrievals suffer in regard to their accuracy due to the lidar ratio assumption; however, daytime comparisons are still presented to demonstrate the importance of the increased signal noise of CALIPSO during daytime measurements (comparing with nighttime). Using the daytime datasets one can conclude about the appropriate spatial averaging of CALIPSO attenuated backscatter profiles, for validation purposes.

Finally, to remove molecular backscatter differences for the comparison needs, the calculation of the atmospheric density was based in temperature and pressure values used by the CALIPSO algorithm. Following the above described methodology for the calculation of attenuated backscatter profiles, we are essentially validating the calibration and linearity of CALIOP.

Finally, for the comparison of the coincidence CALIPSO's and NTUA's lidar profiles we are using a percentage bias calculated by the following formula:

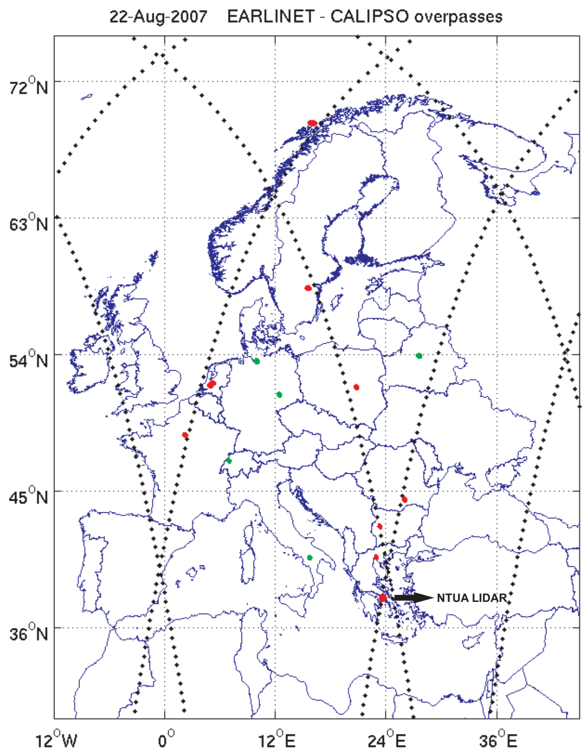

Fig. 1. NTUA's lidar station (red square) and CALIPSO ascending and descending orbits overpassing Athens (cross lines), on 22 August 2007. All the other EARLINET stations are reported as red dots for "case 1" and "case 2" and green dots for "case 3", according to CALIPSO correlative measurement strategy of EARLINET.

$$\text{bias}(z) = \frac{\text{CALIPSOat.bp(z)} - \text{G.Bat.bp(z)}}{\text{CALIPSOat.bp(z)}} \times 100 \quad (4)$$

where, CALIPSO at.bp and G.B at.bp are the satellite and the ground-based attenuated backscatter at 532 nm, respectively.

3 Results and discussion

In this paper a total of 40 coincident ground-based lidar measurements for CALIPSO overpasses over Athens for the time period between July 2006 to December 2007 are analysed. During this period, a total of 87 "case 1" correlative measurements were performed. From this dataset, 47 cases were excluded for the purposes of our aerosol concentrated analysis, due the presence of low clouds (e.g. 2–4 km a.s.l.) and high atmospheric variability during the day. The procedure followed for the analysis of the final 40 coincidential ground-based and CALIPSO profiles is first demonstrated for a specific case study in the following.

In Fig. 1, the CALIPSO overpasses (nighttime on 00:34 UT and daytime on 11:34 UT) are presented for the case study of 22 August 2007, selected for analysis demonstration purposes. The location of the ground-based station

