

**General comment**

The paper “CALIOP near-real-time backscatter products compared to EARLINET data”, by T.Grigas, M.Hervo, G.Gimmestad, H.Forrister, P.Schneider, J.Preißler, L.Tarrason, C.O'Dowd has been thoroughly revised based on the comments of two reviewers and two scientists expert in the domain. Although most of the comments have been properly addressed, the most crucial ones, the one raising doubts about the scientific relevance have not been entirely addressed. In my opinion there are mainly three points that have been only superficially answered:

1. The assimilation of CALIOP profiles in NWP
2. Error/uncertainty of Level 1.5 products
3. Is the improvement of 5% in R significant?

**The reviewer suggests:**

Pg 7 ln 26-29, pg 28 ln 1-6: replace the text with: “where  $\beta_{\text{par}}$  is the EARLINET particle backscatter coefficient and  $S_a$  is the particulate extinction-to-backscatter ratio, (commonly known as the LIDAR ratio). The LIDAR ratios have been extracted from the dataset of the aerosol types identified in the CALIOP Level 1.5. The reason why these values have not been taken directly from the EARLINET dataset is that only a limited number of LIDAR ratios were available for the coincident measurements. In fact, this number is significantly reduced by the fact that a LIDAR needs to be equipped with a Raman channel for the independent extinction profile measurements, and these measurements are normally available only during night-time because of low signal-to-noise ratio during daytime.”

*Response: the text have been altered as suggested by the reviewer*

**The reviewer's comment on point 1**

The authors have added a sentence in the abstract to justify the fact that the NWP assimilation objective is somehow missing in the study. But the way the abstract has been revised is not appropriate. It sounds like the authors were saying that they were motivated to provide the tools and recommendations how to assimilate CALIOP profiles into NWP, but then they just stopped and did something less challenging. Shall this manuscript be published it cannot be delivered with such a message in the abstract. I suggest that the authors provide a more detailed explanation in the introduction instead of the abstract if they feel like the information is really needed, otherwise that they simply describe what they have done and not what they would have liked to do but that they could not do.

Besides, the abstract remains poorly “attractive”. As highlighted in my first review I wonder whether a 5% improvement in the PBL correlation coefficient is the best achievement of this study.

*Response 1: we have altered the abstract as suggested by the reviewer*

The expedited near-real-time Level 1.5 Cloud-Aerosol Lidar (Light Detection and Ranging) with Orthogonal Polarization (CALIOP) products version 3 were evaluated against data from the ground-based European Aerosol Research Lidar Network (EARLINET). The statistical framework and results of the three-year evaluation of 48 CALIOP overpasses with ground tracks within a 100 km distance from operating EARLINET stations are presented and include analysis for the following CALIOP classifications of aerosol type: dust, polluted dust, clean marine, clean continental, polluted continental, mixed and/or smoke/biomass burning. For the complete dataset comprising both the

planetary boundary layer (PBL) and the free troposphere (FT) data, the correlation coefficient ( $R$ ) was 0.86. When the analysis was conducted separately for the PBL and FT, the correlation coefficients were  $R=0.6$  and  $R=0.85$ , respectively. From analysis of selected specific cases, it was initially thought that the presence of FT layers, with high attenuated backscatter, led to poor agreement of the PBL backscatter profiles between the CALIOP and EARLINET and prompted a further analysis to filter out such cases; however, removal of these layers did not improve the agreement as  $R$  reduced marginally from  $R=0.86$  to  $R=0.84$  for the combined  $R=PBL$  and  $R=FT$  analysis; increased marginally from  $R=0.6$  up to  $R=0.65$  for the PBL on its own, and decreased marginally from  $R=0.85$  to  $R=0.79$  for the FT analysis on its own. This suggests considerable variability, across the dataset, in the spatial distribution of the aerosol over spatial scales of 100 km or less around some EARLINET stations rather than influence from elevated FT layers. For specific aerosol types, the correlation coefficient between CALIOP backscatter profiles and the EARLINET data ranged from  $R=0.37$  for polluted continental aerosol in the PBL, to  $R=0.57$  for dust in the FT.

***Response 2: The conclusions have been also changed to:***

While it was suspected that the presence of high-concentration layers in the FT affected the agreement between CALIOP and EARLINET, after filtering out these cases with notable FT aerosol layers, no real improvement in the correlation coefficient was observed. This suggests that the lack of a high correlation between the datasets is more likely due to variability in the distribution of aerosols across the 100 km area selected around the EARLINET stations.

***The reviewer's comment on point 2.***

Regarding the uncertainty and the error evaluation of Level 1.5, as raised by Lucia Mona, nothing or very little has been done. Apart from equation 1 the error and the uncertainty of the Level 1.5 product has not been properly discussed in the manuscript.

Comments 37 and 79 were also aimed at a better definition of the error and possibly of a use of RMSE on top of the FoE.

***Response:***

Equation (1) is embedded in a 12-line paragraph that presents a top-level description of the Level 1.5 data product and provides a reference to a NASA publication. We refer, in this paper, to a total of eight NASA publications. The reason for this is that the questions of CALIOP data uncertainties and bias errors have been addressed extensively over the past nine years; the interested reader can become fully informed by reading those references. That work was mostly with Level 2 data, but we described the differences between Level 2 and Level 1.5 data processing, as well as our spatial averaging (both horizontal and vertical). The paper by Burton et al. (2013) shows that excellent agreement with CALIOP can be obtained by under-flying the CALIPSO satellite with an appropriate lidar, but years of ground-based comparisons have not shown such agreement, and so the results in our paper do not add new knowledge on the topic of CALIOP data uncertainties and bias errors. This fact was not obvious at the start of our study, but EARLINET investigators have recently reached a similar conclusion (private communication with Ulla Wandinger at an AEOLUS cal-val workshop, 2015).

***The reviewer's comment on point 3.***

Unfortunately the authors have not directly answered to this point.

***Response:***

The reviewer questions whether the improvement of 5% in  $R$  is significant, and he says that "... listing out all correlation coefficients in the abstract is not that interesting." We are confident that the inclusion of those numbers in the abstract is appropriate for a statistical study. We do not claim anywhere that a change in  $R$  from 0.60 to 0.65 is significant; the point is that we tried a data filtering approach and it led to only a minor improvement. Please see also the response to comment Nr.1.

# CALIOP near-real-time backscatter products compared to EARLINET data

T.Grigas<sup>1</sup>, M.Hervo<sup>1\*</sup>, G.Gimmestad<sup>2</sup>, H.Forrister<sup>2,\*\*</sup>, P.Schneider<sup>3</sup>, J.Preißler<sup>1</sup>,  
L.Tarrason<sup>3</sup>, C.O'Dowd<sup>1</sup>

<sup>1</sup>School of Physics and Centre for Climate and Air Pollution Studies, Ryan Institute, National  
University of Ireland Galway, Galway, Ireland

<sup>2</sup>Electro-Optical Systems Laboratory, Georgia Tech Research Institute, Georgia Institute of  
Technology, 225 North Avenue, Atlanta, Georgia 30332, USA

<sup>3</sup>NILU – Norwegian Institute for Air Research, P.O. Box 100, 2027 Kjeller, Norway

\* now at: Federal Office of Meteorology and Climatology, MeteoSwiss, Payerne 1530,  
Switzerland

\*\* now at: School of Earth and Atmospheric Sciences, Georgia Institute of Technology, 225  
North Avenue, Atlanta, Georgia 30332, USA

Correspondence to: T.Grigas (tomas.grigas@nuigalway.ie)

## Abstract

The expedited near-real-time Level 1.5 Cloud-Aerosol Lidar (Light Detection and Ranging) with Orthogonal Polarization (CALIOP) products version 3 were evaluated against data from the ground-based European Aerosol Research Lidar Network (EARLINET). The statistical framework and results of the three-year evaluation of 48 CALIOP overpasses with ground tracks within a 100 km distance from operating EARLINET stations are presented and include analysis for the following CALIOP classifications of aerosol type: dust, polluted dust, clean marine, clean continental, polluted continental, mixed and/or smoke/biomass burning. For the complete dataset comprising both the planetary boundary layer (PBL) and the free troposphere (FT) data, the correlation coefficient ( $R$ ) was 0.86. When the analysis was conducted separately for the PBL and FT, the correlation coefficients were  $R=0.6$  and  $R=0.85$ , respectively. From analysis of selected specific cases, it was initially thought that the presence of FT layers, with high attenuated backscatter, led to poor agreement of the PBL backscatter profiles between the CALIOP and EARLINET and prompted a further analysis to filter out such cases; however, removal of these layers did not improve the agreement as  $R$  reduced

marginally from  $R=0.86$  to  $R=0.84$  for the combined PBL and FT analysis; increased marginally from  $R=0.6$  up to  $R=0.65$  for the PBL on its own, and decreased marginally from  $R=0.85$  to  $R=0.79$  for the FT analysis on its own. This suggests considerable variability, across the dataset, in the spatial distribution of the aerosol over spatial scales of 100 km or less around some EARLINET stations rather than influence from elevated FT layers. For specific aerosol types, the correlation coefficient between CALIOP backscatter profiles and the EARLINET data ranged from  $R=0.37$  for polluted continental aerosol in the PBL, to  $R=0.57$  for dust in the FT. The study was motivated by the desire for data assimilation, but the outcome is a description of a methodology that we developed for doing a large statistical study and applying it to a level 1.5 data product, along with statistical results. Over a period of three years, lidar data from 48 CALIOP overpasses with ground tracks within a 100 km distance from an operating EARLINET station were deemed suitable for analysis and they included a valid aerosol type classification (e.g. dust, polluted dust, clean marine, clean continental, polluted continental, mixed and/or smoke/biomass burning). For the complete dataset comprising both the planetary boundary layer (PBL) and the free troposphere (FT) data, the correlation coefficient was 0.86, and when separated into separate layers, the PBL and FT correlation coefficients were 0.6 and 0.85 respectively. The presence of FT layers with high attenuated backscatter led to poor agreement in PBL backscatter profiles between the CALIOP and EARLINET measurements and prompted a further analysis filtering out such cases. However, the correlation coefficient value for the complete dataset decreased marginally from 0.86 to 0.84 while the PBL coefficient increased from 0.6 up to 0.65 and the FT coefficient also decreased from 0.85 to 0.79. For specific aerosol types, the correlation coefficient between CALIOP backscatter profiles and ground-based lidar data ranged from 0.37 for polluted continental aerosol in the PBL to 0.57 for dust in the FT. The results suggest different levels of agreement based on the location of the dominant aerosol layer and the aerosol type.

