We thank the reviewers for thorough consideration of the manuscript and the constructive comments, which contributed to the improvement of this manuscript, responses are presented below.

Referee #3 (RC C1207), Received and published: 30 March 2015

Review of the manuscript #acp-2014-998 by T.Grigas, M.Hervo, G.Gimmestad, H.Forrister, P.Schneider, J.Preißler, L.Tarrason, and C.O'Dowd "CALIOP near-real-time backscatter products compared to EARLINET data" Atmospheric Chemistry and Physics Discussion (ACPD)

Summary:

This article describes an evaluation of (lev 1.5) attenuated backscatter profiles from the CALIOP space lidar with EARLINET ground-based lidar profiles, based on a 3 years dataset from 2010-2012. It investigates the agreement of profiles depending on the ground-track vs EARLINET station distance, the altitude of aerosol layers, the aerosol type and separate for the planetary boundary layer (defined as the lowest 2.5km) and the free troposphere. Two specific cases are discussed in detail.

Significance:

The topic is relevant and interesting for ACP readers, because this CALIOP data product at present is the only mature operationally available near-real-time aerosol profile information with global coverage, suitable for assimilation into global forecast models. The article is well structured, understandable and fits well into the MACC special issue. Many of the conclusions are sound but some of them are not yet convincing. Particularly the discussion requires considerable improvement, stating the significance, consequences and applicability of the results for the development of NRT aerosol profile assimilation.

Evaluation:

Therefore, I recommend that some significant revisions are done before it is published in ACP (minor revisions).

Major comments:

1. I understand that you adapt CALIOP and EARLINET profiles in the vertical (60m layers) but not in the horizontal and that 'synchronicity' means that EARLINET and CALIOP profiles are at the same time, neglecting wind drift between both. CALIOP is averaged over ~20-100 x 20 km, but I do not find a specification over how many minutes (??) EARLINET profiles are averaged.

Response: We followed up on this in the revised manuscript to describe over how many minutes EARLINET profiles were averaged.

2. Air-masses and scales would probably be closer comparable if the EARLINET profiles were drift-corrected and averaged over a similar scale as CALIOP, both with wind speed (e.g. estimated from the trajectories) see discussion. For example 50km average spatial distance corresponds to ~1.5h temporally at 10 m/s wind-component along the station track-center axis. Keep in mind that EARLINET lidars are often located in or close to large towns with corresponding horizontal gradients. Regarding the limited number of 48/27 coincident overpasses, this seems feasible.

Response: We agree that the reviewer's proposed method would make the comparison more feasible; however we do not have the access to EARLINET non-averaged measurements because they are non-publically accessible.

3. The section about data filtering addresses a relevant question but is not yet convincing. The results from this approach are not really discussed and I wonder whether they are significant. Attenuation errors should clearly reduce when attenuation (layers) are excluded. But I can't really take this message from figs 8-11. It seems to me that simply the data at small values are missing when large values (layers) are filtered out.

Response: We partly agree with the reviewer's point and we included a concluding statement that statistical improvements due to data filtering were not significant.

4. You often use the acronym 'FT' where I'm not sure whether the stratosphere isn't included. I found no other indication of the upper altitude range than on P6047L19, where it is 20km.

Response: We thank the reviewer for pointing this out. We have included this detail (20km) in the revised manuscript.

Specific comments:

5. Abstract L7: should this read '…included a valid aerosol type classification…'?

Response: We have changed this part of the sentence in the abstract.

6. P6044L20pp.: To most readers it won't be obvious how a product, which is available within 6-30h, is used for operational forecasting. There is little information on that in (Powell et al, 2013). Any other reference. If not, please explain briefly.

Response: Assimilations related questions were the motivation for the study, however answering them was not the main output of this study. Additional reference about using the CALIOP measurements for assimilations is Vaughan, M., C. Trepte, D. Winker, M. Avery, J. Campbell, R. Hoff, S. Young, B. Getzewich, J. Tackett, and J. Kar, 2011: "Adapting CALIPSO Climate Measurements for Near Real Time Analyses and Forecasting", Proceedings of the 34th International Symposium on Remote Sensing of Environment, which can be found here http://www-calipso.larc.nasa.gov/resources/pdfs/VaughanM_211104015final00251.pdf

7. P6045L15: level ->levels

Response: The expression "processing level" (P6045L15) was changed into "Level 0".

8. P6048L7: tempus: correspond

Response: The verb form was corrected.

9. P6050L15/16 and annotation Fig2: colors for different aerosol types can hardly be distinguished spread the color scale.

Response: The annotation and the colours were changed.

10. P6051, L9pp: another reason for the discrepancy could be an invalid type classification (e.g. some Sahara dust plumes are mixed with fire smoke) which affects the lidar ratio and the calculated attenuation. The layers' AOD can be roughly calculated to ~0.2 (with a dust LR 50-60), but ~0.3 with a dust/smoke LR around 60-100). This would result in too small attenuation re-scaling of the EARLINET profile. Do the EARLINET observations exclude this possibility?

Response: For this specific case, CALIOP detected the layer as dust layer and the lidar ratio provided in EARLINET file was equal to 55 (dust). That eliminates the possibility of invalid type classification for this case. The paragraph P6051L9-15 was updated to include this.

11. P6051, L11: can a cross-track variability of this layer be confirmed by the EARLINET observation, as variability in time, due to the cross-wind component that is evident in the trajectory plot?

Response: We do not have access to EARLINET non-averaged measurements. For this reason, we cannot check "be confirmed EARLINET observation, as variability in time".

12. P6051, l13: wouldn't difficulty to detect layers at all require an enormous AOD of the upper layer? Was there a thick Ci cloud above? Which AOD can typically be transmitted by CALIOP @ 532 nm?

Response: Indeed, we agree with that. The statement starting with "Second, the CALIOP measurements.." on P6051 L13 and ending on P6051 L14 was deleted.

13. P6052, L8pp: This should be expected, but for me is not obvious from Fig 6, where many points with large distance (red) match quite well but particularly around CALIOP=2Mm-1sr-1/EARLINET=3Mm-1sr-1 and also below the 1:1 line several data points with small distance show large deviation as well.

Response: We think that the problem is simply in the way how the program plots the 7405 data points. In this case, the statistical results tell the true story.

14. P6052 L16: Does this mean your 'FT' includes the stratosphere or what is the upper altitude range?

Response: We included this detail in the revised manuscript. See the reply to the comment Nr.4.

15. The choice of the threshold separating FT and PBL domains has considerable impact on the correlation of profiles, because errors due to the deviations of the highly variable PBL height are assigned to either the FT or the PBL analysis. 2.5 km will mostly be too high (particularly during night), such that the majority of PBL height issues will feed into the PBL analysis and reduce the correlation.

Response: The PBL aerosols can certainly extend as high as 2.5 km, as it was shown in Mona et al.2009. The definition & variability of the PBL height are not the most important issue; it is rather the vertical extend of locally-produced aerosols.

16. P6053 L23pp: The larger neg bias of CALIOP profile averages vs. (more locally influenced) EARLINET profiles seems to me a matter of representativeness. (see comment on averaging above)

Response: We think that the representativeness of the stations might be only a part of the problem; another part (potentially even more important) is related to the fundamental differences between the measurements by CALIOP (flying at 7-8km/s speed) and ground-based averaged lidar.

17. P6053 L21: The 'corespondingly' only holds for the first part of the sentence not the second e.g. replace 'and they deceased…' by 'but they decreased…'

Response: We corrected the phrase by 'but they decreased…'.

18. P6053 L24-28: doesn't this only repeat (with zero criterion) the previous filtering according to the threshold?

Response: We agree with that, the lines (P6053 L24-L28) were deleted.

19. P6054 L21/22: why should the quantifyability of a particle layer depend on its mixing state? Because of the uncertain lidar ratio?

Response: We think that yes.

20. P6055 L14-17: I'm not convinced of that by the analysis you show (cf. comment on methodology 2)

Response: We answered related aspects to this comment in our replies to the comments Nr. 3 and Nr. 13.

21. Figs 5-11: move statistical parameters into the plot instead as headline (I needed some time to recognize them)

Response: The statistical parameters were moved into the plot.

22. Is there any more specific source of information about the Lev 1.5 data product than Powell, 2010?

Response: The reference provided in reply to Nr.6 comment delivers additional information on how the CALIOP level 1.5 is produced.

Referee #2 (RC C1278), Received and published: 2 April 2015

Review of the manuscript #acp-2014-998 by T.Grigas, M.Hervo, G.Gimmestad, H.Forrister, P.Schneider, J.Preißler, L.Tarrason, and C.O'Dowd "CALIOP near-real-time backscatter products compared to EARLINET data" Atmospheric Chemistry and Physics Discussion (ACPD)

I have little criticisms about the clearness of the content and its description. There are few inaccuracies that I point out in my technical comments below.

My major concern is the relatively low scientific relevance that this paper can have on the state of the art.

Evaluation:

I have wondered whether this concern should be a reason to reject a paper and I think it is not. I am then in favor of the publication of this paper as it brings anyway a clear description about how to improve the interpretation of the CALIOP data by highlighting the limitations related to the downward measurements and helps separating the PBL from the FT advected aerosol layers.

The abstract could be improved, the last part where the authors state the relevance of their work should highlight clearly the novel/important aspects of their study. A relative increase of 5% in the correlation coefficient would probably not be enough.

Summary:

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 describe a technique to filter the data and improve the correlation between EARLINET and CALIOP backscatter data over a period of three years. The proposed technique deals with a straightforward separation of the Troposphere into a PBL and a FT region in order to distinguish the aerosol contributions in the two regions. The technique allows improving the understanding of the different top-down and down-top signal attenuations experienced by the satellite and ground-based lidar systems. I have little criticisms about the clearness of the content and its description. There are few inaccuracies that I point out in my technical comments below.

Significance:

My major concern is the relatively low scientific relevance that this paper can have on the state of the art. I am then in favour of the publication of this paper as it brings anyway a clear description about how to improve the interpretation of the CALIOP data by highlighting the limitations related to the downward measurements and helps separating the PBL from the FT advected aerosol layers.

Evaluation:

I have wondered whether this concern (the relatively low scientific relevance) should be a reason to reject a paper and I think it is not.

23. Pg 1, ln 28 (P6042, L24) : incoming and reflected solar Radiation

Response: The sentence was corrected according to the comment.

24. Pg 2, ln 2 (P6043, L2): from the depolarization channel…

Response: The expression "polarization signal" was replaced by "depolarization channel".

25. Pg 2, ln 21 (P6043, L22): several comparison of ground-based LIDAR data with…

Response: The expression "several comparisons" was left.

26. Pg 2, ln 26 (P6043, L27): remove the brackets at the beginning of the sentence

Response: The brackets were removed in latest version of the manuscript.

27. Pg 2, ln 28-29 (P6044, L1-L2): explain why only measurements with independent extinction calculation were retained for the study.

Response: The manuscript was updated to address this by adding a sentence at (P6044, L2): "That allowed (a) calculating the lidar ratio and (b) converting EARLINET backscatter into attenuated backscatter as seen from space at 532 nm without any assumptions."

28. Pg 2, ln 33 (P6044, L6): remove the brackets at the end of the line.

Response: The citation was corrected.

29. Pg 2, ln 32-33 (P6044, L5-L7): Please state which kind of EARLINET product was compared to CALIOP, Attenuated Backscatter?

Response: The manuscript was updated to describe the EARLINET product by adding additional sentence (P6055, L7): "In this study, the measurements were averaged approximately for two hours and were centred on the CALIOP overpass time."

30. Pg 3, ln 6 (P6044, L12): remove brackets when you refer directly to a citation throughout the entire manuscript.

Response: It was fixed in latest version of the manuscript. The rest of the manuscript was reviewed and the places with such citations were accordingly corrected.

31. Pg 3, ln 25 (P6045,L3): dropped by 54% …

Response: The word "declined" was replaced by "dropped".

32. Pg 4, eq.1 (P6046, eq 1): if represents the uncertainty of the attenuated backscatter at the bin, than N should be the number of individual Level 1 lidar profiles, no?

Response: Thank you for mentioning about this aspect. No, the uncertainties are calculated per bin and not per profile. N is the number of level 1 profile range bins within the 20 km x 60 m interval remaining after clouds, overcast, surface, subsurface, totally attenuated, and invalid features were screened out (CALIPSO Quality Statements Lidar Level 1.5 Data Product Version Release: 3.02).

33. Pg 5, ln 8 (P6046, L23-L25): provide the definition of total as sum of aerosol plus molecular rather at the beginning of section 2 than here.