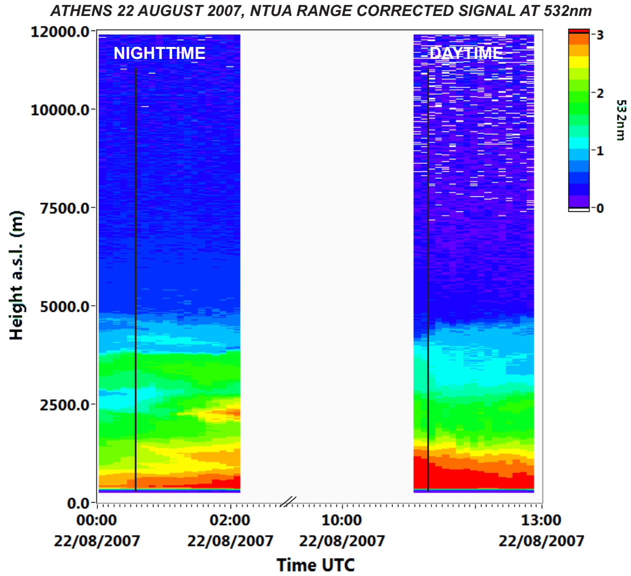

Fig. 2. NTUA's range corrected signal at 532 nm on 22 August 2007. Black lines correspond to the CALIPSO overpass time over NTUA lidar station for nighttime (00:34 UT) (left) and for daytime (11:39 UT) (right).

is presented on the map of Fig. 1 with a red square highlited with an arrow. For the daytime overpass the distance between the CALIPSO's and NTUA's lidar is of the order of 80 km, while for the nighttime overpass is 16 km. Synchronous daytime and nighttime measurements were performed by NTUA's lidar within two hours centred on CALIPSO overpass time. In Fig. 2, timeseries of the ground-based range-corrected lidar signal at 532 nm are shown for 22 August 2007, along with the overpass times of CALIPSO highlighted with black lines. This figure shows that one hour around the CALIPSO overpass time the dust atmospheric structure is quite stable for both the daytime and nighttime measurements. The attenuated ground-based backscatter profiles used for the validation purposes were calculated from range-corrected lidar signals averaged around CALIPSO overpass time for a time period of approximately 1 h. This approach was followed for the total of 40 coincidental datasets to minimize the atmospheric aerosol structure variability mainly due to evolution of the boundary layer during daytime measurements.

The CALIPSO's total attenuated backscatter at 532 nm is presented in Fig. 3 for the case study of 22 August 2007. The CALIPSO location nearest to ground-based station is superimposed (black lines). Additional vertical rectangles are plotted to indicate the distance covered by CALIPSO that corresponds to the two different horizontal resolutions that were adapted in this validation study, namely at 5 km (grey rectangle) and 20 km (black rectangle). The homogeneity of the aerosol load during these distances is confirmed by CALIPSO overpass image (Fig. 3). On 22 August 2007

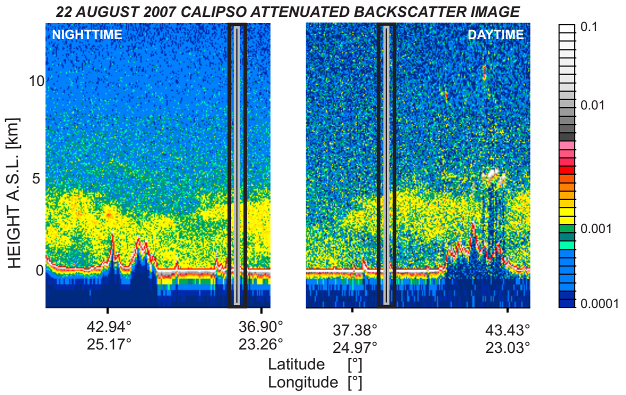

Fig. 3. CALIPSO total attenuated backscatter at 532 nm on 22 August 2007. Black lines correspond to the nearest overpass over NTUA lidar station for nighttime (00:34 UT) (left) and for daytime (11:39 UT) (right). Grey and black rectangles represent 5 km and 20 km horizontal resolution averaging period for the CALIPSO data, respectively.

a Saharan dust outbreak occured and elevated dust layers were observed by CALIPSO over European mid-latitudes, in height ranges between 2.5 and 4.5 km. The ground-based range-corrected backscatter lidar signal (Fig. 2) confirms that an aerosol load located in the height range between 2.5 and 4.0 km was also present over Athens for both the nighttime and daytime measurements above the NTUA lidar station.