## 1 Introduction

Aerosols have an impact on the global radiative budget directly via scattering and absorbing incoming and reflected solar Radiation, and indirectly, via the modification of cloud microphysical properties that lead to changes in cloud radiative properties along with cloud lifetimes (Haywood et al., 2003; Yu et al., 2006). Lidar is a very useful technique for characterising the vertical dispersion of aerosol plumes through examination of the

1 backscatter signal and aerosol properties such as shape, from the depolarization channel, that  
2 can elucidate particle composition, in particular, for Saharan dust or volcanic ash plumes  
3 (Groß et al., 2010; Papayannis et al., 2002). Several research programmes in Europe  
4 performed routine long-term observations of the optical properties of different aerosol types  
5 (Giannakaki et al., 2009; Mattis et al., 2004, 2008); however, such studies were typically  
6 limited to single geographical locations. In order to study aerosol transport on a larger spatial  
7 scale, lidar networks are deployed (Bösenberg et al., 2003; Pappalardo et al., 2014), in  
8 conjunction with space borne platforms. In 2000, EARLINET was established to provide a  
9 comprehensive statistically representative data set of the aerosol vertical distribution. At  
10 present, 27 European stations contribute to this network by performing the measurements few  
11 times per week according to the schedule (Pappalardo et al., 2014). There are other lidar  
12 networks and one of them is the NASA Micro-Pulse Lidar Network (MPLNET). 21  
13 permanent stations of this network are deployed worldwide from the Arctic to the Antarctic  
14 regions, which continuously measure aerosol and cloud vertical structure day and night (Lolli  
15 et.al., 2014). Besides, there is the Global Atmosphere Watch (GAW) Aerosol Lidar  
16 Observation Network (GALION), which is based on the cooperation between existing lidar  
17 networks: the Latin America Lidar Network (ALINE), the Asian Dust and Aerosol Lidar  
18 Observation Network (AD-Net), the Commonwealth of Independent States (CIS) Lidar  
19 Network (CIS-LINET), the Canadian Operational Research Aerosol lidar Network  
20 (CORALNet), EARLINET, the Network for the Detection of Atmospheric Composition  
21 Change (NDACC), the Regional East Atmospheric Lidar Mesonet (REALM/CREST), and  
22 MPLNET. Global coverage may be achieved by using satellite-based lidar systems and  
23 striving towards such an aim, the National Aeronautics and Space Administration (NASA), in  
24 collaboration with the French space agency Centre National d'Etudes Spatiales (CNES),  
25 developed a satellite-based lidar system called CALIOP, which is on board the CALIPSO  
26 satellite platform (Omar et al., 2009; Vaughan et al., 2011). CALIOP performs measurements  
27 simultaneously at wavelengths of 532 nm and 1064 nm. The CALIPSO satellite was launched  
28 into orbit in April 2006 and is part of the A-Train constellation of scientific satellites  
29 dedicated to observations of the atmosphere (Stephens et al., 2002). It follows a sun-  
30 synchronous polar orbit of 705 km altitude and has a 16 day repeat cycle.

31 The EARLINET community has performed several comparisons with CALIOP data since its  
32 launch in April 2006 (Mattis et al., 2007; Pappalardo et al., 2010) using CALIOP overpasses  
33 with ground tracks within 100 km from EARLINET stations. Several studies inter-comparing

1 CALIOP Level 1 and Level 2 data with the ground-based measurements were performed in  
2 recent years (Mamouri et al., 2009; Molero and Pujadas, 2008; Pappalardo et al., 2009, 2010).  
3 Pappalardo et al., (2010) found good agreement between the 532 nm CALIOP Level 1  
4 attenuated backscatter and EARLINET measurements with a relative mean difference of  
5 4.6 % and a relative standard deviation (SD) of 50 %. The attenuated backscatter was used  
6 only from those EARLINET stations that provided independent extinction measurements.  
7 That allowed (a) calculating the lidar ratio and (b) converting EARLINET backscatter into  
8 attenuated backscatter as seen from space at 532 nm without any assumptions. The correlation  
9 coefficient as a function of the CALIOP ground track offset distances was assessed as well.  
10 The correlation coefficient  $R = 0.9$  was found for distances smaller than 100 km, while it  
11 decreased rapidly with larger distances. The mean bias between the CALIOP Level 1 and  
12 EARLINET Athens station's measurements as assessed by Mamouri et al., (2009) for daytime  
13 measurements was 22 %, and for night-time measurements, 8 %. In this study, the  
14 measurements were averaged approximately for two hours and were centred on the CALIOP  
15 overpass time. Mona et al., (2009) found a mean difference of  $(-2 \pm 12)$  % between data from  
16 the EARLINET station in Potenza and CALIOP Level 1 measurements within the 3–8 km  
17 altitude range, while the mean difference of the measurements within the PBL was equal to  
18  $(-24 \pm 20)$  %. The influence of the presence of cirrus clouds on the measurements was  
19 assessed in a study by Mamouri et al., (2009). The mean biases without cirrus clouds were  
20  $-26 \pm 22$  % for 5 km horizontal resolution and  $-14 \pm 15$  % for 20 km; the biases were higher in  
21 cirrus cases with  $-104 \pm 129$  % for 5 km horizontal resolution and  $-85 \pm 93$  % for 20 km.

22 Assimilation of the CALIOP Level 1 data product into atmospheric models has been carried  
23 out successfully in the past using an ensemble Kalman filter (Sekiyama et al., 2010).  
24 However, processed CALIOP Level 1 and Level 2 data products are generally only available  
25 several days after acquisition at the earliest, thus severely limiting their use for operational  
26 data assimilation. An expedited CALIOP Level 1.5 near-real-time (NRT) product, usually  
27 provided between 6 and 30 hours after downlink, has been made available by NASA for  
28 purposes of operational forecasting since November 2010 (Vaughan et al. 2011). Level 1.5 is  
29 derived by cloud-clearing level 1 attenuated backscatter profiles using the Level 2 vertical  
30 feature masks, and then spatially averaging the cloud-cleared profiles. Level 1.5 expedited  
31 products uses a simplified calibration scheme compared to Levels 1 and 2. Also, it is derived  
32 by using the Global Modelling and Assimilation Office (GMAO) molecular model number  
33 densities, which can be occur to be out of date (sometimes by as much as two days). As a

1 result, the scientific quality of the expedited data compared to the standard CALIOP products  
2 can be degraded. In Level 1.5 dataset, the FT is limited by 20 km.

3 The European Centre for Medium-Range Weather Forecasts (ECMWF) is currently  
4 evaluating the potential use of an expedited CALIOP Level 1.5 data product (the total  
5 attenuated backscatter profile) for assimilation into their global forecasting model IFS-  
6 MOZART (A. Benedetti, ECMWF, personal communication, 2014) under the Monitoring  
7 Atmospheric Composition and Climate (MACC) project. A similar idea of using ground-  
8 based lidar measurements in the model assimilation was implemented in a study by Wang et  
9 al., (2013). They found that the root mean square error (RMSE) of  $PM_{10}$  concentrations  
10 declined by 54 % when the lidar measurements were used in the assimilation. This indicates  
11 the importance of evaluating the CALIOP Level 1.5 data by inter-comparing them with  
12 ground-based measurements. The inter-comparison of the 532 nm wavelength attenuated  
13 backscatter profiles between CALIOP and EARLINET reported here was performed for  
14 coincident daytime and night-time measurements.

## 15 **2 Data and methodology**

16 The CALIOP instrument directly measures the vertical profile of the total (molecular plus  
17 aerosol) attenuated backscatter as seen from above the atmosphere, with a spatial resolution of  
18 30 m vertically and 333 m horizontally (Winker et al., 2009). This Level 0 raw data is  
19 averaged both horizontally and vertically before it is downlinked to the NASA Langley  
20 Research Centre (LaRC) where the scientific data products of the various levels are produced  
21 (Level 1, Level 1.5, Level 2 and Level 3). The vertical resolution for this Level 0 varies from  
22 30 m (-0.5 km to 8.2 km) up to 300 m (30.1 km to 40 km), while the horizontal resolution  
23 varies from 333 m (-0.5 km to 8.2 km) up to 5 km (30.1 km to 40 km) (Powell et al., 2010).

24 CALIOP has an automatic aerosol classification algorithm that uses altitude, location, surface  
25 type, volume depolarization ratio  $\delta_v$ , and integrated attenuated backscatter  $\gamma'$  at 532 nm to  
26 determine the aerosol type (Burton et al., 2013; Omar et al., 2009). The algorithm detects six  
27 main aerosol types: clean marine, polluted dust, dust, polluted continental, clean continental  
28 and smoke/burning biomass. Such aerosol type detection is implemented in Level 2 aerosol  
29 subtyping algorithm. Level 1.5 product does report feature types having the designation “clear  
30 air” and “mixed aerosol”. The first type is used to describe range bins absent of detected  
31 features while the second type is used if the 20 km horizontal averages contain more than one



1 of the six CALIOP aerosol types. The Level 2 vertical feature mask provides information on  
2 cloud and aerosol layers as well as the type of aerosol in each identified layer.