Response: The manuscript was changed to include the total backscatter definition at the beginning (P6045 L9-10): "… of the total (molecular plus aerosol) attenuated backscatter as seen from …".

34. Pg 5, ln 20 (P6047, L9): from the lidar to the outer atmosphere and back down …

Response: The original expression was left.

35. Pg 6, ln 13 (P 6048, L9): are the LIDAR ratios values used in eq.6 to calculate the EARLINET extinction coming from CALIOP or from independent calculation of the EARLINET algorithm?

Response: The LIDAR ratio values were extracted from CALIOP level 1.5 files. See also the response to the comment Nr.75

36. Pg 6, ln 27 (P 6048, L23): As the authors compare two LIDAR measurements I think the word "comparison" is more appropriate.

Response: The end of the sentence "are inter-compared" was replaced with "are compared".

37. Pg 7, eq.9 (P 6049, eq.9): what is the advantage of including a -0.5 term? Could not the FoE simply vary within [0-1]?

Response: The FoE value could be in different range, however keeping FoE in the range of [-0.5;0.5] gives some advantages. It gives more intuitively obvious way to understand either the CALIOP were higher (and how much more in percent compared to EARLINET) or they were lower (and how much less in percent compared to EARLINET).

38. Pg 8, ln 1-2 (P6050, L10-11): this has been said already on pg 7, ln 21-22 (P6049,L6-7).

Response: The lines (P6050, L10-11) of the manuscript were changed: "The CALIOP overpass map for the first case study (Barcelona) is shown in Figure 1."

39. Pg 9 ln 8: I suggest to slightly modify the structure of Sections 3.2, 3.3 and 3.4 to a more straightforward structure. Section 3.2 deals with all the dataset for the overpasses with distances < 100km, then a separation of the dataset is performed in Sect. 3.3 in order to separate the contribution of PBL and FT always keeping d < 100km and finally in 3.4 a filtering of the separated PBL and FT dataset is performed. As I see this, it would make more sense to have Sect. 3.2 "EARLINET-CALIOP comparison with ground track distance 100 km", Sect. 3.2.1 "PBL and FT with ground track distance 100 km" and Sect. 3.2.2 "Filtered PBL and FT with ground track distance 100 km".

Response: We thank the reviewer for advice and we agree that it would become better structured manuscript. The manuscript sections 3.2, 3.3 and 3.4 were modified accordingly:

Sect. 3.2 "EARLINET-CALIOP comparison with ground track distance 100 km"

Sect. 3.2.1 "PBL and FT with ground track distance 100 km"

Sect. 3.2.2 "Filtered PBL and FT with ground track distance 100 km".

40. Pg 9-10, ln 29-2 (P6052,L18-19): no need to repeat the criteria of selection, these are the same as before.

Response: The paragraph of the manuscript was changed (P6052, L16-20) into the following:

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

41. Pg 10, ln 9-10 (P6052, L27,28-P6053, L1): replace by “The aerosol layers in the free troposphere are often characterized by smaller horizontal variability compared to the PBL, it is then likely that a higher EARLINET-CALIOP correlation can occur in the FT”.

Response: The lines in the manuscript (P6052, L27,28 - P6053, L1) were changed according to the suggestion.

42. Pg 10, ln 11 (P6053, L1): one may argue this statement simply based on the definition of the PBL as the atmospheric region where aerosols get homogeneously mixed. I suggest to replace by “On the other hand, the boundary layer, especially during convective periods, undergoes higher temporal and spatial variability due to continuous PBL updraft and FT downdraft. Moreover, local sources of aerosols inside the PBL may not appear in the CALIOP profile due to its distance from the source.”

Response: Thanks the reviewer for the suggestion, the part of the paragraph (P6053, L1-4) was rewritten and ‘homogenous’ is not used anymore to describe the correlation within the PBL.

43. Pg 10, ln 11-12 (P6053, L1-2): I don’t see the relation with the considerations made in ln 9-11. I suggest to cut this sentence and replace with “When an aerosol layer occurs in the FT, it attenuates the CALIOP lidar signal that will have less energy to penetrate further down into the PBL.”

Response: The part of original paragraph (P6053, L1-4) was rewritten; please also see the reply to the comment Nr.42.

44. Pg 10, ln 21 (P6053, L11-12): the author statement “with aerosol layers present in both the PBL and FT” is redundant, the PBL is by definition the region with aerosols. I’d change it to “with aerosol layer occurring in the FT above the PBL”

Response: The statement (P6053, L11-12) was replaced by “with aerosol layer occurring in the FT above the PBL”

Short comment by Jason Tackett (SC C1465), Received and published: 9 April 2015

45. The CALIOP level 1.5 expedited products is derived from expedited level 1 and level 2 CALIOP data. It would help to emphasize that expedited products (a) use a simplified calibration scheme and (b) that the GMAO molecular model number densities used to derive molecular attenuated backscatter coefficients are slightly out of date (sometimes by as much as two days). These two effects degrade the science quality of the expedited data compared to the standard CALIOP products which have a more robust calibration scheme and use the most current GMAO molecular model. The following paper details these issues and their consequences on expedited level 1 and level 2 CALIOP data products (and ultimately, expedited level 1.5). It would be worth referencing this paper at a minimum since changes in CALIOP calibration could impact comparisons with EARLINET. Vaughan, M., C. Trepte, D. Winker, M. Avery, J. Campbell, R. Hoff, S. Young, B. Getzewich, J. Tackett, and J. Kar, 2011: "Adapting CALIPSO Climate Measurements for Near Real Time Analyses and Forecasting", Proceedings of the 34th International Symposium on Remote Sensing of Environment, http://www-calipso.larc.nasa.gov/resources/pdfs/VaughanM_211104015final00251.pdf

Response: Thanks the reviewer for providing very useful information and suggestions about the CALIOP level 1.5. It will help to improve the manuscript. We have included Vaughan. et. al (2011)

reference in the manuscript. Also, above mentioned differences between level 1.5, level 1 and 2 were included in replying for the comment Nr.47 in this document.

46. Equation 3 and page 6047, lines 15-16: "…the molecular backscatter coefficient β_{mol} is provided as a Level 1.5 data product." The level 1.5 product actually provides the molecular attenuated backscatter coefficient; i.e., the molecular backscatter coefficient multiplied by the two-way molecular transmittance (CALIPSO Quality Statements, 2011, pgs. 6-7). If the molecular attenuated backscatter coefficient is used rather than the molecular backscatter coefficient (as equation 3 expects), then the molecular extinction coefficient will be in error (equation 5). It follows then that the EARLINET total attenuated backscatter computations will also be in error. If this has already been taken into account, perhaps text could be added to clarify.

Response: We thank the reviewer for bringing attention to this aspect. We updated the manuscript to address this issue.

47. Page 6044, lines 22-24: "This (Level 1.5) product is derived (Powell et al., 2013) by spatially averaging the Level 1 profiles and merging them with the Level 2 vertical feature mask product." A clearer way to describe the level 1.5 product would be something like: "Level 1.5 is derived by cloud-clearing level 1 attenuated backscatter profiles using the level 2 vertical feature masks, and then spatially averaging the cloud-cleared profiles." In fact, the paper does not mention that level 1.5 is a cloud-cleared product. Adding this clarification would make this important point.

Response: We have rewritten the lines (Page 6044, lines 22-24) of the manuscript: "Level 1.5 is derived by cloud-clearing level 1 attenuated backscatter profiles using the Level 2 vertical feature masks, and then spatially averaging the cloud-cleared profiles. Level 1.5 expedited products uses a simplified calibration scheme compared to Levels 1 and 2. Also, it is derived by using the Global Modelling and Assimilation Office (GMAO) molecular model number densities, which can be occur to be out of date (sometimes by as much as two days). As a result, the scientific quality of the expedited data compared to the standard CALIOP products can be degraded."

48. Page 6045, lines 20-22: "The (aerosol classification) algorithm detects eight main aerosol types: clean air, clean marine, polluted dust, dust, polluted continental, clean continental, smoke/burning biomass and mixed aerosols." The paragraph in which this statement appears describes the CALIOP level 2 aerosol subtyping algorithm which only classifies six aerosol types: clean marine, polluted dust, dust, polluted continental, clean continental and smoke. The aerosol subtyping algorithm does not detect clean air or identify mixed aerosol. However, the level 1.5 product does report feature types having the designation clear air and mixed aerosol to describe range bins absent of detected features ("clear air", not "clean air") or 20 km horizontal averages containing more than one of the six CALIOP aerosol types (mixed aerosol). I think this paragraph and the following paragraph which describes the level 1.5 product should be revised to make clear that six aerosol types are detected by the level 2 aerosol subtyping algorithm and the categories "clear air" and mixed aerosol are specific to how level 1.5 describes the features (or lack thereof) in each level 20 km x 60 meter (horizontal x vertical) range bin. The level 1.5 product does report feature types having the designation clear air and mixed aerosol to describe range bins absent of detected features ("clear air", not "clean air") or 20 km horizontal averages containing more than one of the six CALIOP aerosol types (mixed aerosol).

Response: The paragraph (P6045, L18-L24) was rewritten to address the comment: "The algorithm detects six main aerosol types: clean marine, polluted dust, dust, polluted continental, clean continental and smoke/burning biomass. Such aerosol type detection is implemented in Level 2 aerosol subtyping algorithm. Level 1.5 product does report feature types having the designation "clear air" and "mixed aerosol". The first type is used to describe range bins absent of detected features while the second type is used if the 20 km horizontal averages contain more than one of the six CALIOP aerosol types." Using only the type "clear air" through the manuscript has been also implemented.

49. Page 6045, lines 25-26: "The Level 1.5 product is derived by spatially averaging 60 individual Level 1 lidar profiles and merging them with the Level 2 vertical feature mask product." Same as comment #3 above (#47).

Response: Thanks the reviewer for paying the attention to this. We described the required details in the reply to the comment Nr.47 (P6044, L/22-24).

50. Figures 12 and 13: Labels are missing for the horizontal and vertical axes from all panels.

Response: Thanks for pointing this out. The labels were restored in Fig. 12 and 13.

51.Figure 12 and 13 captions: Consistent with comment #4 above, "clean air" is not a detected aerosol type. A better description would be, "Eight level 1.5 feature types …" rather than "Eight aerosol types … ". For that matter, there are only six panels, so why does the caption say eight types?

Response: The captions in Fig. 12 and 13 were corrected according to the comment; the number of different aerosol types was also addressed.

52. It is important to mention that CALIOP version 3 data products are being used.

Response: This detail was added to the manuscript (P6042, L3): "… with Orthogonal Polarization (CALIOP) products version 3 were evaluated …".

Short comment by L. Mona (SC C1872), Received and published: 24 April 2015

53. The title "CALIOP near-real-time backscatter products compared to EARLINET data", is misleading: NRT backscatter product is not a correct wording. Even if, after reading the Data and methodology section, an expert can understand, that total attenuated backscatter profiles are compared, this title gives the impression that aerosol backscatter profiles are compared and this is definitively not true.

Response: We disagree. The general term "backscatter products" certainly includes total attenuated backscatter profiles. "Near-real-time" is important in the title; it is the reason that the level 1.5 data products were created.

54. "CALIOP near-real-time backscatter products compared to EARLINET data", the comparison methodology is not a CALIOP vs EARLINET independent comparison, because the methodology

described in section 2 uses CALIOP derived information into EARLINET backscatter to total attenuated backscatter conversion, so that EARLINET derived products are not independent from CALIPSO ones. This has some relevant outcomes: it is nowadays well known that CALIPSO typing has some troubles for marine type and in coastal regions (Kanitz et al., 2014; Winker et al., 2013), that polluted dust is oversampled (Burton et al., 2013) and also that dust lidar ratio value should be adjusted (Amiridis et al., ACPD, 2015). The impact of using these assumptions in this comparison for assessing the effectiveness of CALIOP lev 1.5 data assimilation is not considered at all. Authors should at least discuss these main critical aspects.

Response: Thanks for this valid point, we included an additional paragraph about this in section 2 "Data and methodology".