In Fig. 4, the CALIPSO attenuated backscatter coefficient is plotted against the coincidental ground-based profile calculated following the approach described by Mona et al. (2007, 2009) for the measurements performed on 22 August 2007 during nighttime (left panel, top) and daytime (left panel, bottom). On the right panels of Fig. 4, the percent biases of CALIPSO to ground-truth lidar measurements with respect to CALIPSO profile for nighttime (right panel, top) and daytime (right panel, bottom) are presented. For the calculation of the percent bias, satellite and ground based lidar data were vertical averaged to 250 m bins, so the profiles from both instruments would be comparable to each other. Regarding the CALIPSO data, the attenuated backscatter profile is rather noisy and requires significant time averaging for a proper identification of the aerosol layers. For time averaging purposes, CALIPSO attenuated backscatter profiles are averaged for two selected horizontal resolutions, one for 5 km (thin grey line) and one for 20 km (thin black line). Averaging daytime CALIPSO data for 20 km distance, resulted in an improved comparison with the ground-based profile, decreasing mean bias from −16% (5 km horizontal averaging) to −8% (20 km horizontal averaging). For nighttime measurements, 5 km horizontal averaging resolution resulted in a satisfactory noise removal, showing no significant improvement when the averaging was performed for 20 km resolution.

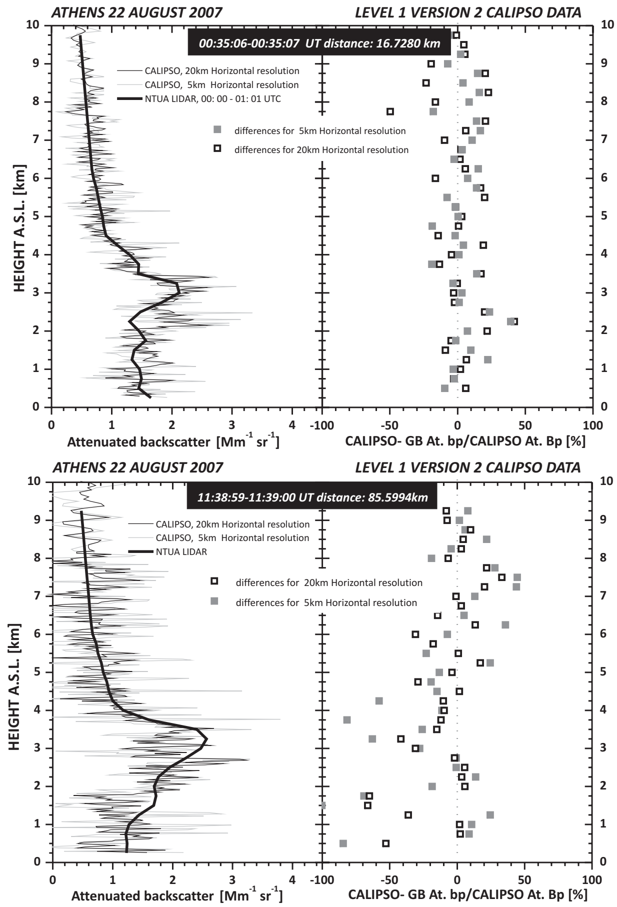

Fig. 4. CALIPSO level 1 total attenuated backscatter coefficient profiles at 532 nm for 5 km and 20 km horizontal averaging period coverage in comparison with NTUA's total attenuated backscatter coefficient (left). Percent bias binned in 0.25 km intervals (right). Nighttime overpass (top), daytime overpass (bottom).