3 The Level 1.5 product is derived by spatially averaging 60 individual Level 1 lidar profiles  
4 and merging them with the Level 2 vertical feature mask product. It has a spatial resolution of  
5 20 km horizontally and 60 m vertically and it is restricted to the altitude range -0.5 to 20 km  
6 (Powell et al., 2010). The main Level 1.5 parameters used in this work are latitude, longitude,  
7 profile UTC time, mean total attenuated backscatter profile at 532 nm, SD of the total  
8 attenuated backscatter for 532 nm, total attenuated backscatter uncertainty for 532 nm  
9 (CALIPSO Quality Statements, 2011, p.02), L2 feature type, and lidar ratio, along with the  
10 Rayleigh extinction and backscatter cross sections for the molecular atmosphere at 532 nm.

11 The CALIOP uncertainties of the attenuated backscatter (CALIPSO Quality Statements,  
12 2011) are calculated using the equation

$$\sigma_{\mu} = \frac{1}{N} \sqrt{\sum_{i=1}^N \sigma_i^2}, \quad (1)$$

14 where  $\sigma_i$  is the attenuated backscatter uncertainty at the range bin  $\mu$  and  $N$  is the number of  
15 Level 1 profile range bins.

16 EARLINET was chosen as the reference network for this inter-comparison. At present, this  
17 network is one of the most sophisticated lidar networks in the world. The ground-based lidar  
18 measurements used in this study were acquired from the EARLINET portal  
19 [www.EARLINET.org](http://www.EARLINET.org) for the period from November 2010 to December 2012 as well as for  
20 several days in April and May 2010 during the Eyjafjallajökull volcano eruption. The aerosol  
21 backscatter coefficient profiles with uncertainties were provided in each of the EARLINET  
22 files. The EARLINET profiles were averaged over the time interval which varied between  
23 30 min and 2 hours. CALIOP-EARLINET inter-comparisons were only considered for  
24 coincident overpasses, defined as having a CALIOP ground track within a 100 km distance  
25 from the EARLINET station. The backscatter coefficients provided by EARLINET were  
26 converted into total attenuated backscatter values using the method described below.

27 The CALIOP instrument directly measures profiles of the total attenuated backscatter as seen  
28 from space, and NASA provides them in the Level 1.5 data set. These profiles were chosen  
29 for the inter-comparison in order to assess CALIOP measurements. The EARLINET stations  
30 produce aerosol backscatter coefficients and so the two different backscatter coefficients

1 cannot be inter-compared directly. For this reason, a method similar to that of Mona et al.,  
 2 (2009) was adopted for converting the EARLINET particulate backscatter coefficients into  
 3 total attenuated backscatter values as observed from space, thus allowing for a valid inter-  
 4 comparison of CALIOP and EARLINET measurements. The following equations were used  
 5 to calculate EARLINET attenuated backscatter. The total attenuated backscatter  $\beta_{att}(z)$  at  
 6 altitude  $z$  is given by

$$7 \quad \beta_{att}(z) = T^2(z)\beta_{tot}(z), \quad (2)$$

8 where  $T^2(z)$  is the two-way transmittance from the lidar in space down to the altitude  $z$ , and  
 9  $\beta_{tot}$  is the total backscatter coefficient, defined as

$$10 \quad \beta_{tot}(z) = \beta_{par}(z) + \beta_{mol}(z), \quad (3)$$

11 where  $\beta_{par}$  is the particulate (aerosol) backscatter coefficient, and  $\beta_{mol}$  is the molecular  
 12 backscatter coefficient.

13 In order to calculate the total backscatter coefficient  $\beta_{tot}$ , the EARLINET particulate  
 14 backscatter coefficient is used as  $\beta_{par}$  in Eq. (3) and the molecular backscatter coefficient  $\beta_{mol}$   
 15 is calculated from the atmospheric temperature and pressure profiles (Sissenwine et al., 1962).  
 16 The molecular backscatter and extinction cross sections for air appropriate for CALIOP are  
 17 given in NASA documentation by Powell et al., (2010) as  $5.167 \times 10^{-31} \text{ m}^2$  and  $5.930 \times 10^{-32}$   
 18  $\text{m}^2 \text{ sr}^{-1}$  respectively. Using the methods of Bucholtz et al (1995), the molecular number  
 19 density  $N_s$  in standard air (defined at reference atmospheric pressure  $P_s = 1013.25 \text{ mbar}$  and  
 20 temperature  $T_s = 15 \text{ }^\circ\text{C}$ ) is  $2.54743 \times 10^{25} \text{ mol. m}^{-3}$ , so (assuming that the atmospheric  
 21 equation of state is accurately represented by the ideal gas law) the molecular backscattering  
 22 coefficient at any altitude  $h$  is given by

$$23 \quad \beta_{mol}(h) = \sigma_{back} N_s \frac{P(h)T_s}{P_s T(h)} \quad (4)$$

24 where  $\sigma_{back}$  is the backscatter cross section given above, and  $P(h)$  and  $T(h)$  are the pressure  
 25 and the temperature of standard atmosphere. The two-way transmittance for a downward-  
 26 looking lidar is calculated using the following equation:

$$27 \quad T^2(z) = \exp[-2 \int_{top}^z \alpha(z') dz'], \quad (5)$$

1 where  $top$  is the highest altitude of the profile (nominally 20 km), and  $\alpha(z)$  is the total  
2 extinction coefficient, which is the sum of the particle extinction coefficient  $\alpha_{par}$  and the  
3 molecular extinction coefficient  $\alpha_{mol}$ .

4 The particle extinction coefficient  $\alpha_{par}$  is calculated according to

$$5 \quad \alpha_{par} = S_a \beta_{par}, \quad (6)$$

6 where  $\beta_{par}$  is the EARLINET particle backscatter coefficient and  $S_a$  is the particulate  
7 extinction-to-backscatter ratio, (commonly known as the lidar ratio). The lidar ratios  $S_a$  have  
8 been extracted from the dataset of the aerosol types identified in the CALIOP Level 1.5. The  
9 reason why these values have not been taken directly from the EARLINET dataset is that only  
10 a limited number of lidar ratios  $S_a$  were available for the coincident measurements. In fact,  
11 this number is significantly reduced by the fact that a lidar needs to be equipped with a  
12 Raman channel for the independent extinction profile measurements, and these measurements  
13 are normally available only during night-time because of low signal-to-noise ratio during  
14 daytime. The lidar ratios are provided by EARLINET stations only for a small fraction of the  
15 coincident measurements. The reason is that the lidar system needs to be equipped with a  
16 Raman channel for independent extinction profile measurements, and these measurements are  
17 available only during night time because of low signal to noise ratio during daytime.  
18 Therefore, the lidar ratios used in this study correspond to the aerosol types identified in the  
19 CALIOP Level 1.5 data set. The extinction coefficients  $\alpha_{par}$  were estimated from the  
20 EARLINET backscatter coefficients  $\beta_{par}$  by using Eq. (6), where the lidar ratios  $S_a$  were  
21 extracted from CALIOP.

22 After calculating the terms  $\alpha_{mol}$  and  $\alpha_{par}$ , the transmittance was derived using Eq. (5) and the  
23 EARLINET total attenuated backscatter profile was calculated using Eq. (2).

24 The methodology described in this section uses the CALIOP derived information (lidar ratio  
25  $S_a$ ) for converting the EARLINET particle backscatter coefficient into total attenuated  
26 backscatter, so the EARLINET derived products are not independent from CALIPSO ones.

27 In order to reduce the noise in the CALIOP signal (especially during daytime), the five  
28 profiles of the CALIOP total attenuated backscatter closest to the EARLINET station were  
29 averaged and then compared to the total attenuated backscatter of the EARLINET station. All  
30 of our CALIOP data points therefore correspond to spatial averages 100 km in length along  
31 the ground tracks, centered at the points of closest approach to the EARLINET stations.

1 To enable direct comparisons, the altitude scales of the EARLINET lidar profiles were  
 2 adjusted to be the same as that of CALIOP (above mean sea level) at 60 m vertical spacing. In  
 3 this way we obtained pairs of values at each altitude, referred to here as “data points”, for  
 4 each overpass.

5 In this work, the total attenuated backscatter for CALIOP ( $\beta_{att.CAL}$ ) and EARLINET ( $\beta_{att.EARL}$ )  
 6 are compared. In order to quantify the agreement between CALIOP and EARLINET  
 7 measurements, the correlation coefficient, the mean bias, and the factor of exceedance are  
 8 used (Kristiansen et al., 2012). Their defining equations are provided below.

9 The correlation coefficient  $R$  is defined in the usual way as

$$10 \quad R = \frac{\sum_{i=1}^N (\beta_{att.CAL_i} - \overline{\beta_{att.CAL}}) (\beta_{att.EAR_i} - \overline{\beta_{att.EAR}})}{\sqrt{\sum_{i=1}^N (\beta_{att.CAL_i} - \overline{\beta_{att.CAL}})^2} \sqrt{\sum_{i=1}^N (\beta_{att.EAR_i} - \overline{\beta_{att.EAR}})^2}}, \quad (7)$$

11  $R$  shows the strength of a linear relationship between the CALIOP and EARLINET values. It  
 12 ranges from  $-1$  to  $+1$ , where a value of  $-1$  means a total negative correlation,  $+1$  is a total  
 13 positive correlation and the value of  $0$  indicates no correlation.

14 The mean bias (MB) is defined as:

$$15 \quad MB = \frac{1}{N} \sum_{i=1}^N (\beta_{att.CAL_i} - \beta_{att.EAR_i}), \quad (8)$$

16 where  $N$  is the number of the data points in the height range where both CALIOP and  
 17 EARLINET attenuated backscatter data are available.