55. Reviewer 2 reports some doubts about the scientific relevance of the paper in this shape. Probably this is related to the lack of some quantitative information. The main point of the paper should be assessing the lev 1.5 quality, however at the present stage they are compared to external ones (EARLINET) but strongly contaminating them with CALIOP assumptions (because typing and lidar ratio values are assumptions for CALIOP algorithm) and without providing quantitative estimation of the Lev 1.5 accuracy. Reading this paper one cannot answer to the question: which is the error on Lev 1.5 over Europe on average? Is this dataset useful for the assimilation purposes at continental level and at which extend? Authors underline already in the abstract that CALIOP could record signal with a too low SNR in case of strong layers in the free troposphere. This is actually a very important point, to be addressed in a more quantitative way. As reviewer 2 wonders, are the differences in R significant? This is the first point. A further really important point is: filtering out data with a layer in FT and in the PBL means going towards clean air, background conditions. Over a highly populated continent as Europe is, one would expect very often the presence of high aerosol content in the PBL but also in the FT for the presence of long range transported aerosol from surrounding areas (Sahara desert, Eastern developing countries, biomass burning, fires from the US-Canada and so on). In fact the authors have filtered out more than 1 2 of the data (page 6053, line 7) and the result of this filtering is that 45% of the cases are clean air in the PBL and 97% of the cases for the FT are clean air. Is this representative for the European continent? My impression is that in less of ½ of the cases over Europe you have this clean air condition, so that if there is an improvement of Lev1.5 reliability for the filtered cases, they would be representative in case just for one half of the situation observed over Europe. Is this sufficient for the assimilation purposes?

Response: Thanks for good points. 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.

56. References are not properly included. Some important ones are missing and in other points (see detailed comment below) others are not relevant.

Response: See responses to the comments Nr.62 – 68.

57. Title: misleading (see above)

Response: See answer to the comment Nr.53, above.

58. Abstract PBL , FT not clear here the meaning but misleading in the abstract.

Response: Thanks for comment. The PBL and FT acronyms were explained at first their use in the abstract.

59.PBL and FT acronyms are explicitly reported at the end of the abstract and not at first appearance

Response: See the response to the comment Nr.58.

60. "The presence of FT …", this presence should be reported in AOD which is what makes the difference for CALIOP SNR. These differences in the correlation coefficient are really relevant and significant?

Response**: **Thanks for the suggestion, however it is impractical to implement it at the moment.

61. "The results …" this sentence is not supported by this paper and it is also very qualitative (different levels???)

Response: "location of the dominant aerosol layer " refers to the data filtering outcomes; "aerosol type" refers to Figs. 12 – 13. It is qualitative because it is a general comment, which we feel is appropriate in an abstract.

62. (Introduction) Here references are very bad. This list reports some examples but it is far to be exhaustive: "Lidar is a very useful technique … (gross et al., 2010; Papayannis et al., 2002)" Many papers about lidar aerosol observations demonstrate its capability for aerosol profiling both from ground based and space-borne lidars. Here just 2 are reported that probably are not the most important (the e.g. or for example wording should be included at least), and nothing from satellite.

Response: We thank the reviewer for several helpful suggestions (Nr.62 – 68) and we implement many of them. We addressed Nr. 67 by adding another CALIOP reference.

63."Several research programme …" Giannakaki and Mattis are both from EARLINET , which are the SEVERAL research programmes which authors refer to? Moreover, authors report that "Several research programme performed routine long-term observations … however such studies are limited to single geographical locations. In order to study … on a larger spatial scale, lidar networks are deployed" in this sentence publications from EARLINET, which IS a network, are reported.

64. ".. lidar networks are deployed (Pappalardo et al 2009b) " Pappalardo et al, 2009 b, reports something about EARLINET for CALIPSO validation purposes. As reference for EARLINET Bosenberg et al, 2003 and Pappalardo et al., AMT 2014 should be used. However EARLINET is not the only network around the globe. The others should be mentioned as well.

65.Bockmann et al 2014 is not appropriate (see above)

66. "At present, 28 European … (Sawamura et al., 2012)" Sawamura is for sure not a reference for EARLINET status, even if EARLINET is there involved.

67. Also for CALIPSO references they are not well included. Only one reference for CALIPSO and one for A-train are reported. Neither Vaughan et al., 2011 reported on Level 1.5 data as main reference is reported.

68. “The EARLINET community …” Several but you included just 2.Moreover, EARLINET database and in particular for the purposes of this paper, EARLINET correlative measurements (<100km) for CALIPSO are published. This reference should be included.

69. Page 6043, line 25: Level 1 and Level 2, it should explain what they are

Response: The important thing is to explain clearly what level 1.5 is, and we have added that. See also our responses to the comments Nr.45 and Nr.47.

70. Page 6044, line 16: Level 1B, what is?

Response: It was a typing error, which was corrected in new version of the manuscript.

71. Page 6045, line 23: mixed aerosols? Level 2 VFM reports clean marine, dust, polluted continental, clean continental, polluted dust, smoke and other. Is this mixed a new product?

Response: See response to the comment Nr.48

72. Page 6046, line 3: SD stands for?

Response: The acronym was explained in new edition of the manuscript.

73. Page 6046, line 14: “The ground-based lidar measurements used in this study were acquired from the EARLINET portal www.EARLINET.org for the period from November 2010 to December 2012 as well as for several days in April and May 2010 during the Eyjafjallajökull volcano eruption.” Why have the authors left out some of the EARLINET sites and did not include all which are available at the data base in their study? How did the authors choose their locations? How many profiles from each station are available (could be included in Table 1) and should show the representativeness of the study.

Response: There was limited amount of published data on the EARLINET portal to match CALIOP measurements, which can be seen on found 48 overpasses (with detected any aerosol type) during the period from November 2010 to December 2012.

74. Page 6048, line 7: this means (see above) that the well-known problem of typing/lidar ratio assumptions in CALIPSO data are not addressed at all. This should be mentioned in the discussion for correctness and intellectual honesty.

Response: See response to the comment Nr.54.

75. Page 6048, line 9: these are not EARLINET extinction coefficient. This sentence is wrong from the scientific point of view.

Response: We thank the reviewer for mentioning about this. This aspect was explained in new edition of the manuscript that the extinction coefficients were estimated by using the EARLINET backscatter coefficient and the lidar ratios extracted from CALIOP.

76. Page 6050, Figure 2 discussion: in the clean marine layer the total attenuated backscatter is higher than for Polluted Dust … is this feasible or is it related to problems on the clean marine identification?

Response: Interesting question, but we are plotting the data from CALIOP here and we have no way of knowing whether there is a classification problem in this particular overpass.

77. Page 6052, discussion in figure 6 and 7: what one could say from these figs is that the larger discrepancies are observed for low altitudes. This is also in agreement with Moan et al., 2009 and Pappalardo et al., 2010.

Response: We thank for this useful comment. The manuscript was updated to reflect this.

78. Page 6052, line 16: The PBL is assumed to be always 2.5km. This is not correct; the authors could refer to low troposphere (below 2.5km) and middle troposphere explaining the 2.5km reference point from EARLINET observations.

Response: We called it PBL for simplicity and clarity in the paper. We divided the atmosphere into two regions, defined by a boundary at 2.5 km, and gave them the names.

79.Page 6052: why not using the RMSE which do not consider the sign of the difference since both mean bias and FoE have it inside?

Response: We prefer FoE instead of RMSE. See the reply to the comment Nr.37.

80. Page 6053, line 2-3: "that could be … time" something is missing

Response: See our replies to the comments Nr.41 and Nr.42.

81. Page 6053, lines 12-13: instead of column backscatter, AOD should be used.

Response: See the response to the comment Nr.60.

82. Figure 12 and 13: what is reported on the axis?

Response: See the response to the comment Nr.50

83. Page 6054, 5: fit on only 5 pt, is this reasonable?

Response: That is the data set which we had.

84. Page 6055, line 15-17: "majority of the outliers" this is not supported by the showed results

Response: See the response to the comment Nr.13

85. Page 6055, lines18-20: the aerosol typing is not discussed at all.

Response: They were discussed in section 3.4 "PBL and FT using data filtering".

86. Table 1 is never referenced.

Response: We thank the reviewer for mentioning about this. The reference was added in new edition of the manuscript.

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

T.Grigas[1], M.Hervo[1*], G.Gimmestad[2], H.Forrister[2,], P.Schneider[3], J.Preißler[1], L.Tarrason[3], C.O'Dowd[1]**

[1]School of Physics and Centre for Climate and Air Pollution Studies, Ryan Institute, National University of Ireland Galway, Galway, Ireland

[2]Electro-Optical Systems Laboratory, Georgia Tech Research Institute, Georgia Institute of Technology, 225 North Avenue, Atlanta, Georgia 30332, USA

[3]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 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 ~~type~~ (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 ~~planetary boundary layer (~~PBL~~)~~ to 0.57 for dust in the ~~free troposphere (~~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~~incoming 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 backscatter signal and aerosol properties such as shape, from the depolarization channel~~polarization signal~~, that can elucidate particle composition, in particular, for Saharan dust or volcanic ash plumes (Groß et al., 2010; Papayannis et al., 2002). Several research programmes in Europe performed routine long-term observations of the optical properties of different aerosol types (Giannakaki et al., 2009; Mattis et al., 2004, 2008); however, such studies were typically limited to single geographical locations. In order to study aerosol transport on a larger spatial scale, lidar networks are deployed (Bösenberg et al., 2003; Pappalardo et al., ~~2009~~2014), in conjunction with space borne platforms. In 2000, EARLINET was established to provide a comprehensive statistically representative data set of the aerosol vertical distribution~~ (Böckmann et al., 2004)~~. At present, 27~~8~~ European stations contribute to this network by performing the measurements few times per week according to the schedule (Pappalardo et al., 2014). ~~.~~There are other lidar networks and one of them is the NASA Micro-Pulse Lidar Network (MPLNET). 21 permanent stations of this network are deployed worldwide from the Arctic to the Antarctic regions, which continuously measure aerosol and cloud vertical structure day and night (Lolli et.al., 2014). Besides, there is the Global Atmosphere Watch (GAW) Aerosol Lidar Observation Network (GALION), which is based on the cooperation between existing lidar networks: the Latin America Lidar Network (ALINE), the Asian Dust and Aerosol Lidar Observation Network (AD-Net), the

Commonwealth of Independent States (CIS) Lidar Network (CIS-LINET), the Canadian Operational Research Aerosol lidar Network (CORALNet), EARLINET, the Network for the Detection of Atmospheric Composition Change (NDACC), the Regional East Atmospheric Lidar Mesonet (REALM/CREST), and MPLNET. Global coverage may be achieved by using satellite-based lidar systems and striving towards such an aim, the National Aeronautics and Space Administration (NASA), in collaboration with the French space agency Centre National d'Etudes Spatiales (CNES), developed a satellite-based lidar system called CALIOP, which is on board the CALIPSO satellite platform (Omar et al., 2009; Vaughan et al., 2011). CALIOP performs measurements simultaneously at wavelengths of 532 nm and 1064 nm. The CALIPSO satellite was launched into orbit in April 2006 and is part of the A-Train constellation of scientific satellites dedicated to observations of the atmosphere (Stephens et al., 2002). It follows a sun-synchronous polar orbit of 705 km altitude and has a 16 day repeat cycle.

The EARLINET community has performed several comparisons with CALIOP data since its launch in April 2006 (Mattis et al., 2007; Pappalardo et al., 2010) using CALIOP overpasses with ground tracks within 100 km from EARLINET stations. Several studies inter-comparing CALIOP Level 1 and Level 2 data with the ground-based measurements were performed in recent years (Mamouri et al., 2009; Molero and Pujadas, 2008; Pappalardo et al., 2009, 2010). Pappalardo et al., (2010) found good agreement between the 532 nm CALIOP Level 1 attenuated backscatter and EARLINET measurements with a relative mean difference of 4.6 % and a relative standard deviation (SD) of 50 %. The attenuated backscatter was used only from those EARLINET stations that provided independent extinction measurements. That allowed (a) calculating the lidar ratio and (b) converting EARLINET backscatter into attenuated backscatter as seen from space at 532 nm without any assumptions. The correlation coefficient as a function of the CALIOP ground track offset distances was assessed as well. The correlation coefficient R = 0.9 was found for distances smaller than 100 km, while it decreased rapidly with larger distances. The mean bias between the CALIOP Level 1 and EARLINET Athens station's measurements as assessed by ~~(~~Mamouri et al., (2009) for daytime measurements was 22 %, and for night-time measurements, 8 %. In this study, the measurements were averaged approximately for two hours and were centred on the CALIOP overpass time. Mona et al., (2009) found a mean difference of (−2±12) % between data from the EARLINET station in Potenza and CALIOP Level 1 measurements within the 3–8 km altitude range, while the mean difference of the measurements within the PBL was equal to

(−24±20) %. The influence of the presence of cirrus clouds on the measurements was assessed in a study by Mamouri et al., (2009). The mean biases without cirrus clouds were −26±22 % for 5 km horizontal resolution and −14±15 % for 20 km; the biases were higher in cirrus cases with −104±129 % for 5 km horizontal resolution and −85±93 % for 20 km.