The approach described for the case study of 22 August 2007 was followed for the analysis of the total of 40 coincidental "case 1" datasets for both 5 km and 20 km horizontal averaging of CALIPSO data. Figure 5 presents the mean percent differences between the CALIPSO and NTUA attenuated backscatter profiles for the total of our cases, grouped in 27 cases when no Cirrus were present above the aerosol layer in CALIPSO's field of view (left panel) and in 13 cases where Cirrus clouds attenuated the CALIOP's signal (right panel). Different horizontal resolutions are plotted with gray filled squares (5 km) and black open squares (20 km). It is evident that the aerosol profiles observed by both instruments are in better agreement when no Cirrus clouds are present. For the total of 27 cases of no Cirrus presence, the calculated mean biases are −26±22 % for 5 km horizontal resolution and −14±15% for 20 km, respectively. Our results indicate that CALIPSO lidar underestimates the attenuated backscatter coefficient. The underestimation becomes much

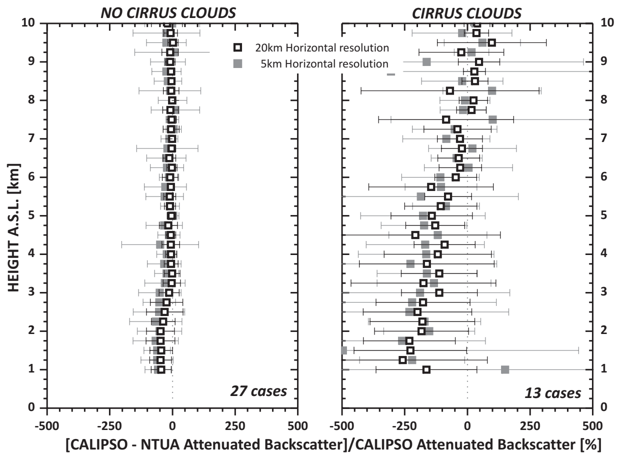

Fig. 5. Mean percent biases between CALIPSO and NTUA attenuated backscatter coefficient for cloud-free (left) and Cirrus presence (right) cases. The differences are calculated both for 5 and 20 km of the CALIPSO horizontal averaging period coverage.

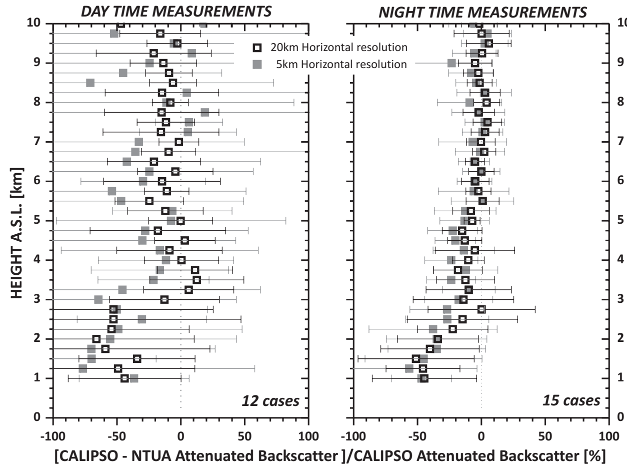

Fig. 6. Mean percent biases between CALIPSO and NTUA attenuated backscatter coefficient with respect to the CALIPSO profiles for daytime and nighttime measurements.

larger below Cirrus clouds, where from the total of 13 Cirrus cases the calculated mean biases are $-104\pm129\%$ for 5 km horizontal resolution and $-85\pm93\%$ for 20 km. The CALIPSO underestimation below Cirrus clouds is attributed mainly to the significant multiple scattering effects in Cirrus clouds experienced by CALIOP which result in an attenuation which is less than that measured by the ground-based lidar. Similarly, Kim et al. (2008), found that the only reliable information in such cases is the retrieval of the cloud top height.