18 The factor of exceedance (FoE) which is defined as:

$$19 \quad FoE = \left[ \frac{N(\beta_{att.CAL} > \beta_{att.EARL})}{N} - 0.5 \right], \quad (9)$$

20 where  $N(\beta_{att.CAL} > \beta_{att.EARL})$  is the number of data points in which CALIOP backscatter  
 21 coefficient measurements are higher than the coincident EARLINET observations. The FoE  
 22 value can vary between  $-0.5$  (all CALIOP values are underestimated) and  $+0.5$  (all CALIOP  
 23 values are overestimated).

## 1 **3 Results**

### 2 **3.1 Case studies**

3 Two particular cases of CALIOP overpasses were chosen to demonstrate the methodology  
4 described in Sect. 2 and to show CALIOP's capability to detect aerosol layers under different  
5 conditions. CALIOP overpasses close to the Barcelona and Granada EARLINET stations are  
6 used in this illustration. The first overpass represents one of the best agreements between  
7 CALIOP and EARLINET stations out of 48 overpasses; the second overpass is an example of  
8 a case with discrepancies between the measurements by the two instruments.

9 The CALIOP overpass map for the first case study (Barcelona) is shown in Figure 1. The  
10 attenuated CALIOP and EARLINET backscatter coefficients vs. altitude are shown in the left  
11 panel of Fig. 2. The aerosol type flag was assigned by the CALIOP aerosol classification  
12 algorithm (Liu et al., 2009) and it is presented in each case by different coloured dots in  
13 Fig. 2. The attenuated backscatter profiles agree well in the FT, and the PBL top was  
14 adequately distinguished by CALIOP (Fig. 2). The results show that the correlation between  
15 the two profiles is strong, with a correlation coefficient of 0.96. The factor of exceedance  
16 equals 0.1, which shows an overestimation of 60 % of the CALIOP data points. For this case,  
17 the calculated mean bias value was  $0.1 \text{ Mm}^{-1}\text{sr}^{-1}$ .

18 The second case study was carried out for a CALIOP overpass over the Granada EARLINET  
19 station (Fig. 3) and it represents a Saharan dust event, which stretched from the region of  
20 western North Africa over Gibraltar towards the southern part of Spain. The hybrid single  
21 particle Lagrangian integrated trajectory model (HYSPLIT) (Draxler and Rolph, 2013) was  
22 used to analyse the origin of the air mass. The backward trajectory analysis confirms that the  
23 air mass came from Africa, the Sahara region. The results of the analysis are shown in Fig. 4.  
24 The attenuated backscatter vs. altitude is shown in the left panel of Fig. 5. A dust layer is  
25 detected between 4 km and 6.5 km by both lidars, however, the CALIOP profile differs from  
26 the EARLINET profile at the higher altitudes by an amount outside the uncertainty bounds of  
27 the instruments. There are some additional discrepancies between CALIOP and EARLINET  
28 measurements (left panel of Fig. 5). The top of the CALIOP-detected dust layer is  
29 approximately 500 m higher. There were two distinguishable aerosol layers in the  
30 EARLINET backscatter profile, namely the primary one between 5 km and 6 km altitude and

1 a secondary one around 2 km altitude. However, the secondary layer in the PBL region is  
2 barely distinguishable in the CALIOP profile.

3 Those differences between two profiles could happen for few reasons. Since Granada is  
4 located in a valley, the temperature inversion is pretty usual phenomena there. The inversion  
5 could trap the pollutants that form near ground-level. It is worth to mention also that both  
6 measurements were separated by a distance of 67 km with the Sierra Nevada mountain range  
7 (elevation 3.5 km) between the station and the CALIOP track. As a result, all earlier  
8 mentioned circumstances (the mountains, the temperature inversion and the distance) could  
9 limit the CALIOP's abilities to detect the local pollution within the PBL. In contrast, this  
10 local pollution event was successfully detected by the EARLINET station in the valley.  
11 Another reason for the discrepancy could be an invalid CALIOP aerosol type classification.  
12 However for this specific case, CALIOP detected the layer as a dust layer and the lidar ratio  
13  $S_a$  provided in EARLINET file was equal to 55 (dust). That eliminates the possibility of  
14 invalid type classification for this case. It is likely that local topographic location combined  
15 with trapped local pollutants during the summer period (e.g. smog) negatively influenced the  
16 agreement between the CALIOP and EARLINET measurements. As a result, the correlation  
17 between two profiles is not as strong as in the first case, during which no obvious obstacles  
18 were present between the Barcelona EARLINET station and the CALIOP track on  
19 Mediterranean Sea. Thus for the second case, the correlation coefficient was 0.47 while the  
20 mean bias was  $-0.09 \text{ Mm}^{-1}\text{sr}^{-1}$ . Consequently, the factor of exceedance was -0.15, which  
21 shows that 65 % of the CALIOP total attenuated backscatter values were lower than  
22 EARLINET values.

23 The next section provides an overview of the agreement between CALIOP and EARLINET  
24 attenuated backscatter values for all of the CALIOP overpasses with ground track offset  
25 distances of 100 km or less.

### 26 **3.2 EARLINET-CALIOP comparison with ground track distance 100 km**

27 From November 2010 to December 2012, 48 CALIOP overpasses occurred within a 100 km  
28 distance from an operating EARLINET station, with aerosol layers classified as dust, polluted  
29 dust, clean marine, clean continental, polluted continental, mixed and/or smoke/biomass  
30 burning. These 48 overpasses resulted in 7405 data points that were deemed valid for

1 evaluation against EARLINET. The scatterplot of CALIOP and EARLINET attenuated  
2 backscatter values for all of these data points is shown in Fig. 6.

3 The CALIOP and EARLINET data correlate well ( $R = 0.86$ ), with a mean bias equal to  $0.03$   
4  $\text{Mm}^{-1}\text{sr}^{-1}$ , while the factor of exceedance value is  $0.17$ . The latter statistical parameter  
5 indicates that  $67\%$  of the CALIOP attenuated backscatter values were higher than the  
6 corresponding EARLINET measurements. However, there were several points that deviated  
7 from the 1:1 line. In order to investigate the cause of these outliers, the data were colour  
8 coded by the overpass distance (Fig. 6) and the vertical height of the aerosol layer (Fig. 7),  
9 which revealed that the majority of the outliers were observed when the distance between the  
10 EARLINET station and CALIPSO overpass exceeded  $30\text{ km}$ . Moreover, the correlation  
11 seemed to be dependent on the height of the aerosol layer, where the larger discrepancies are  
12 observed for low altitudes. This is also in agreement with Mona et al., (2009) and Pappalardo  
13 et al., (2010). Furthermore, the correlation seemed to be dependent also on the presence of  
14 multiple layers in the FT and the PBL at the same time (as in the second case study).  
15 Therefore, further analysis was performed for the PBL and the FT separately.

### 16 **3.2.1 PBL and FT with ground track distance 100 km**

17 The PBL height was assumed to always be  $2.5\text{ km}$  for this analysis (Mattis et al., 2004;  
18 Pappalardo et al., 2004). The scatterplots for the separated PBL and FT datasets are shown in  
19 Figs. 8 and 9 and characterized by  $R$ ,  $MB$  and  $FoE$  parameters (Table 2).

20 The correlation is significantly stronger for the FT ( $R = 0.85$ ) compared to the PBL  
21 ( $R = 0.60$ ). The factor of exceedance for the FT equals  $0.22$ , which indicates that  $72\%$  of the  
22 CALIOP total attenuated backscatter values were higher than the EARLINET values, with a  
23 mean bias of  $0.06\text{ Mm}^{-1}\text{sr}^{-1}$ . Correspondingly, the  $FoE$  for the PBL was equal to  $-0.12$  and  
24  $MB = -0.14\text{ Mm}^{-1}\text{sr}^{-1}$ , which suggests that only  $38\%$  of CALIOP values were higher than  
25 EARLINET values in the PBL.

26 The aerosol layers in the free troposphere are often characterized by smaller horizontal  
27 variability compared to the PBL, it is then likely that a higher EARLINET-CALIOP  
28 correlation can occur in the FT. On the other hand, the boundary layer, especially during  
29 convective periods, undergoes higher temporal and spatial variability due to continuous PBL  
30 updraft and FT downdraft. That could influence lower correlation between CALIOP and  
31 EARLINET in the PBL. Moreover, when an aerosol layer occurs in the FT, it attenuates the

1 CALIOP lidar signal that will have less energy to penetrate further down into the PBL. To  
2 investigate that idea, data filtering with threshold values from the second case study were  
3 used. However, this choice reduced the amount of CALIOP overpasses from 48 down to 27,  
4 while the number of data points available for the comparison dropped from 7405 down to  
5 3398.

### 6 **3.2.2 Filtered PBL and FT with ground track distance 100 km**

7 In this analysis, the data points were selected from the CALIOP overpasses based on  
8 threshold values of the column backscatter coefficient (vertically summed values). These  
9 values were derived from the second case study (with aerosol layer occurring in the FT above  
10 the PBL) in two chosen altitudes ranges (up to 3 km and above 3km). The threshold column  
11 backscatter value for the altitude range up to 3 km was  $38 \text{ Mm}^{-1}\text{sr}^{-1}$ , while the value above 3  
12 km was  $71 \text{ Mm}^{-1}\text{sr}^{-1}$ . Next, only CALIOP overpasses with detected aerosol with lower than  
13 these threshold values were used in the analysis. After applying such filtering, the statistics  
14 are presented in Table 3.