Assimilation of the CALIOP Level 1~~B~~ data product into atmospheric models has been carried out successfully in the past using an ensemble Kalman filter (Sekiyama et al., 2010). However, processed CALIOP Level 1~~B~~ and Level 2 data products are generally only available several days after acquisition at the earliest, thus severely limiting their use for operational data assimilation. An expedited CALIOP Level 1.5 near-real-time (NRT) product, usually provided between 6 and 30 hours after downlink, has been made available by NASA for purposes of operational forecasting since November 2010 (Vaughan et al. 2011). Level 1.5 is derived by cloud-clearing level 1 attenuated backscatter profiles using the Level 2 vertical feature masks, and then spatially averaging the cloud-cleared profiles. Level 1.5 expedited products uses a simplified calibration scheme compared to Levels 1 and 2. Also, it is derived by using the Global Modelling and Assimilation Office (GMAO) molecular model number densities, which can be occur to be out of date (sometimes by as much as two days). As a result, the scientific quality of the expedited data compared to the standard CALIOP products can be degraded.~~This product is derived (Powell et al., 2013) by spatially averaging the Level 1 profiles and merging them with the Level 2 vertical feature mask product.~~ In Level 1.5 dataset, the FT is limited by 20 km.

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

2 Data and methodology

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

CALIOP has an automatic aerosol classification algorithm that uses altitude, location, surface type, volume depolarization ratio δ_v and integrated attenuated backscatter γ' at 532 nm to determine the aerosol type (Burton et al., 2013; Omar et al., 2009). The algorithm detects six main aerosol types: clean marine, polluted dust, dust, polluted continental, clean continental and smoke/burning biomass. Such aerosol type detection is implemented in Level 2 aerosol subtyping algorithm. Level 1.5 product does report feature types having the designation “clear air” and “mixed aerosol”. The first type is used to describe range bins absent of detected features while the second type is used if the 20 km horizontal averages contain more than one of the six CALIOP aerosol types. ~~The algorithm detects eight main aerosol types: clean air, clean marine, polluted dust, dust, polluted continental, clean continental, smoke/burning biomass and mixed aerosols.~~ The Level 2 vertical feature mask provides information on cloud and aerosol layers as well as the type of aerosol in each identified layer.

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

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

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

where σ_i is the attenuated backscatter uncertainty at the range bin μ and N is the number of Level 1 profile range bins.

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

The CALIOP instrument directly measures profiles of the total ~~(molecular plus aerosol)~~ attenuated backscatter as seen from space, and NASA provides them in the Level 1.5 data set. These profiles were chosen for the inter-comparison in order to assess CALIOP measurements. The EARLINET stations produce aerosol backscatter coefficients and so the two different backscatter coefficients cannot be inter-compared directly. For this reason, a method similar to that of Mona et al., (2009) was adopted for converting the EARLINET particulate backscatter coefficients into total attenuated backscatter values as observed from space, thus allowing for a valid inter-comparison of CALIOP and EARLINET measurements. The following equations were used to calculate EARLINET attenuated backscatter. The total attenuated backscatter $\beta_{att}(z)$ at altitude z is given by

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

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

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

where β_{par} is the particulate (aerosol) backscatter coefficient, and β_{mol} is the molecular backscatter coefficient.

In order to calculate the total backscatter coefficient β_{tot}, the EARLINET particulate backscatter coefficient is used as β_{par} in Eq. (3) and the molecular backscatter coefficient β_{mol} is calculated from the atmospheric temperature and pressure profiles (Sissenwine et al., 1962). The molecular backscatter and extinction cross sections for air appropriate for CALIOP are given in NASA documentation by Powell et al., (2010) as 5.167 x 10^{-31} m^2 and 5.930 x 10^{-32} m^2 sr^{-1} respectively. Using the methods of Bucholtz et al (1995), the molecular number density N_S in standard air (defined at reference atmospheric pressure P_S = 1013.25 mbar and temperature T_S = 15 °C) is 2.54743 x 10^{25} mol. m^{-3}, so (assuming that the atmospheric equation of state is accurately represented by the ideal gas law) the molecular backscattering coefficient at any altitude *h* is given by

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

where σ_{back} is the backscatter cross section given above, and *P(h)* and *T(h)* are the pressure and the temperature of standard atmosphere. ~~In order to calculate the total backscatter coefficient β_{tot}, the EARLINET particulate backscatter coefficient is used as β_{par} in Eq. (3) and the molecular backscatter coefficient β_{mol} is provided as a Level 1.5 data product.~~ The two-way transmittance for a downward-looking lidar is calculated using the following equation:

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

where *top* is the highest altitude of the profile (nominally 20 km), and *α(z)* is the total extinction coefficient, which is the sum of the particle extinction coefficient α_{par} and the molecular extinction coefficient α_{mol}.

The particle extinction coefficient α_{par} is calculated according to

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

where β_{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 are provided by EARLINET stations only for a small fraction of the coincident measurements. The reason is that the lidar system needs to be equipped with a Raman channel for independent extinction profile measurements, and these measurements are available only during night-time because of low signal-to-noise ratio during daytime. Therefore, the lidar ratios used in this study correspond~~ed~~ to the aerosol types identified in the CALIOP Level 1.5 data set. ~~The EARLINET extinction coefficients α_{par} were then calculated using Eq. (6).~~The extinction coefficients α_{par} were estimated from the EARLINET backscatter coefficients β_{par} by using Eq. (6), where the lidar ratios S_a were extracted from CALIOP.

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

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

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

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

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

The correlation coefficient R is defined in the usual way as

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

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

The mean bias (MB) is defined as:

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

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

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

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

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

3 Results

3.1 Case studies

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

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

The second case study was carried out for a CALIOP overpass over the Granada EARLINET station (Fig. 3) and it represents a Saharan dust event, which stretched from the region of western North Africa over Gibraltar towards the southern part of Spain. The hybrid single particle Lagrangian integrated trajectory model (HYSPLIT) (Draxler and Rolph, 2013) was used to analyse the origin of the air mass. The backward trajectory analysis confirms that the air mass came from Africa, the Sahara region. The results of the analysis are shown in Fig. 4. The attenuated backscatter vs. altitude is shown in the left panel of Fig. 5. A dust layer is detected between 4 km and 6.5 km by both lidars, however, the CALIOP profile differs from the EARLINET profile at the higher altitudes by an amount outside the uncertainty bounds of the instruments. There are some additional discrepancies between CALIOP and EARLINET measurements (left panel of Fig. 5). The top of the CALIOP-detected dust layer is approximately 500 m higher. There were two distinguishable aerosol layers in the EARLINET backscatter profile, namely the primary one between 5 km and 6 km altitude and a secondary one around 2 km altitude. However, the secondary layer in the PBL region is barely distinguishable in the CALIOP profile.

Those differences between ~~the~~ two profiles could happen for ~~two~~ few reasons. ~~First, the measurements were performed at a separation distance of 67 km, and therefore CALIOP and EARLINET are not measuring exactly the same portion of the dust layer.~~ Since Granada is located in a valley, the temperature inversion is pretty usual phenomena there. The inversion could trap the pollutants that form near ground-level. It is worth to mention also that both measurements were separated by a distance of 67 km with the Sierra Nevada mountain range (elevation 3.5 km) between the station and the CALIOP track. As a result, all earlier mentioned circumstances (the mountains, the temperature inversion and the distance) could limit the CALIOP's abilities to detect the local pollution within the PBL. In contrast, this local pollution event was successfully detected by the EARLINET station in the valley. Another reason for the discrepancy could be ~~Second,~~ an invalid CALIOP aerosol type classification. However for this specific case, CALIOP detected the layer as a dust layer and the lidar ratio S_a provided in EARLINET file was equal to 55 (dust). That eliminates the possibility of invalid type classification for this case. It is likely that local topographic location combined with trapped local pollutants during the summer period (e.g. smog) negatively ~~the CALIOP measurements were performed in the top down direction and there may be sufficient attenuation to make it more difficult to detect a second layer below. These issues~~ influenced~~d~~ the ~~mean bias and the correlation between backscatter profiles~~agreement between the CALIOP and EARLINET measurements. As a result, the correlation between ~~the~~ two profiles is not as strong as in the first case, during which no obvious obstacles were present between the Barcelona EARLINET station and the CALIOP track on Mediterranean Sea. Thus for the second case, ~~:~~ the correlation coefficient ~~for this case~~ was 0.47 while the mean bias was -0.09 $Mm^{-1}sr^{-1}$. Consequently, the factor of exceedance was -0.15, which shows that 65 % of the CALIOP total attenuated backscatter values were lower than EARLINET values.

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

3.2 ~~–~~EARLINET-CALIOP comparison with ground track distance 100 km ~~Summary of CALIOP overpasses with ground track distance ≤100 km~~

From November 2010 to December 2012, 48 CALIOP overpasses occurred within a 100 km distance from an operating EARLINET station, with aerosol layers classified as dust, polluted dust, clean marine, clean continental, polluted continental, mixed and/or smoke/biomass burning. These 48 overpasses resulted in 7405 data points that were deemed valid for evaluation against EARLINET. The scatterplot of CALIOP and EARLINET attenuated backscatter values for all of these data points is shown in Fig. 6.

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

3.2.1 PBL and FT with ground track distance 100 km

~~PBL and FT with ground track distance ≤ 100 km~~

The PBL height was assumed to always be 2.5 km for this analysis (Mattis et al., 2004; Pappalardo et al., 2004). The scatterplots for the separated PBL and FT datasets are shown in Figs. 8 and 9 and characterized by R, MB and FoE parameters (Table 2).~~The PBL height was assumed to always be 2.5 km for this analysis . The scatterplots for the separated PBL and FT datasets are shown in Fig. 8 and 9. In our analysis, averaging of CALIOP data is performed along the closest 100 km ground tracks and the statistical agreement is characterized by R, MB and FoE parameters (Table 2).~~

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

The aerosol layers in the free troposphere are often characterized by smaller horizontal variability compared to the PBL, it is then likely that a higher EARLINET-CALIOP correlation can occur in the FT.~~Free tropospheric aerosol layers are more uniform and have less spatial variation, therefore the comparisons between CALIOP and EARLINET in the FT show higher correlations.~~ ~~-~~On the other hand, the boundary layer, especially during convective periods, undergoes higher temporal and spatial variability due to continuous PBL updraft and FT downdraft. That could influence lower correlation between CALIOP and EARLINET in the PBL. Moreover, when an aerosol layer occurs in the FT, it attenuates the CALIOP lidar signal that will have less energy to penetrate further down into the PBL. ~~Boundary layer aerosol, on the other hand, is less homogeneous. That could be a result of the presence of aerosol layers in the FT and PBL at the same time. In this case, the first layer would attenuate the lidar signal and the signal would have less power to penetrate a second layer.~~ To investigate that idea, data filtering with threshold values from the second case study were used. However, this choice reduced the amount of CALIOP overpasses from 48 down to 27, while the number of data points available for the comparison dropped from 7405 down to 3398.

3.2.2 Filtered PBL and FT with ground track distance 100 km

~~3.3 PBL and FT using data filtering~~

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

The scatterplots of the attenuated backscatter for CALIOP and EARLINET after applying this data filtering are presented in Fig.10 and 11. The correlation between the two sets of attenuated backscatter measurements became stronger in the PBL ($R = 0.65$), while the same parameter for the FT decreased from $R = 0.85$ to $R = 0.79$. Correspondingly, the other statistical parameters improved for the PBL (MB = -0.09 and FoE = -0.09) ~~and~~ but they decreased by a factor of two for the FT (MB = 0.03 and FoE = 0.11).

~~Filtering also improved the agreement between CALIOP and EARLINET for different types of aerosol in the PBL. Figures 12a and 13a show that clean air (according to the CALIOP documentation, this type is flagged when no aerosol is detected) cases have the best correlation (0.61 and 0.80, PBL and FT respectively) among all aerosol types, because clean air has very little spatial variability.~~

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

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

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

On the other hand, the polluted continental aerosol originates from local sources, which is consistent with the fact that CALIOP detected this type exclusively in the PBL (Fig.12e); however, this localization affected CALIOP's ability to represent the variations of the polluted aerosol, because significant spatial averaging is required to obtain adequate SNR. Strong local sources could result in ~~a~~ higher temporal and spatial variability ~~very inhomogeneous aerosol distribution~~ in the PBL.~~;~~ T~~t~~herefore, a poorer correlation ($R = 0.37$) between CALIOP and EARLINET could be a result of different area coverage for the two methods.