From the 27 cases of no Cirrus presence, the mean percent biases of attenuated backscatter coefficient, binned into 250 m layers are presented in Fig. 6, grouped in daytime (left panel) and nighttime (right panel) measurements. The mean difference between the two instruments is larger for the daytime data. Averaging the CALIPSO data for 20 km distance, showed an improvement in the comparison, in contrary to 5 km distance. For the total of 12 daytime cases with no Cirrus presence, the calculated mean biases were found to be $-34\pm34\%$ for 5 km horizontal resolution and $-19\pm20\%$ for 20 km, respectively. For the total of 15 nighttime cases with no Cirrus presence, the calculated mean biases are $-15\pm16\%$ for 5 km horizontal resolution and $-10\pm5\%$ for 20 km. The results indicate that CALIPSO measurements have a larger diversity from ground-truth during daytime. Differences between daytime and night-time calibration procedures applied by CALIPSO algorithm could also be an explanation for the daytime discrepancies. Calibration constants are calculated over the dark side of each orbit and then interpolated on the day side (Winker, 2006). Another possible source of discrepancies between the correlative measurements during daytime could be the different free tropospheric height regions for the calibration of the two instruments. As the aerosol backscatter in stratosphere is insignificant with respect to molecular backscatter and the molecular density, exhibiting very small variations, CALIPSO's algorithm uses the height range between 30 and 34 km for signal calibration. For NTUA ground based lidar data, the calibration is performed at the height region between 7 and 9 km.

From Figs. 5 and 6, it is evidenced that the comparison differences become larger for the height ranges between 1 and 3 km. This can be attributed to the fact that free tropospheric aerosol load (for heights greater than 3 km) over Athens is lower than the anthropogenic aerosol load of the boundary layer. However, it is well documented in the literature that over Greece (Balis et al., 2003, 2004; Amiridis et al., 2005; Gerasopoulos et. al., 2006; Kazadzis et al. 2007; Amiridis et al., 2008) and especially over Athens (e.g. Papayannis et al., 2005; Papayannis et al., 2007), transboundary aerosol advection in the free troposphere is frequently observed due to the proximity of the region to the Sahara desert and regions with significant biomass burning activities. To compare the coincident CALIPSO-ground based dataset under different free tropospheric aerosol loads, we present in Fig. 7, the mean biases of attenuated backscatter coefficient for the 27 cases of no Cirrus presence, grouped in 12 (8 nighttime and 4 daytime) cases with low free tropospheric contribution (left panel) and 15 (5 nighttime and 10 daytime) cases of large free tropospheric contribution (right panel). For the total of 12 cases with low free tropospheric contribution, the calculated mean biases are $-22\pm2\%$ for 5 km horizontal resolution and $-7\pm9\%$ for 20 km. For the total of 15 cases with large free tropospheric contribution, the calculated mean biases are $-32\pm$ 57% for 5 km horizontal resolution and $-35\pm57\%$ for 20 km. For both cases presented in Fig. 7, the comparison differences become larger for the height ranges between 1 and 3 km, while the differences between the two lidars in the

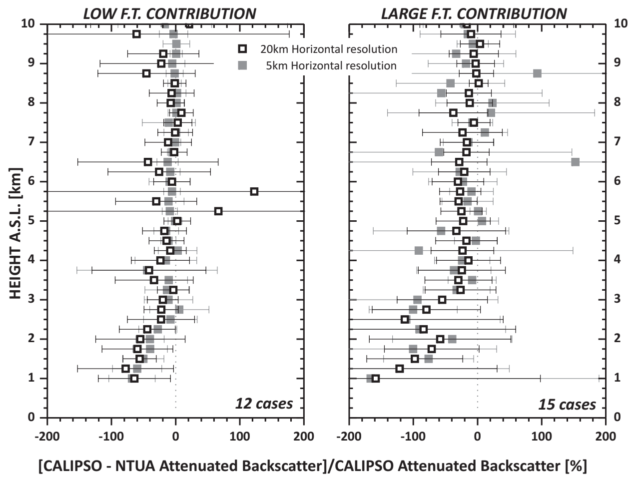

Fig. 7. Mean percent biases between CALIPSO and NTUA attenuated backscatter coefficient for low (left) and large (right) free tropospheric contribution.