15 The scatterplots of the attenuated backscatter for CALIOP and EARLINET after applying this  
16 data filtering are presented in Fig.10 and 11. The correlation between the two sets of  
17 attenuated backscatter measurements became marginally stronger in the PBL ( $R = 0.65$ ),  
18 while the same parameter for the FT decreased from  $R = 0.85$  to  $R = 0.79$ . Correspondingly,  
19 the other statistical parameters improved for the PBL ( $MB = -0.09$  and  $FoE = -0.09$ ) but they  
20 decreased by a factor of two for the FT ( $MB = 0.03$  and  $FoE = 0.11$ ). This suggests  
21 considerable variability, across the dataset, in the spatial distribution of the aerosol over  
22 spatial scales of 100 km or less around some EARLINET stations rather than influence from  
23 elevated FT layers.

24 The clean marine type of aerosol was detected by CALIOP exclusively in the PBL (Fig.12b),  
25 which is consistent with the marine surface source. However, a negative correlation  
26 coefficient was found for this aerosol type. One data point looks like an outlier. If this data  
27 point is removed, the statistics for clean marine aerosol type become the following:  $R = 0.96$ ,  
28  $MB = 0$ ,  $FoE = 0.01$ .

29 The dust aerosol is usually transported over long distances in the FT (Fig.13b), where its  
30 correlation is stronger ( $R = 0.57$ ) compared to the PBL ( $R = 0.46$ , Fig.12c), because the PBL  
31 aerosol is more affected by local sources.



1 The polluted dust aerosol detected by CALIOP represents a mix of dust and biomass  
2 burning/smoke aerosol. Both types of aerosol contribute to trans-boundary air pollution and  
3 are transported in the FT. However, the correlation coefficient for polluted dust aerosol is  
4 higher in the PBL ( $R = 0.44$ ) than in the FT ( $R = 0.38$ ) (Fig.12d and 13c).

5 On the other hand, the polluted continental aerosol originates from local sources, which is  
6 consistent with the fact that CALIOP detected this type exclusively in the PBL (Fig.12e);  
7 however, this localization affected CALIOP's ability to represent the variations of the  
8 polluted aerosol, because significant spatial averaging is required to obtain adequate SNR.  
9 Strong local sources could result in higher temporal and spatial variability in the PBL.  
10 Therefore, a poorer correlation ( $R = 0.37$ ) between CALIOP and EARLINET could be a result  
11 of different area coverage for the two methods.

12 The mixed aerosol (Fig.13d) was detected only in FT cases, with the lowest  $R = 0.35$  value  
13 across all aerosol types. The reason for this is that it is a mix of other aerosol types, which  
14 causes a low value of the correlation coefficient.

15 The technique of data filtering allowed improving the agreement between different aerosol  
16 types, but at the same time the improvements were not very significant.

#### 17 **4 Conclusions**

18 Over three years, 48 CALIOP overpasses occurred within a 100 km ground track offset  
19 distance from an operating EARLINET station, resulting in 7405 data points for the analysis  
20 presented here. The inter-comparison of the total attenuated backscatter profiles from near-  
21 real-time CALIOP Level 1.5 data and converted EARLINET data showed fairly good  
22 agreement, with the correlation around 0.86, a mean bias of  $0.03 \text{ Mm}^{-1}\text{sr}^{-1}$  and a factor of  
23 exceedance of 0.17. On average, the CALIOP attenuated backscatter values were slightly  
24 higher (by 3 %) than the EARLINET values.

25 While it was suspected that the presence of high-concentration layers in the FT affected the  
26 agreement between CALIOP and EARLINET, after filtering out these cases with notable FT  
27 aerosol layers, no real improvement in the correlation coefficient was observed. This suggest  
28 that the lack of a high correlation between the datasets is more likely due to variability in the  
29 distribution of aerosols across the 100 km area selected around the EARLINET stations.~~The~~  
30 ~~level of agreement between the CALIOP and EARLINET attenuated backscatter values was~~  
31 ~~influenced by the presence of aerosol layers in the PBL and FT and by the aerosol layer~~

1 ~~height. A type of data filtering was used to mitigate the multiple layers influence, and the~~  
2 ~~filtering improved the agreement between the two data sets in the PBL. In addition, splitting~~  
3 ~~the aerosol layer heights into two categories distinguished the differences between the PBL~~  
4 ~~and the FT.~~ Before applying the filtering, the CALIOP attenuated backscatter values were  
5 lower by 20 % in the PBL compared to the EARLINET measurements, however, they were  
6 higher by 8 % in the FT. After applying the filtering, the correlation coefficient improved  
7 (from  $R = 0.60$  up to  $R = 0.65$ ) within the PBL, and the mean bias decreased from  $MB = -0.14$   
8  $\text{Mm}^{-1}\text{sr}^{-1}$  down to  $MB = -0.09 \text{Mm}^{-1}\text{sr}^{-1}$ . The factor of exceedance decreased as well, from  
9  $FoE = -0.12$  to  $FoE = -0.09$ . Finally, the majority of the outliers in the regression plot of  
10 CALIOP and EARLINET attenuated backscatter were shown to be caused by the presence of  
11 layers in both the PBL and the FT.

12 The aerosol types detected by CALIOP were consistent with the source of the aerosol and the  
13 transport mechanism. Aerosols from local sources were mainly detected in the boundary  
14 layer, while long range transport pollution was observed in the FT. The correlation for  
15 different aerosol types was stronger within the FT and it was in the range of 0.35 to 0.80, with  
16 mean bias values of -0.24 to  $0.27 \text{Mm}^{-1}\text{sr}^{-1}$ , and the factor of exceedance between -0.05 and  
17 0.11. The correlation for the PBL was slightly weaker ( $R = 0.37-0.61$ ) and the mean bias  
18 values were in the range of -0.19 to  $0.19 \text{Mm}^{-1}\text{sr}^{-1}$ , with the factor of exceedance -0.16 to  
19 0.02.

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- 18 *Table 1 EARLINET stations that had coincident measurements with CALIOP during the observational*  
19 *period (Pappalardo et al., 2014)*

Nr.	Station Code	Station name, location	Coordinates
1	at	Athens, Greece	37.96° N, 23.78° E
2	ba	Barcelona, Spain	41.389° N, 2.112° E
3	be	Belsk, Poland	51.84° N, 20.79° E
4	bu	Bucharest, Romania	44.348° N, 26.029° E
5	ca	Cabauw, Netherlands	51.97° N, 4.93° E
6	ev	Evora, Portugal	38.568° N, 7.912° W
7	gr	Granada, Spain	37.164° N, 3.605° W
8	hh	Hamburg, Germany	53.568° N, 9.973° E
9	is	Ispira, Italy	45.811° N, 8.621° E
10	ma	Madrid, Spain	40.456° N, 3.726° W
11	ms	Maisach, Germany	48.209° N, 11.258° E
12	na	Napoli, Italy	40.838° N, 14.183° E
13	pl	Palaiseau, France	48.7° N, 2.2° E
14	po	Potenza, Italy	40.601° N, 15.724° E

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21 *Table 2 Statistics of CALIOP and EARLINET agreement within the PBL and the FT with ground track*  
22 *distance within 100 km*

Region	<i>R</i>	MB (Mm <sup>-1</sup> sr <sup>-1</sup> )	FoE
Entire range	0.86	0.03	0.17
PBL	0.60	-0.14	-0.12
FT	0.85	0.06	0.22

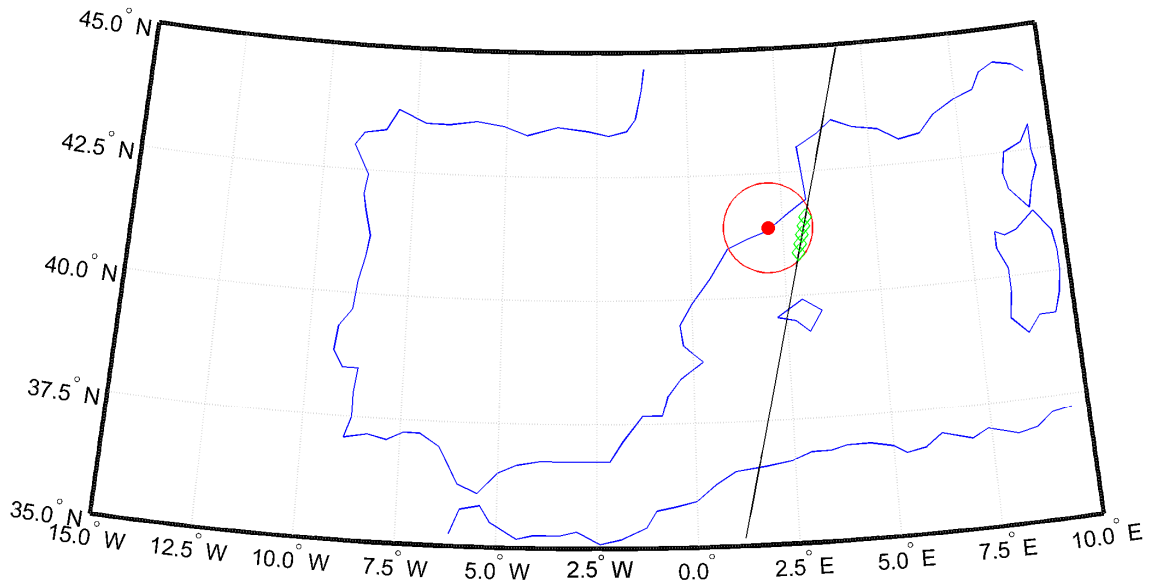
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1 *Table 3 Statistics of CALIOP and EARLINET agreement within the PBL and the FT using data*  
 2 *filtering*