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

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

4 Conclusions

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

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

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

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Table 1 EARLINET stations that had coincident measurements with CALIOP during the observational 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	Ispra, 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

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

Region	R	MB ($Mm^{-1}sr^{-1}$)	FoE
Entire range	0.86	0.03	0.17
PBL	0.60	-0.14	-0.12
FT	0.85	0.06	0.22

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

Region	*R*	MB ($Mm^{-1}sr^{-1}$)	FoE
Entire range	0.84	0.01	0.08
PBL	0.65	-0.09	-0.09
FT	0.79	0.03	0.11

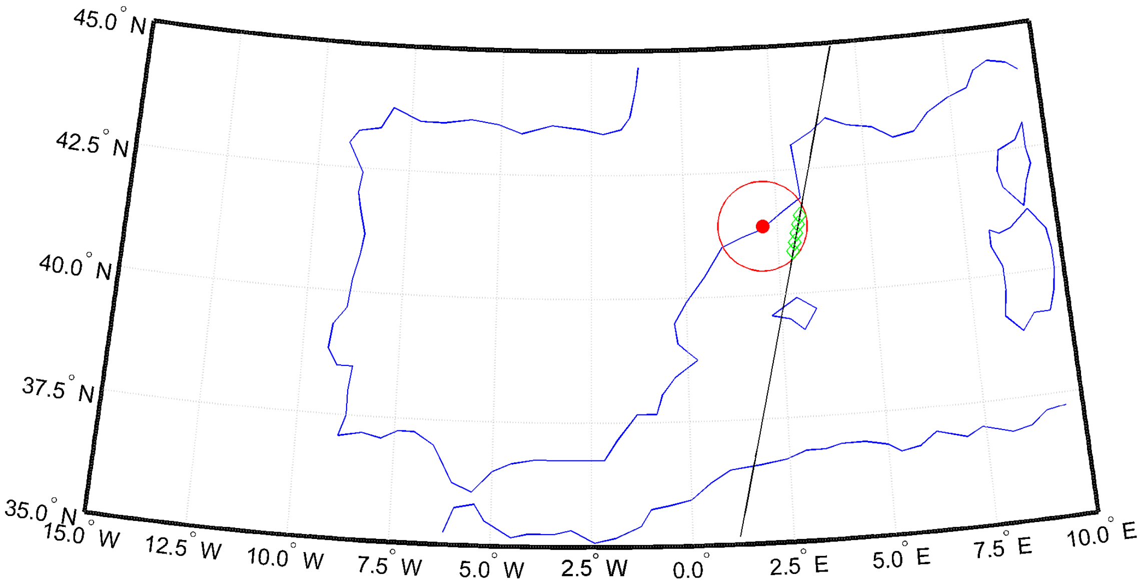


Figure 1 CALIOP overpass over Barcelona station on 20 September 2011 at 02:00 UTC at 77.9 km distance from the station. The red circle shows 100 km distance from the EARLINET station (the red dot in the center). The black line represents the CALIOP ground track, while the green empty diamonds represent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

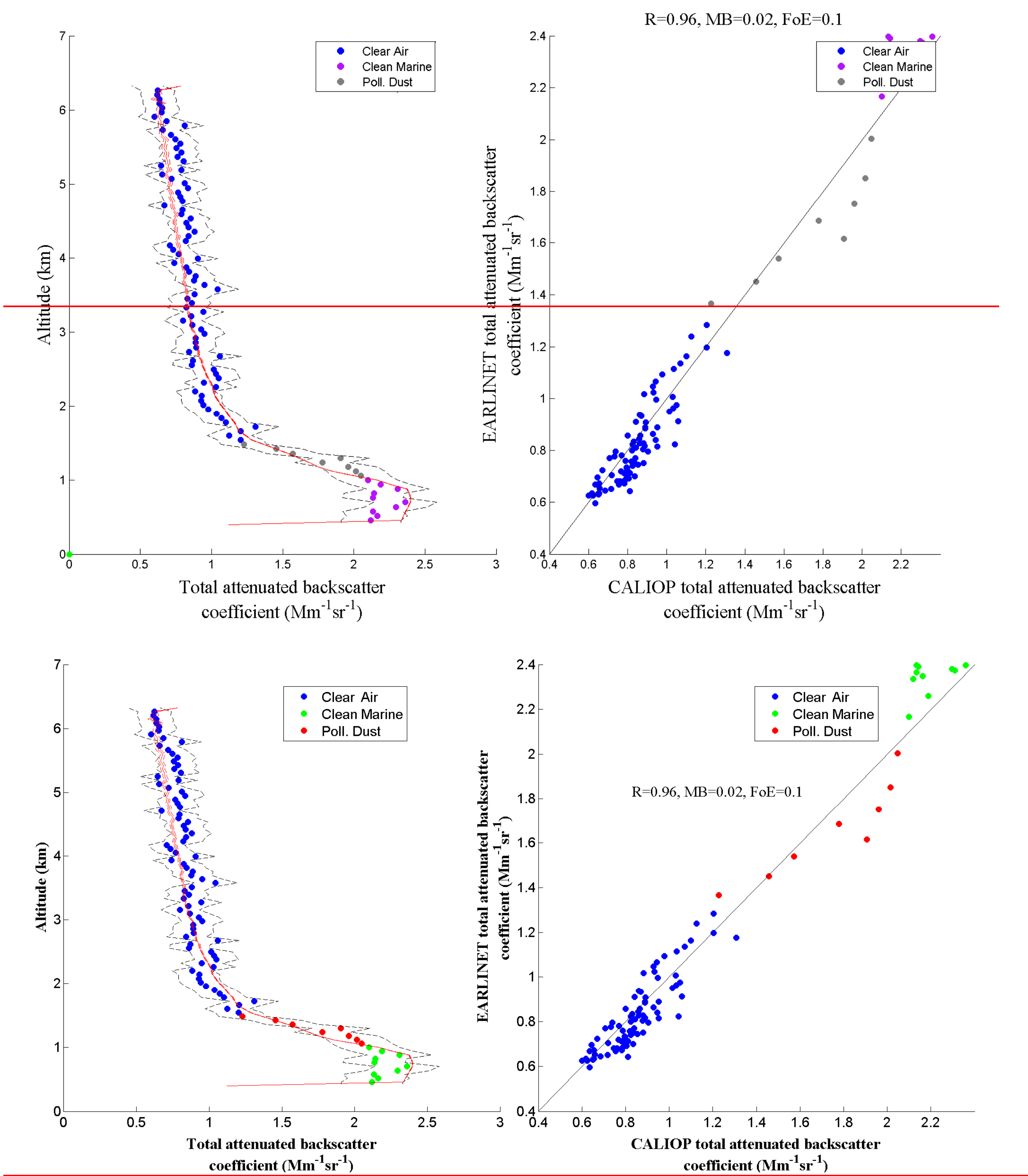


Figure 2 Left panel: attenuated backscatter versus altitude for a CALIOP overpass at Barcelona station on 20 September 2011 at 02:00 UTC at 77.9 km distance from the station, (the red line shows the EARLINET attenuated backscatter profile, the red dashed lines show EARLINET uncertainties, the dots represent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

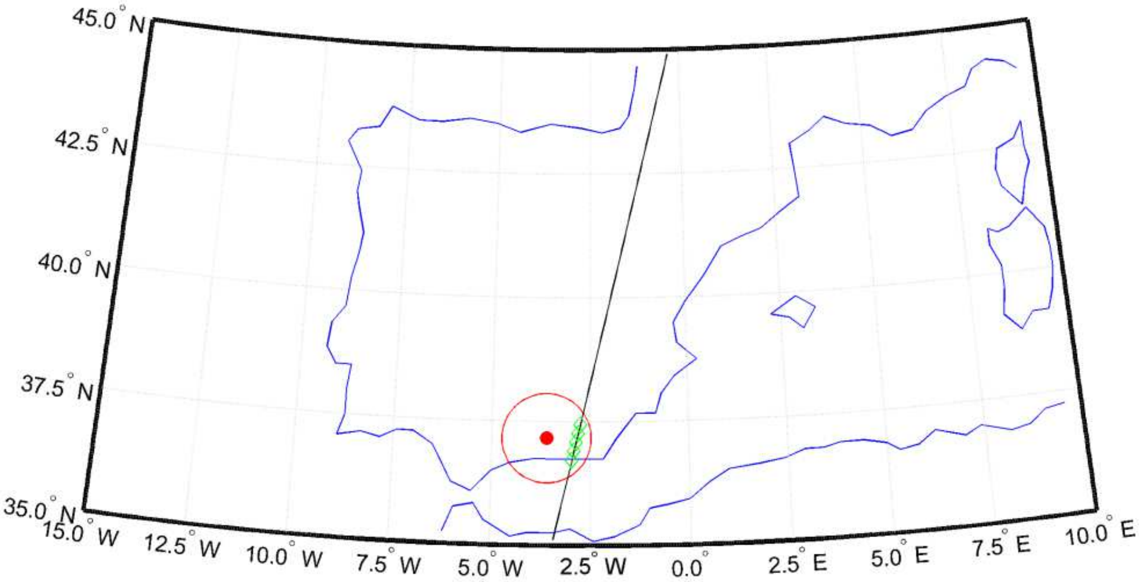


Figure 3 CALIOP overpass over Granada station on 7 July 2011 at 02:20 UTC at 67 km distance from the station. The red circle shows 100 km distance from EARLINET station (the red dot in the center). The black line represents the CALIOP ground track while the green empty diamonds represent five CALIOP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

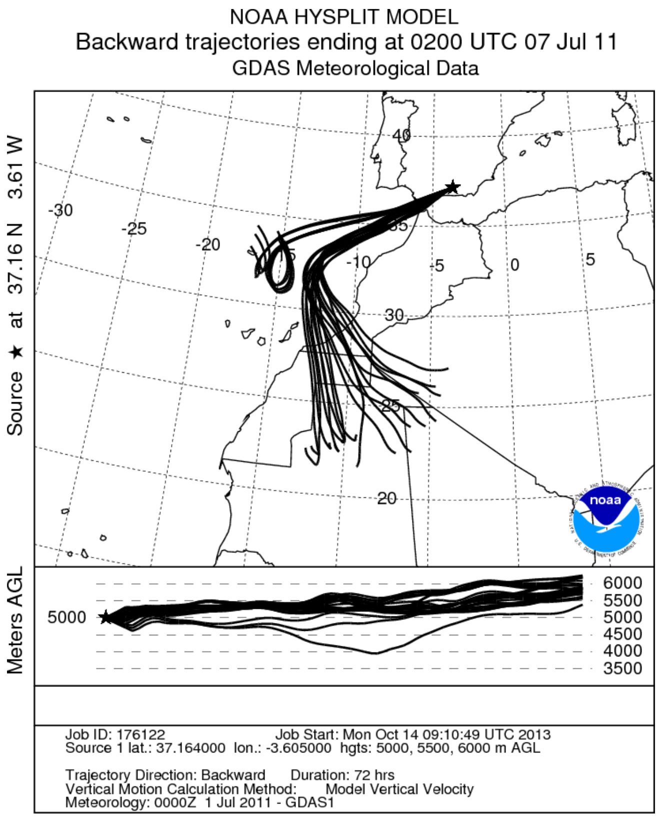
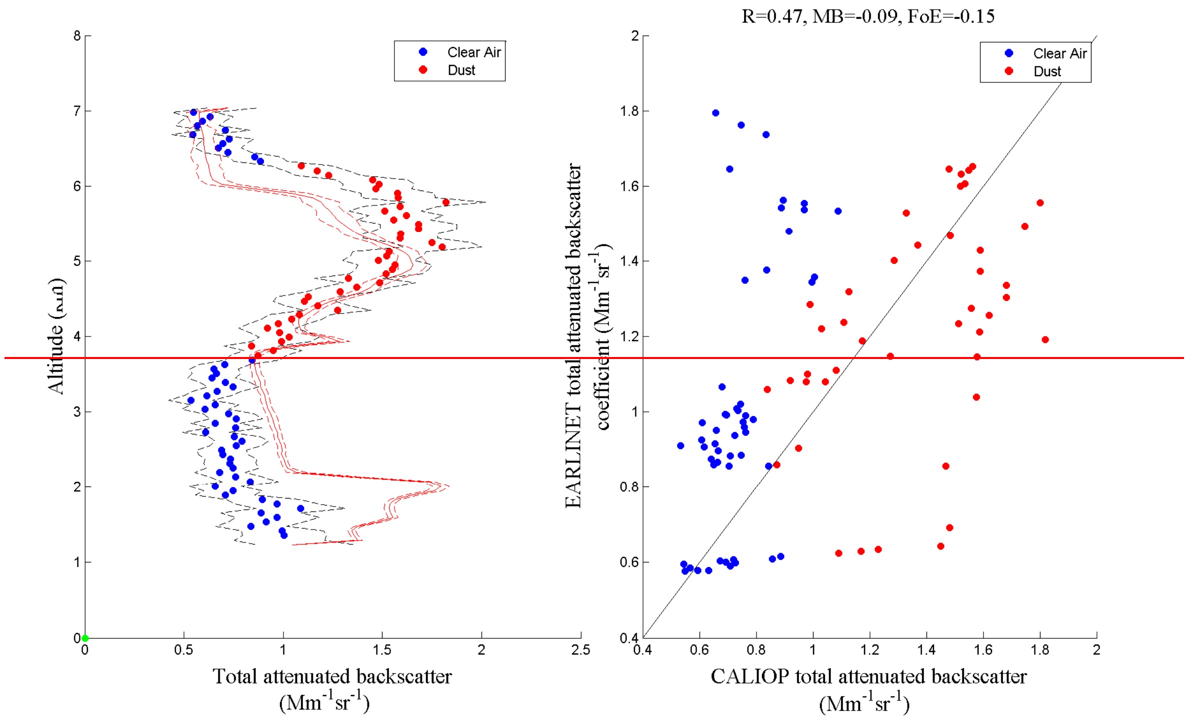


Figure 4 Hysplit backward trajectories for the overpass over the EARLINET station in Granada on 7 July 2011 at 02:00 UTC confirm that the air mass came from the region of western North Africa, over Gibraltar, and towards the southern part of Spain.