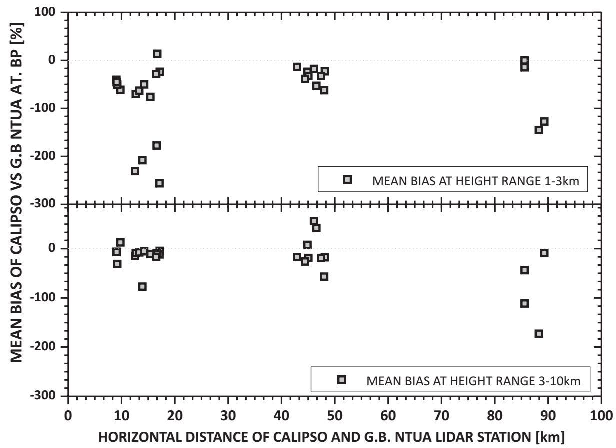

Fig. 8. Mean percent biases (1–3 km (top) and 3–10 km (bottom)) between the attenuated backscatter profiles of the two instruments, in relation with distance.

free troposphere over Athens are in good agreement. Specifically for the free troposphere over Athens, mean biases for the height range between 3 and 10 km, are −15±56% for low free tropospheric contribution and −17±47% for large free tropospheric contribution, for 5 km horizontal resolution for CALIPSO data, showing no significant difference. According to our findings, the mean biases for the height range between 1 and 3 km are of the order of −70%. These large biases are attributed to the strong aerosol horizontal inhomogeneity within the mixed layer. To investigate CALIPSO performance within the mixed layer into detail, our data had to be retrieved closer to CALIPSO ground track since the spatial matching of the two datasets becomes very critical when we study aerosol within the mixed layer.

In Fig. 8, the mean biases between CALIOP and NTUA ground-based measurements for the total of 27 correlative measurements are presented against the minimum horizontal distance between the two instruments, grouped in mean biases for the height range between 1 to 3 km (top panel) and 3 to 10 km (bottom panel). Figure 8 indicates that the distance between the two instruments is not a criterion to classify difference levels, and small distances do not guarantee better agreement between ground-based and space-borne aerosol measurements due to the fact that aerosol horizontal distributions are in the most cases inhomogeneous.

4 Summary and conclusions

In this paper, an initial CALIPSO validation study is presented using ground-based lidar measurements. CALIPSO level 1 Version 2 attenuated backscatter profiles are compared for 40 cases when coincident lidar measurements were performed by NTUA's 6-wavelength Raman lidar system. A detailed statistical analysis was presented for the total of 40 "case 1" correlative measurements performed at the NTUA station. The first categorization of the correlative dataset was based on the presence or not of Cirrus clouds below the satellite track. The mean biases for the height range between 3–10 km was found equal to −7±6% under clear skies and −53±78% in case of Cirrus presence. 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.

Under no Cirrus presence bellow the satellite track, a better agreement was found during nighttime measurements throughout the free troposphere. Specifically, an agreement of the order of −10±12% for daytime measurements and of −4±6% for nighttime measurements was found for altitudes between 3 and 10 km. The differences between 1 and 3 km were much larger (−34±34% for daytime and −15±16% for nighttime). An improvement on the agreement between CALIPSO and NTUA lidars for daytime measurements was demonstrated, when the horizontal resolution for CALIOP was increased from 5 to 20 km. The results indicated that both systems revealed similar structures above the 3 km, but the discrepancy became worse for altitudes lower than 3 km, especially during daytime. This was attributed to the increase of the horizontal aerosol inhomogeneity in case of boundary layer aerosols. For this reason, differences due to spatial mismatch of the measurements will be much larger within the mixed layer than in the free troposphere. Furthermore, the correlative measurements could deviate due to the different free tropospheric height regions used for the calibration of the signals.

Finally, the mean biases between CALIOP and NTUA ground-based measurements for the total of 27 correlative cloud-free measurements versus the minimum horizontal distance between the two instruments indicate that the distance between the instruments is not a criterion to classify difference levels, and small distances do not guarantee better agreement between ground-based and space-borne aerosol measurements due to the fact that aerosol horizontal distributions are in the most cases non-homogeneous. The EARLINET network performed more than 1000 correlative observations during the first year of operation of the space lidar CALIOP and the three-stage measurement schedule continues. In the future, NTUA lidar data will be used in synergy with other EARLINET's stations data for CALIPSO data validation on continental scale.

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