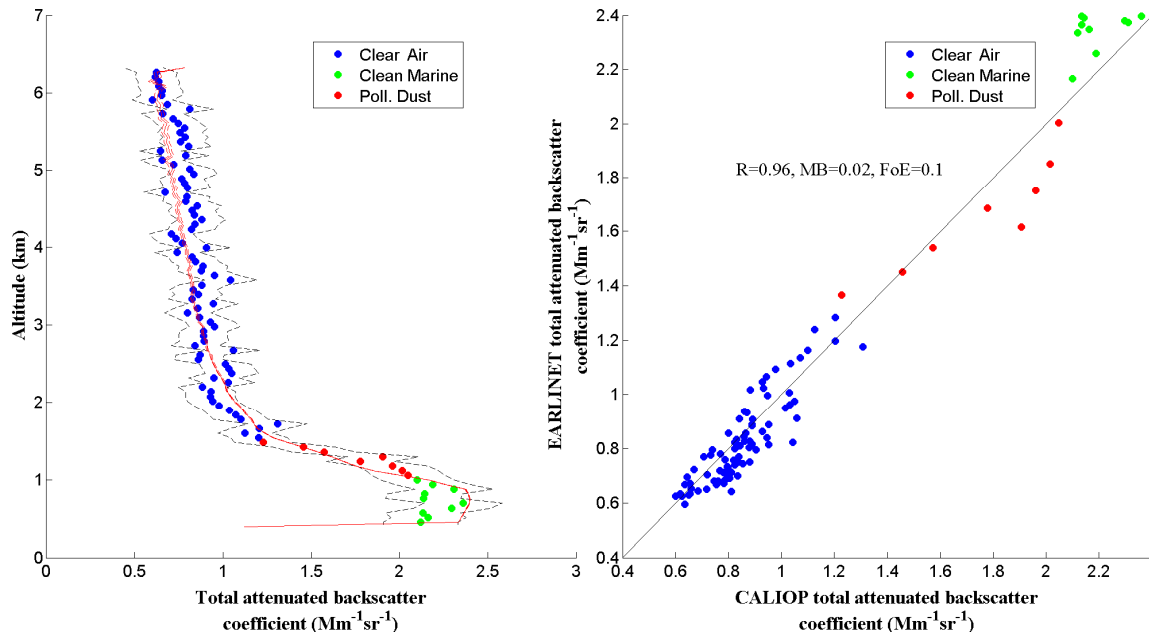
Region	<i>R</i>	MB ( $\text{Mm}^{-1}\text{sr}^{-1}$ )	FoE
Entire range	0.84	0.01	0.08
PBL	0.65	-0.09	-0.09
FT	0.79	0.03	0.11

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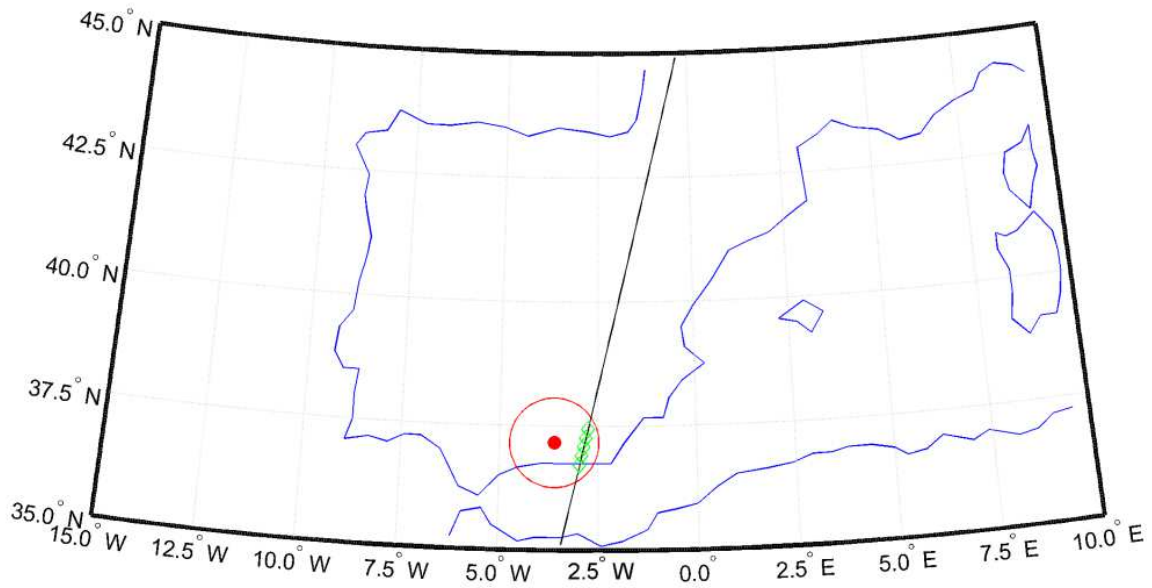
5 *Figure 1 CALIOP overpass over Barcelona station on 20 September 2011 at 02:00 UTC at 77.9 km*  
 6 *distance from the station. The red circle shows 100 km distance from the EARLINET station (the red*  
 7 *dot in the center). The black line represents the CALIOP ground track, while the green empty*  
 8 *diamonds represent five CALIOP profiles that were averaged and compared to EARLINET*  
 9 *measurements.*



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 2 *Figure 2 Left panel: attenuated backscatter versus altitude for a CALIOP overpass at Barcelona*  
 3 *station on 20 September 2011 at 02:00 UTC at 77.9 km distance from the station, (the red line shows*  
 4 *the EARLINET attenuated backscatter profile, the red dashed lines show EARLINET uncertainties, the*  
 5 *dots represent CALIOP data, and the black dashed lines show the CALIOP uncertainties); right*  
 6 *panel: corresponding scatterplot of CALIOP attenuated backscatter (different colours represents*  
 7 *different detected aerosol type; see legend) against EARLINET attenuated backscatter with a 1:1*  
 8 *reference line (black).*

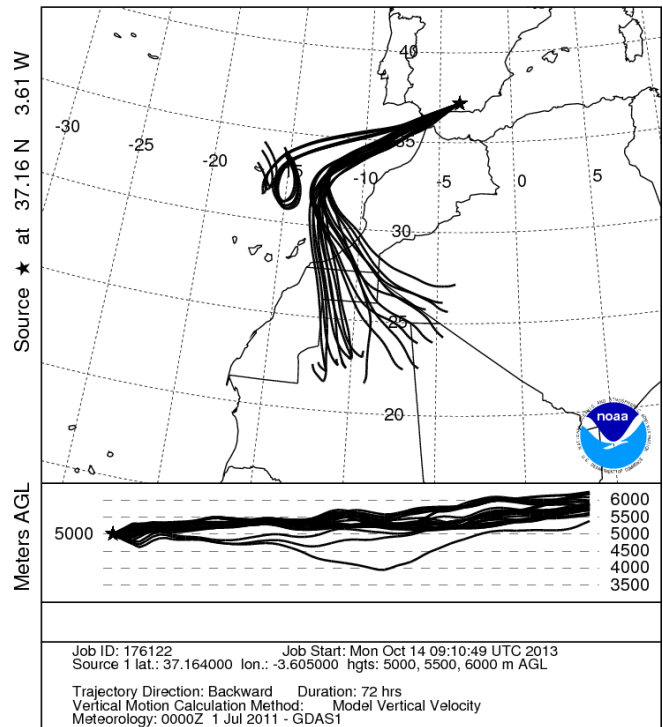
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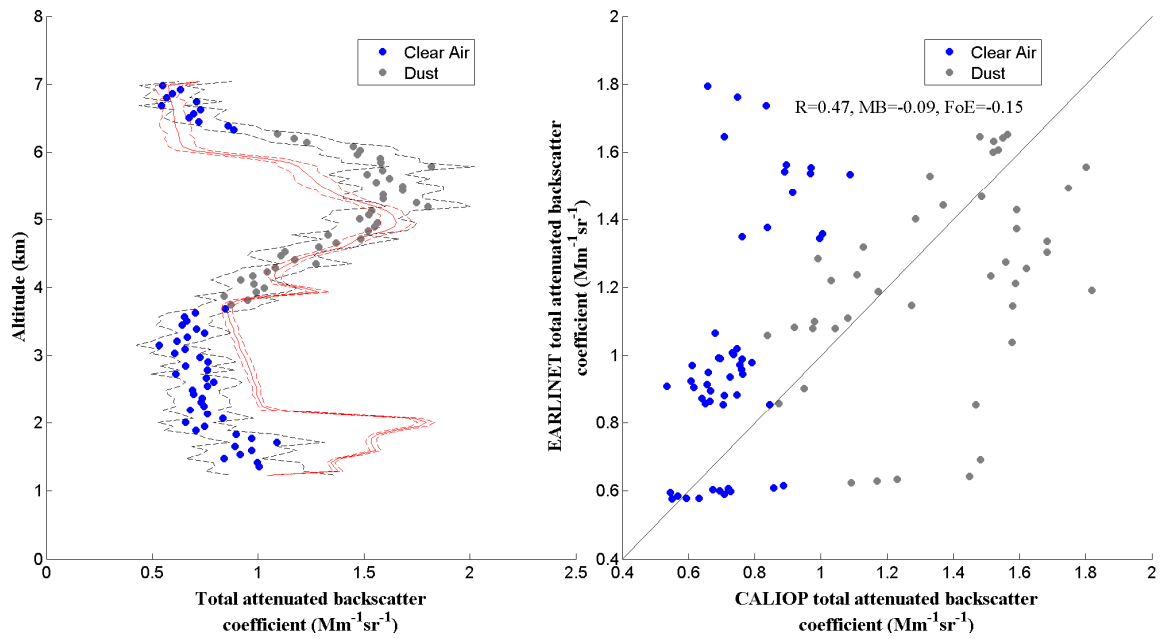
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 2 *Figure 3 CALIOP overpass over Granada station on 7 July 2011 at 02:20 UTC at 67 km distance*  
 3 *from the station. The red circle shows 100 km distance from EARLINET station (the red dot in the*  
 4 *center). The black line represents the CALIOP ground track while the green empty diamonds*  
 5 *represent five CALIOP profiles that were averaged and compared to EARLINET measurements.*