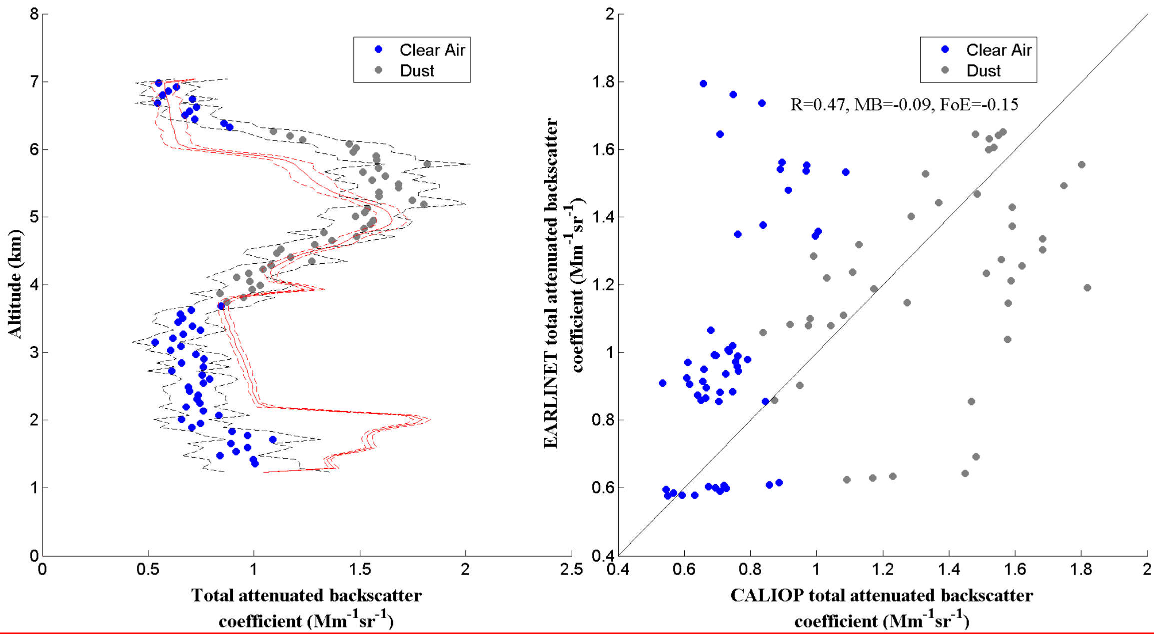


Figure 5 Left panel: Attenuated backscatter versus altitude for a CALIOP overpass over Granada station on 7 July 2011 at 02:20 UTC at 67 km distance from the station (the red line shows the EARLINET attenuated backscatter profile, the red dashed lines show EARLINET uncertainties, the dots represent CALIOP 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)

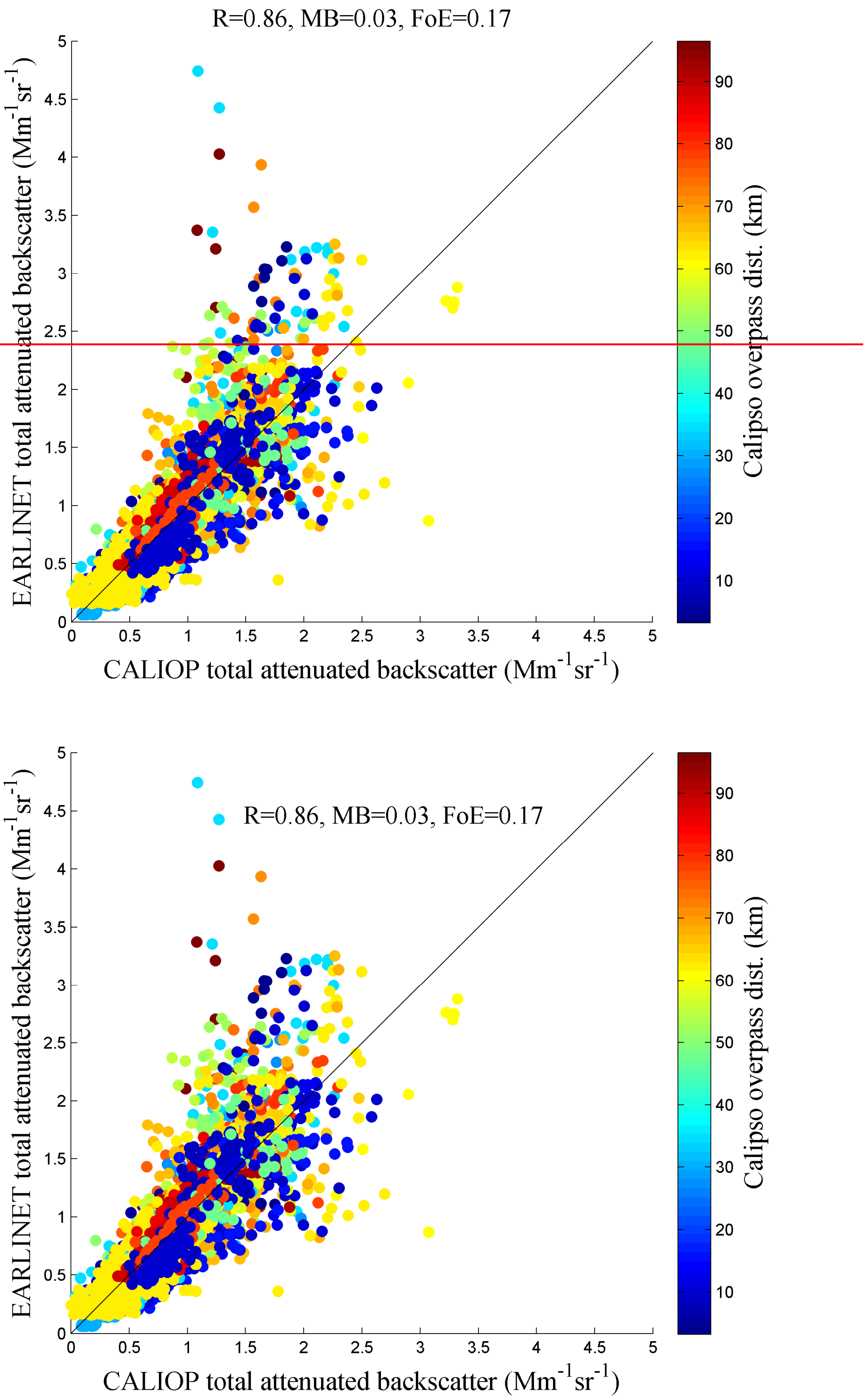


Figure 6 CALIOP vs EARLINET total attenuated backscatter for CALIOP overpasses over EARLINET stations within 100 km ground track offset distance. The colour scale shows the ground track distance from the EARLINET station.

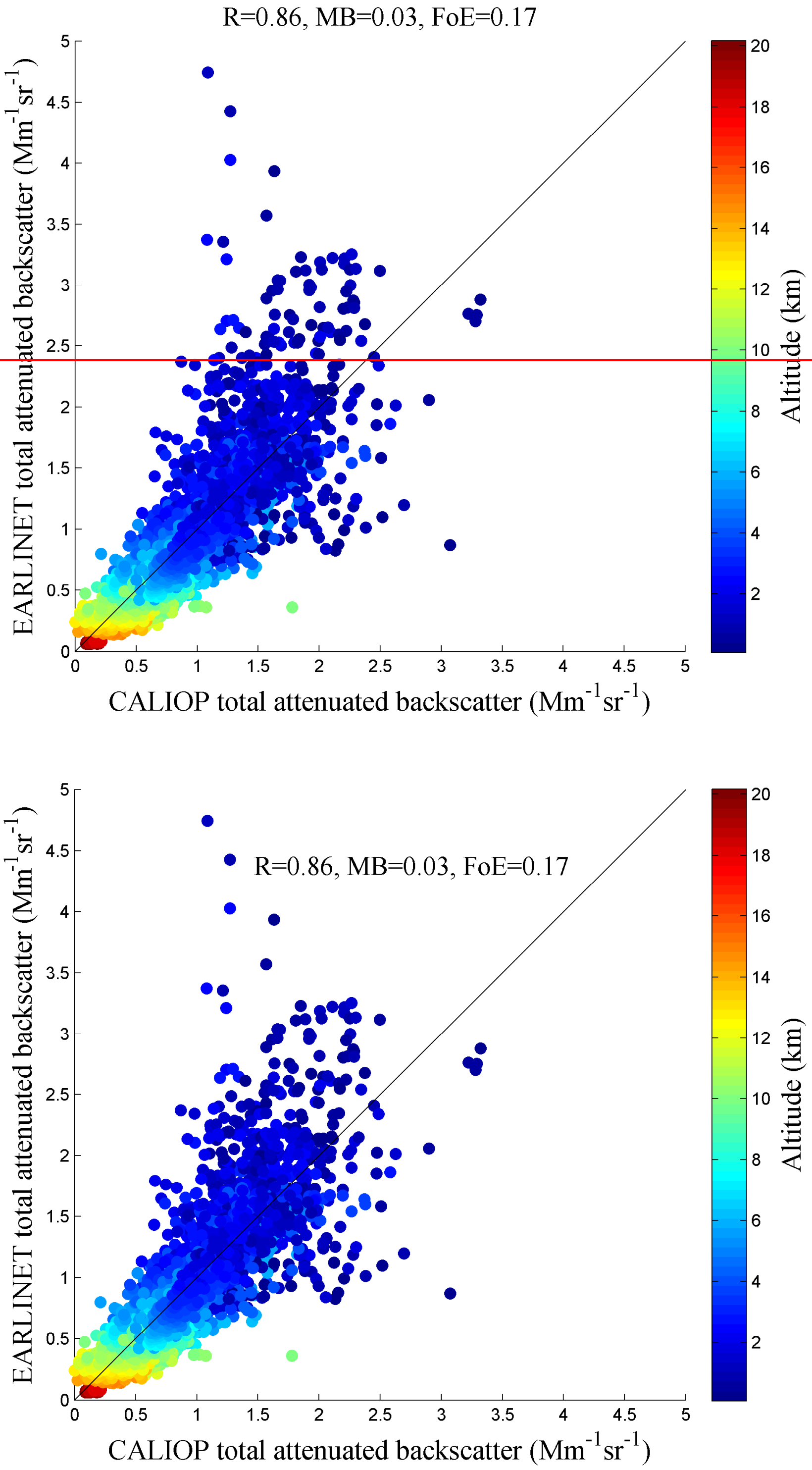
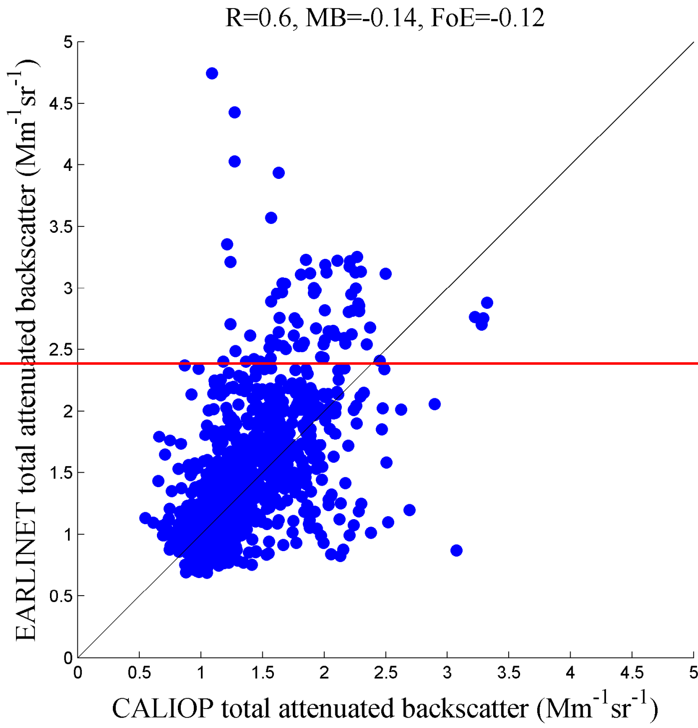


Figure 7 CALIOP vs. EARLINET total attenuated backscatter for CALIOP overpasses over EARLINET stations points within 100 km ground track distance, with colour coding showing the aerosol layer altitude.