NOAA HYSPLIT MODEL  
 Backward trajectories ending at 0200 UTC 07 Jul 11  
 GDAS Meteorological Data



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 7 *Figure 4 Hysplit backward trajectories for the overpass over the EARLINET station in Granada on 7*  
 8 *July 2011 at 02:00 UTC confirm that the air mass came from the region of western North Africa, over*  
 9 *Gibraltar, and towards the southern part of Spain.*

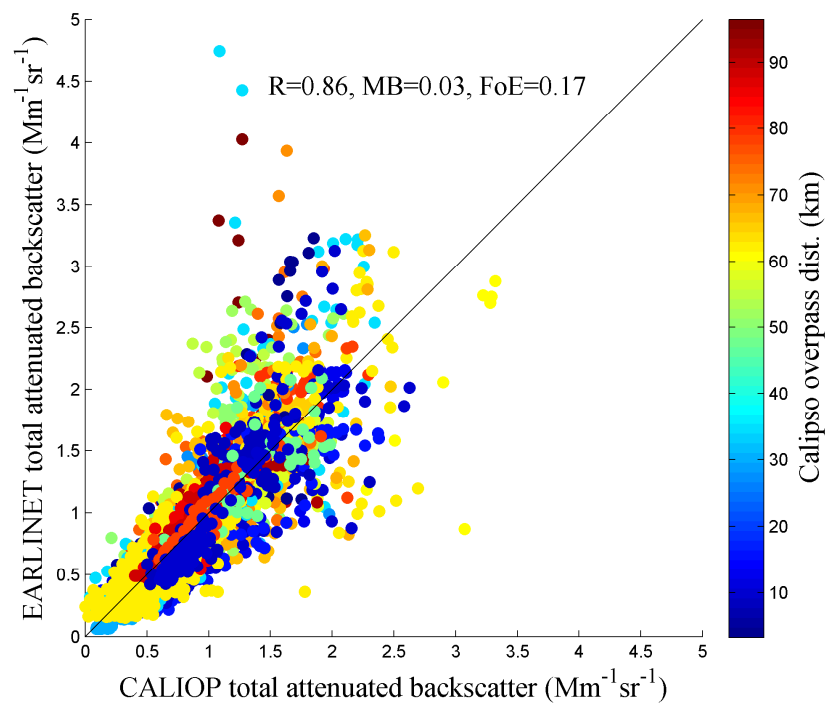
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Figure 5 Left panel: Attenuated backscatter versus altitude for a CALIOP overpass over Granada station on 7 July 2011 at 02:20 UTC at 67 km distance from the station (the red line shows the EARLINET attenuated backscatter profile, the red dashed lines show EARLINET uncertainties, the dots represent CALIOP data, and the dashed lines show the CALIOP uncertainty); right panel: corresponding scatterplot of CALIOP attenuated backscatter (different colours represents different detected aerosol; see legend) against EARLINET attenuated backscatter, with a 1:1 reference line (black)

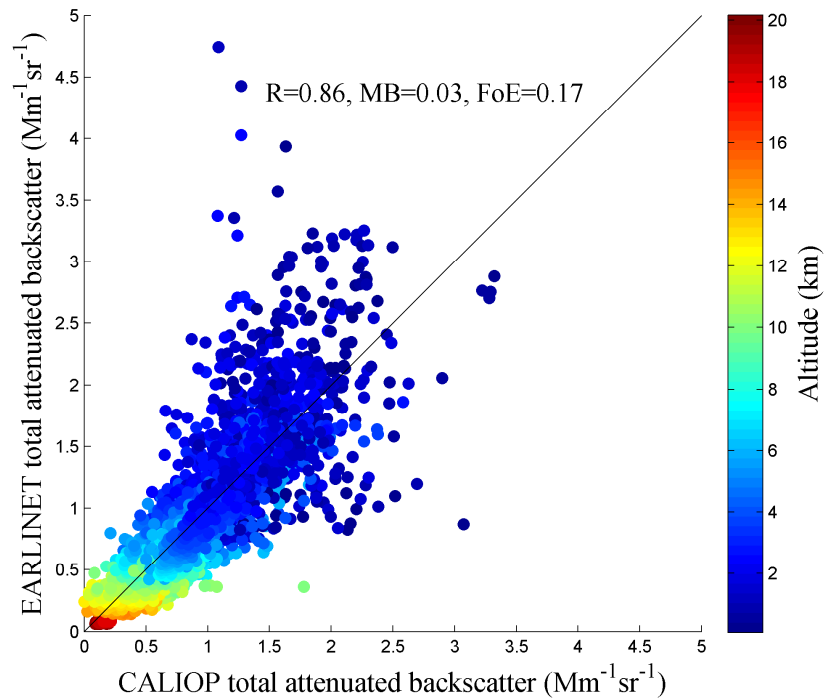
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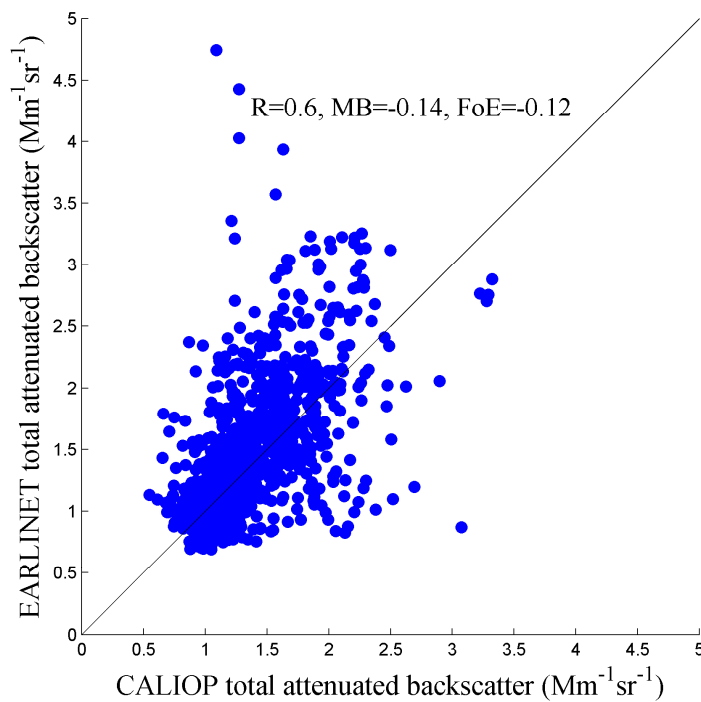
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3 *Figure 6 CALIOP vs EARLINET total attenuated backscatter for CALIOP overpasses over EARLINET*  
4 *stations within 100 km ground track offset distance. The colour scale shows the ground track distance*  
5 *from the EARLINET station.*

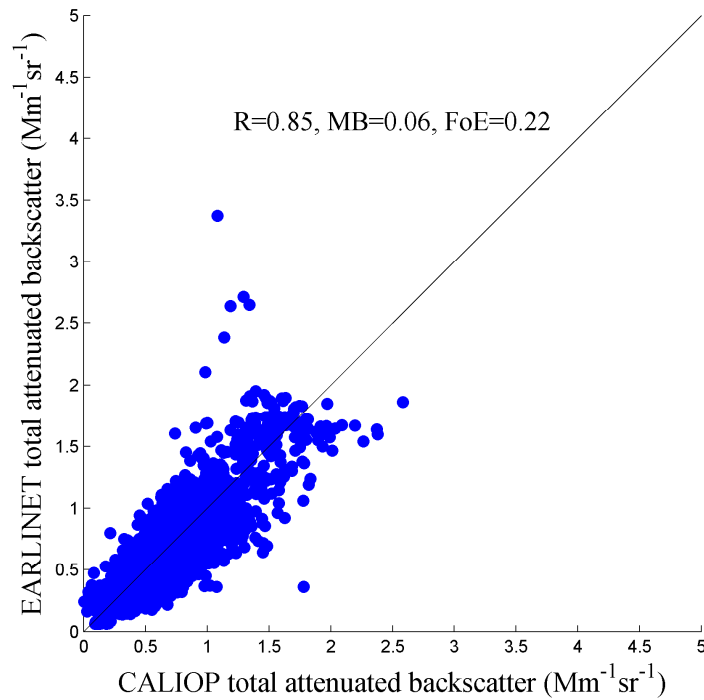
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 2 *Figure 7 CALIOP vs. EARLINET total attenuated backscatter for CALIOP overpasses over*  
 3 *EARLINET stations points within 100 km ground track distance, with colour coding showing the*  
 4 *aerosol layer altitude.*

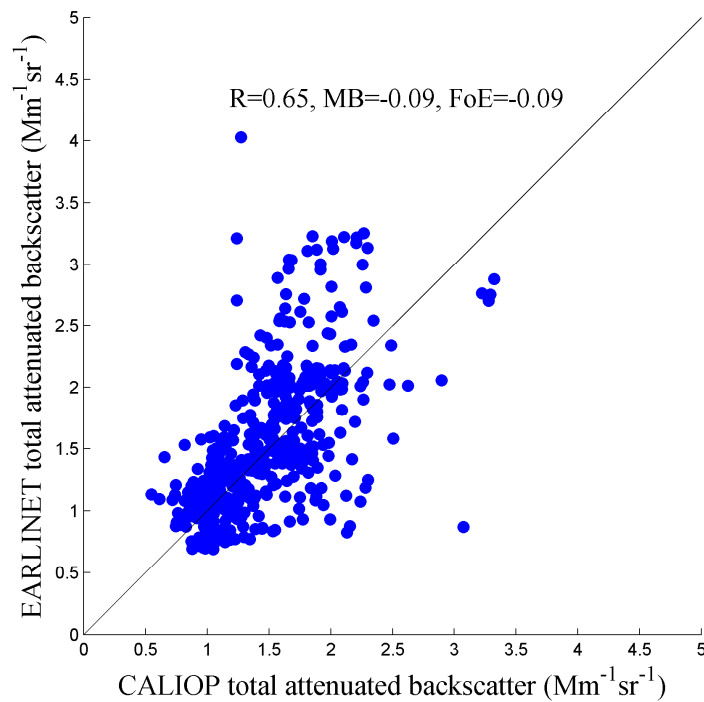


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 6 *Figure 8 CALIOP vs EARLINET total attenuated backscatter for CALIOP overpasses over EARLINET*  
 7 *stations for the PBL only, within 100 km ground track distance.*