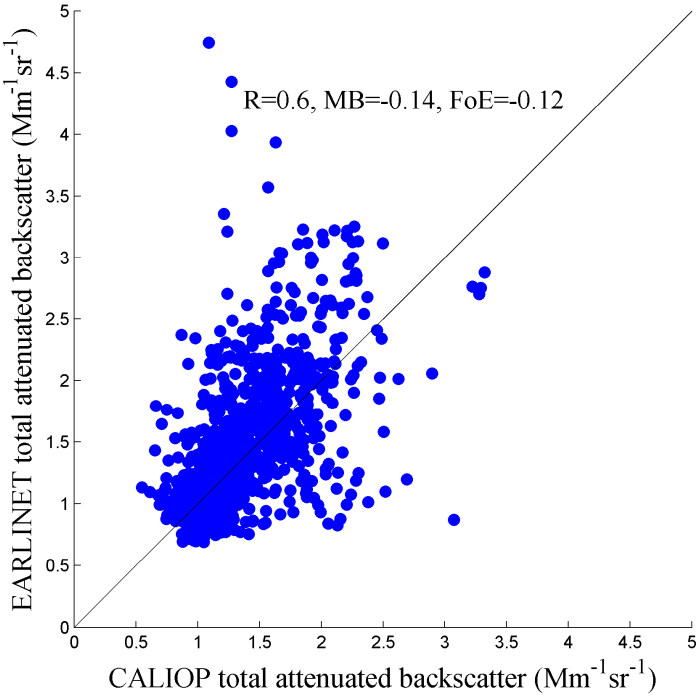
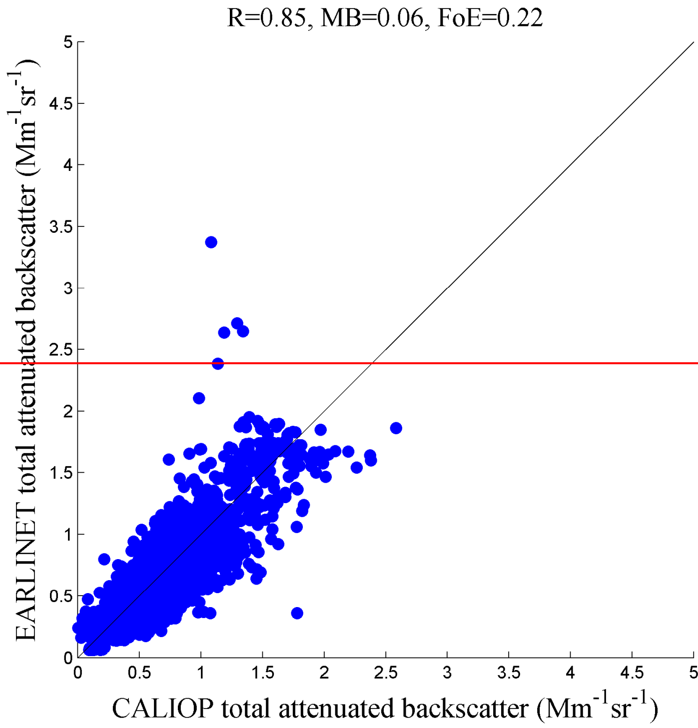


Figure 8 CALIOP vs EARLINET total attenuated backscatter for CALIOP overpasses over EARLINET stations for the PBL only, within 100 km ground track distance.



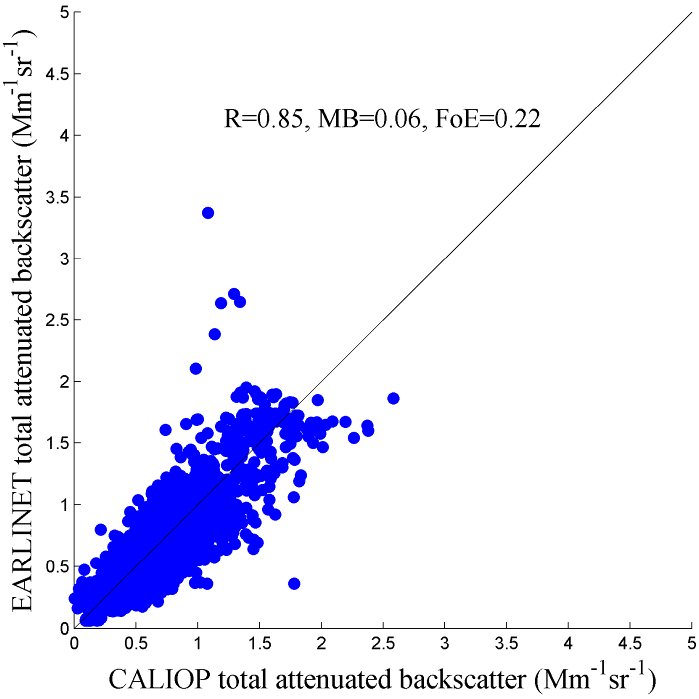
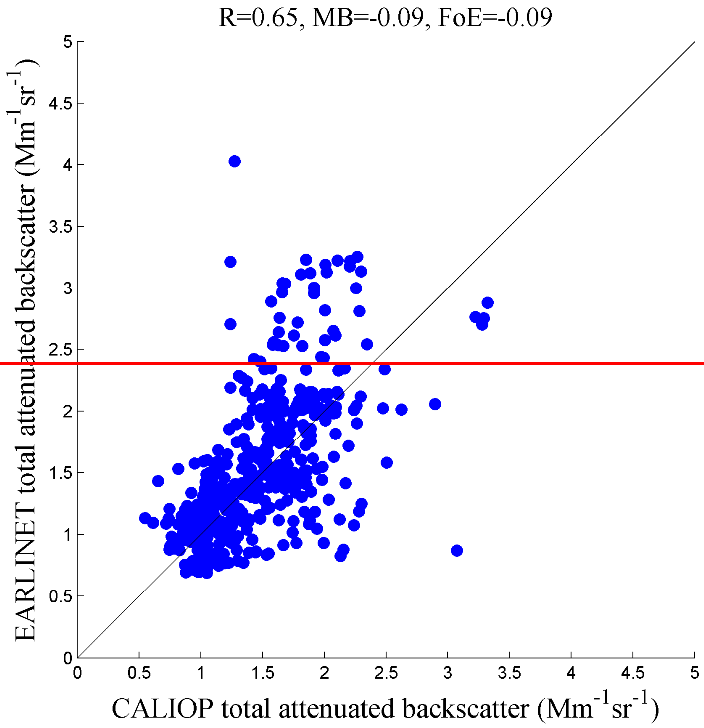


Figure 9 CALIOP vs. EARLINET total attenuated backscatter for CALIOP overpasses over EARLINET stations for the FT_only, within 100 km ground track distance.



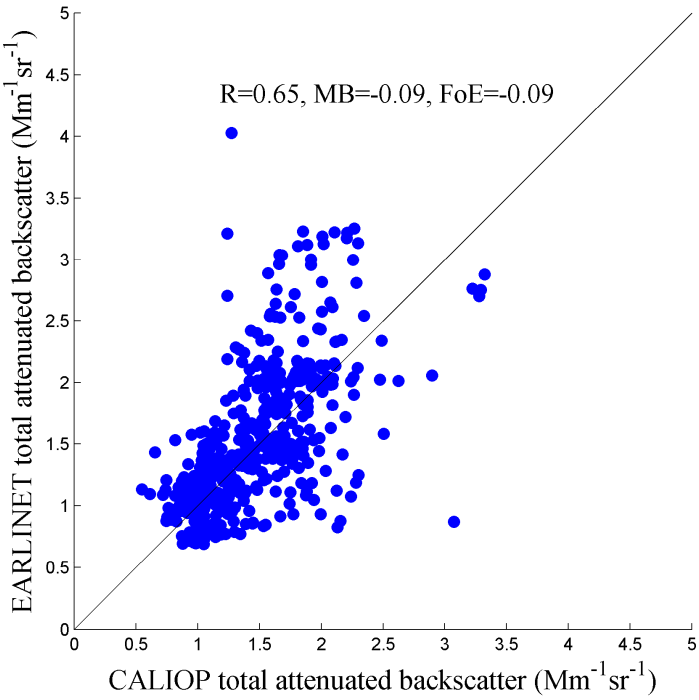
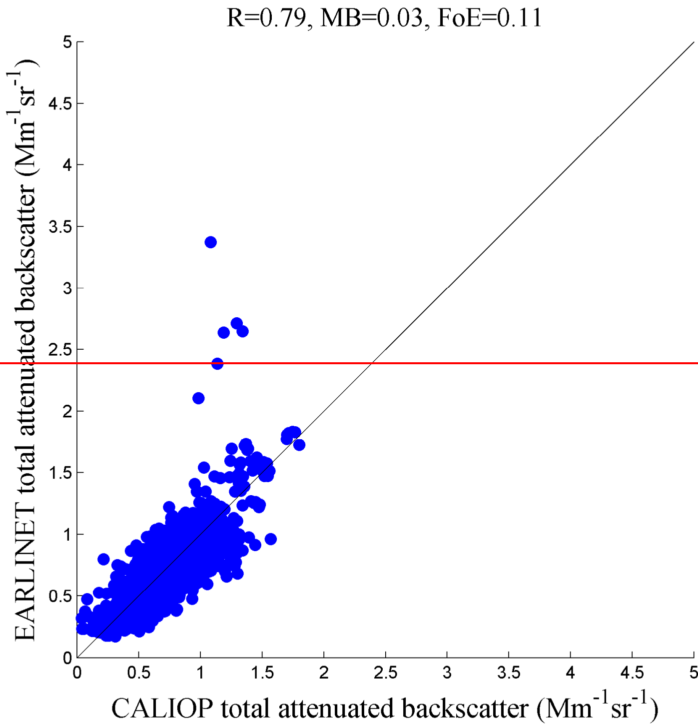


Figure 10 CALIOP vs. EARLINET total attenuated backscatter for CALIOP overpasses over EARLINET stations only for PBL. The plot includes all data points for overpasses without layers present in both the PBL and the FT.



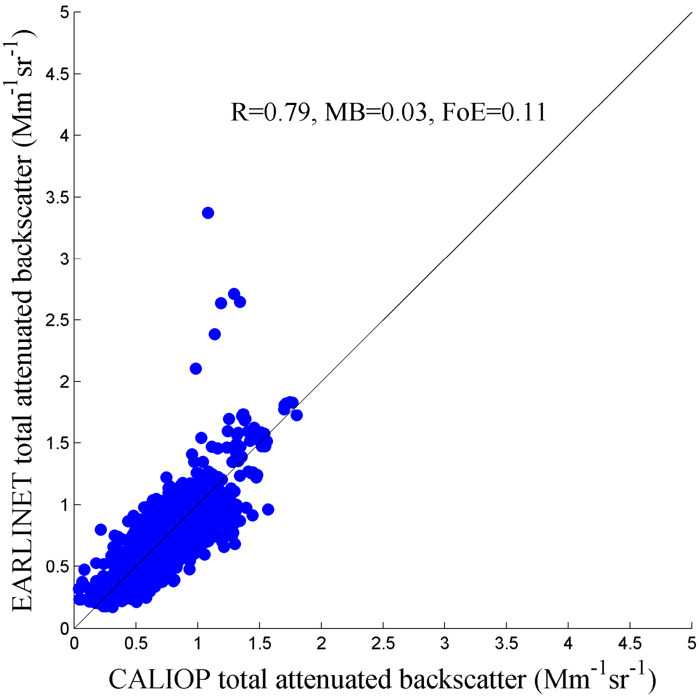
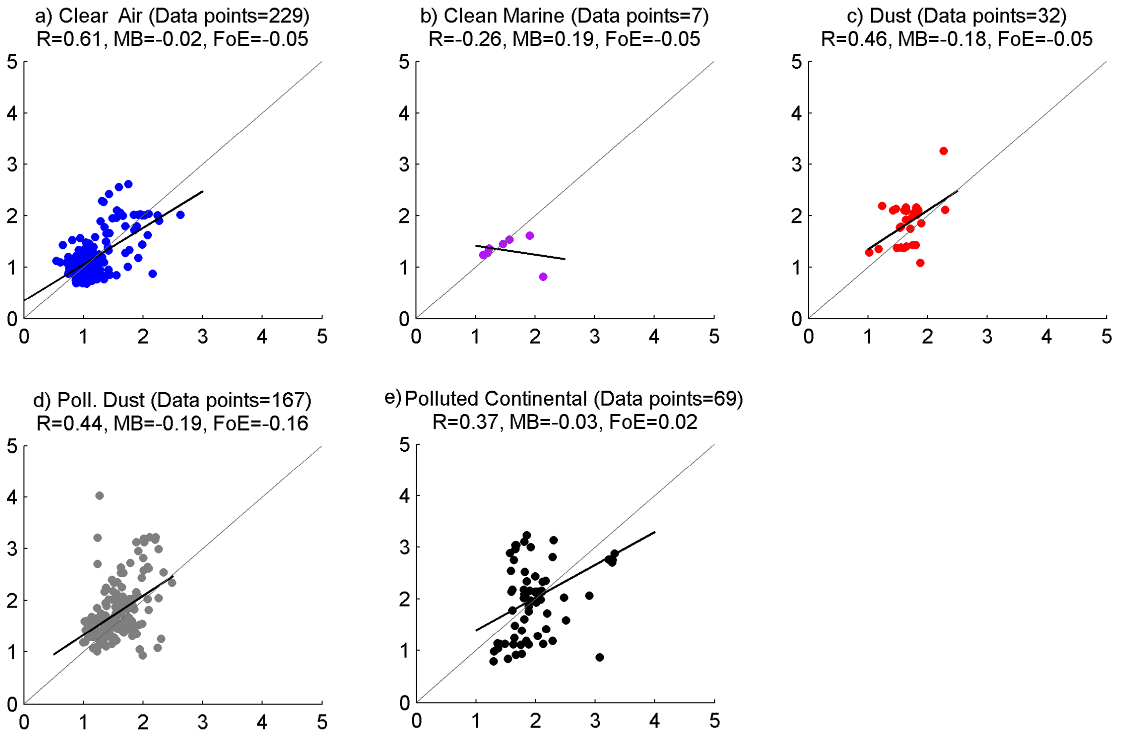


Figure 11 CALIOP vs. EARLINET total attenuated backscatter for CALIOP overpasses over EARLINET stations within 100 km overpass distance only for FT. The plot includes all data points for overpasses without present layers present in both the the PBL and the FT .



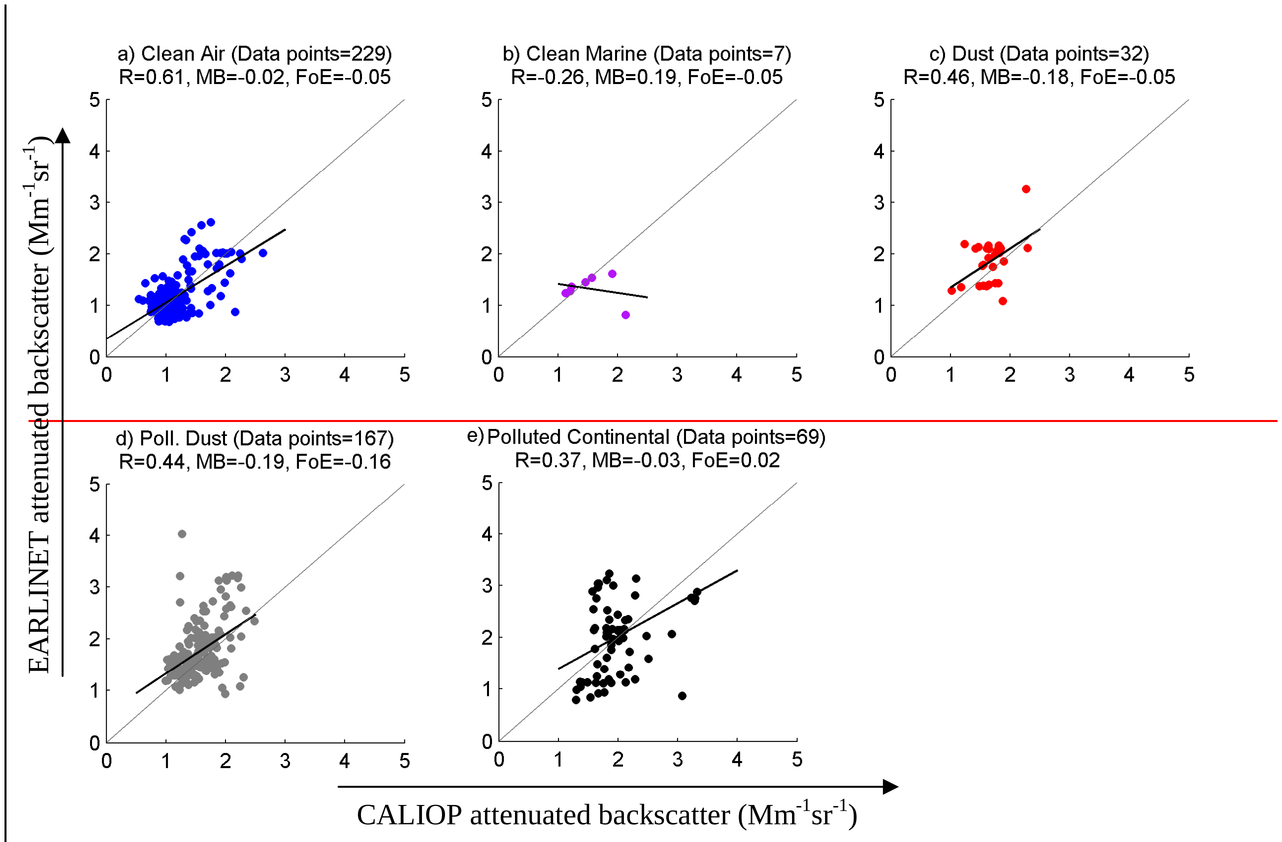
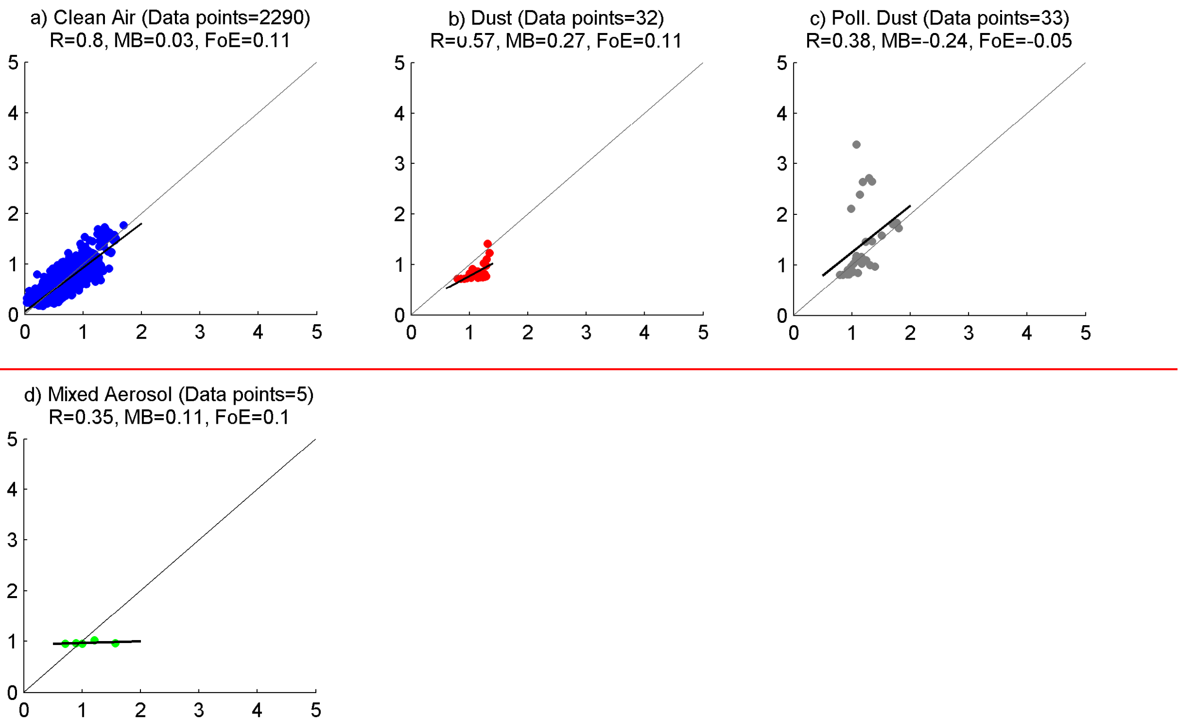


Figure 12 ~~Eight~~ Five level 1.5 feature types~~aerosol types~~ for CALIOP overpasses over EARLINET stations for the PBL. The plot includes filtered data points for overpasses without layers present in both the PBL and the FT.



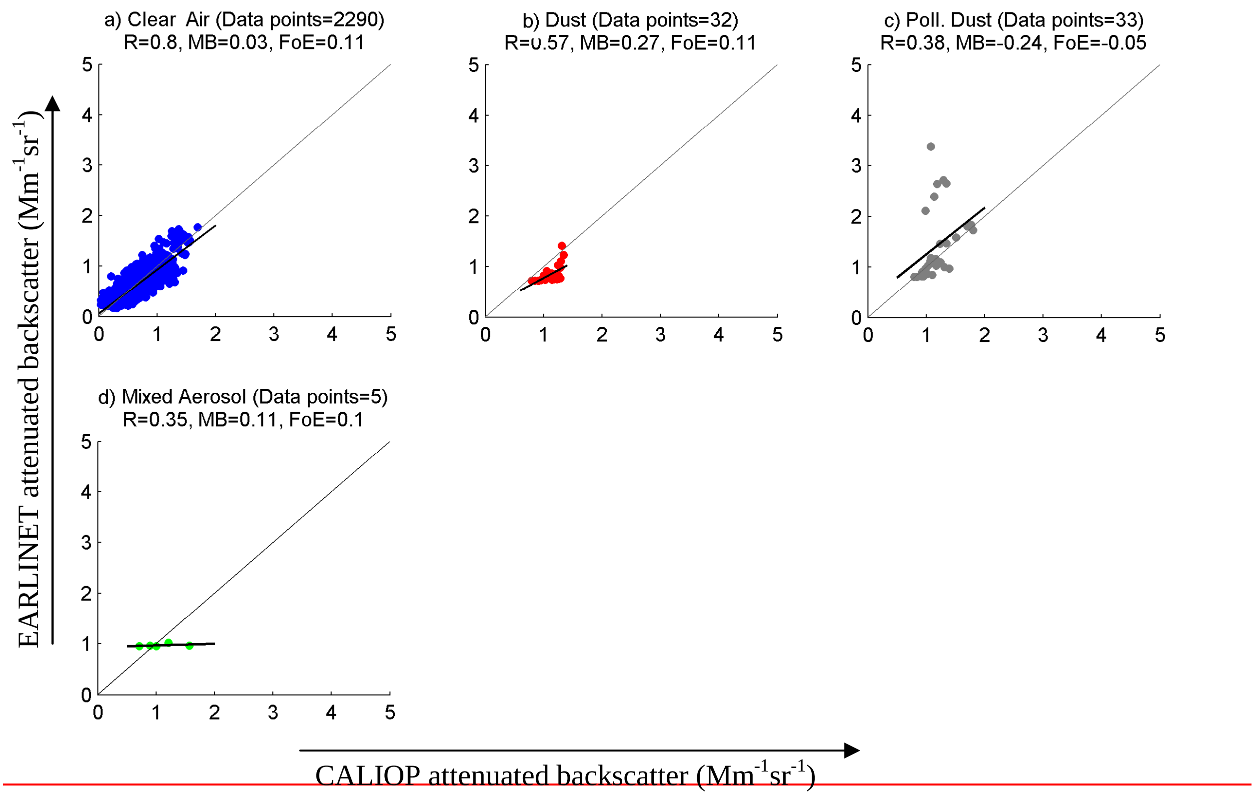


Figure 13 ~~Eight aerosol types~~Four level 1.5 feature types for CALIOP overpasses over EARLINET stations for the FT. The plot includes filtered data points for overpasses without layers present in both the PBL and the FT.