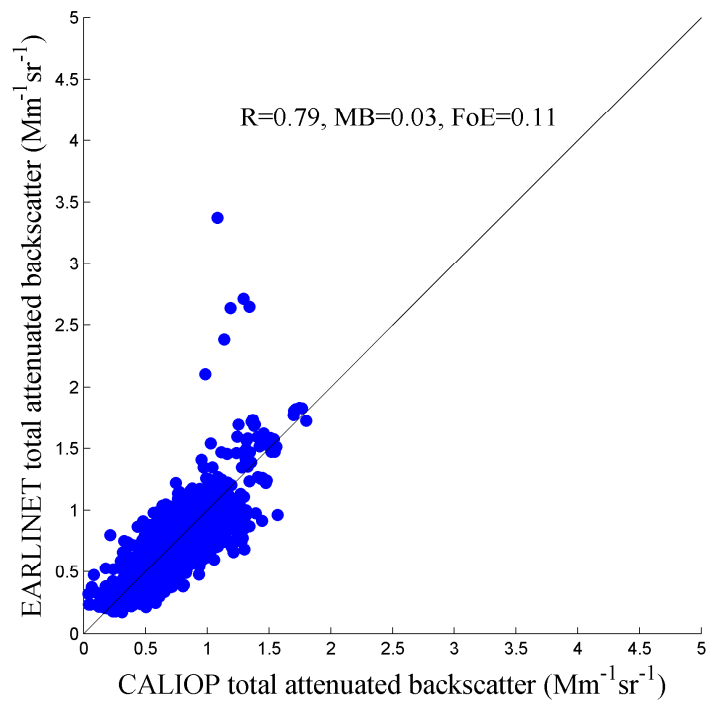
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2 *Figure 9 CALIOP vs. EARLINET total attenuated backscatter for CALIOP overpasses over*  
 3 *EARLINET stations for the FT\_only, within 100 km ground track distance.*



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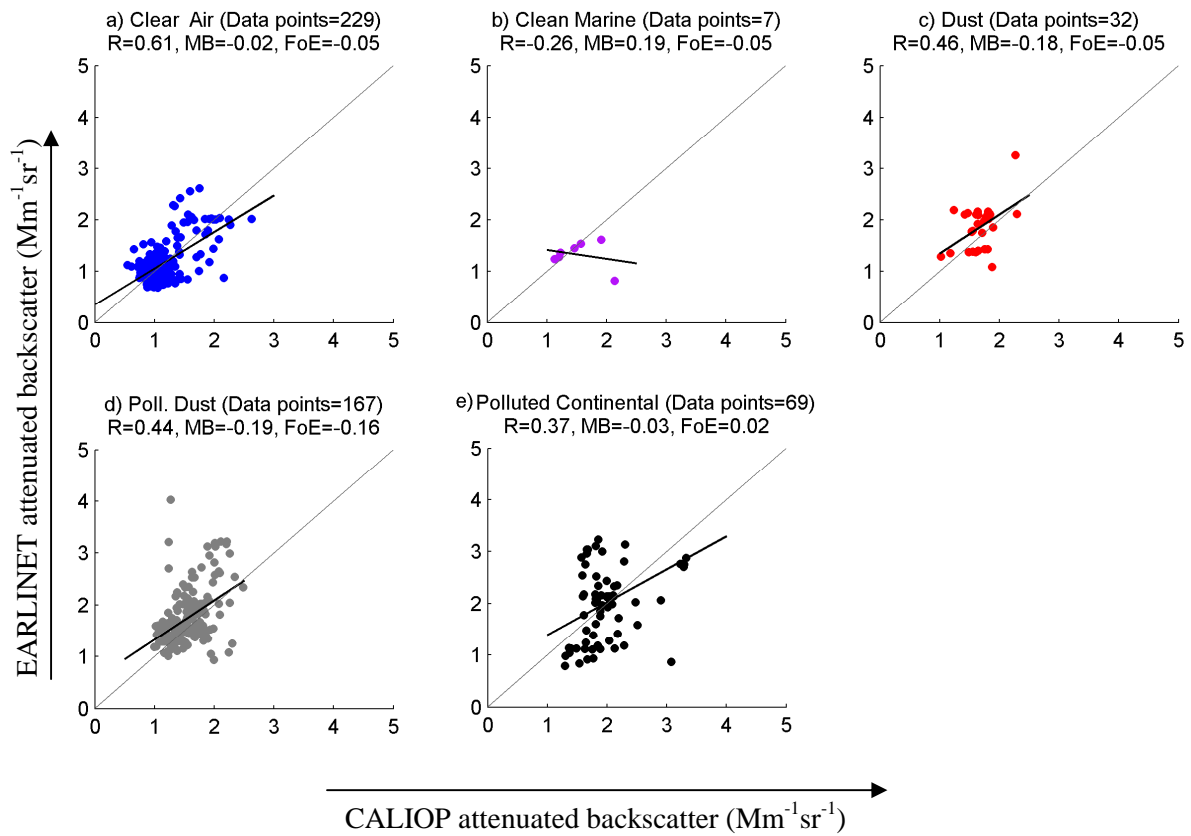
5 *Figure 10 CALIOP vs. EARLINET total attenuated backscatter for CALIOP overpasses over*  
 6 *EARLINET stations only for PBL. The plot includes all data points for overpasses without layers*  
 7 *present in both the PBL and the FT.*



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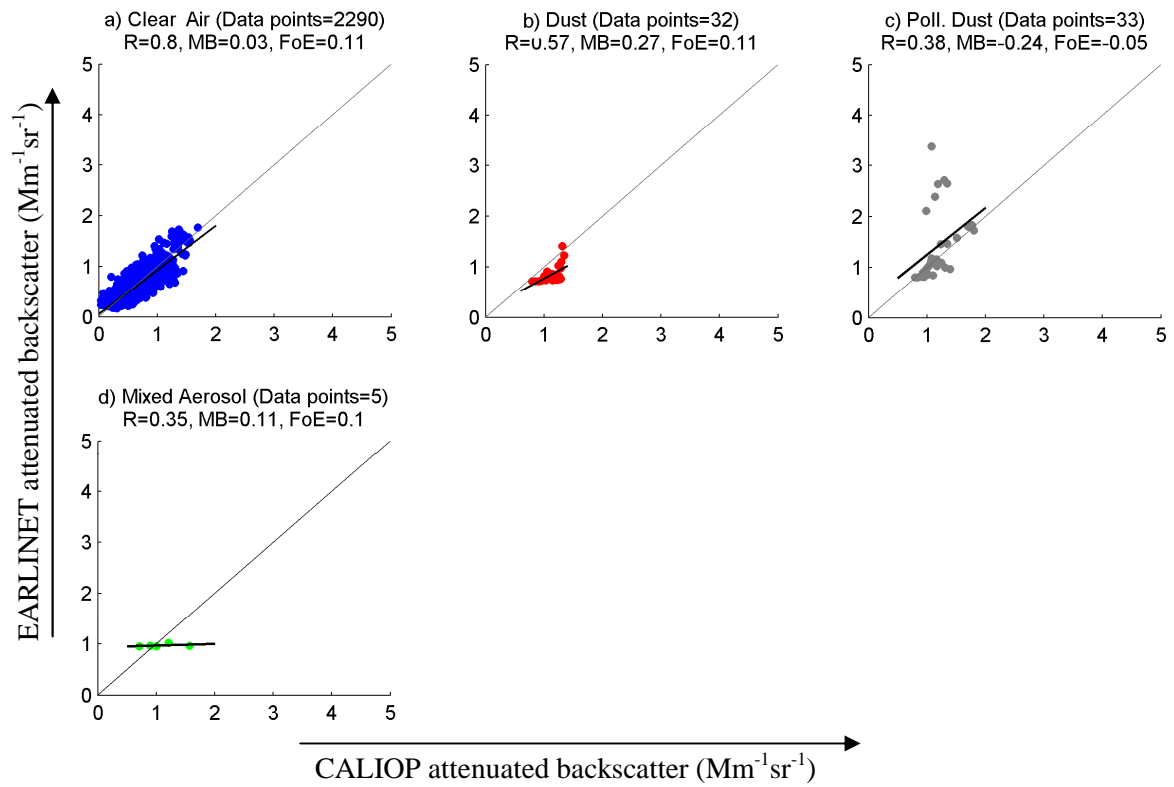
2 *Figure 11 CALIOP vs. EARLINET total attenuated backscatter for CALIOP overpasses over*  
3 *EARLINET stations within 100 km overpass distance only for FT. The plot includes all data points for*  
4 *overpasses without present layers present in both the the PBL and the FT .*

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Figure 12 Five level 1.5 feature types for CALIOP overpasses over EARLINET stations for the PBL. The plot includes filtered data points for overpasses without layers present in both the PBL and the FT.



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Figure 13 Four level 1.5 feature types for CALIOP overpasses over EARLINET stations for the FT. The plot includes filtered data points for overpasses without layers present in both the PBL and the FT.