Anonymous Referee #1

We thank this Reviewer for his careful reading of the manuscript and for his suggestions to help us improve the paper.

The answers are given in a direct response (bold, italic).

The paper by Groß et al. investigates the contribution of Saharan dust to the boundary layer over Barbados as observed during SALTRACE. The paper is of interest to the scientific community but major revisions are necessary before further consideration for publication in ACP.

Major points:

A description of the used instrumentation is completely missing in the text. Section 2 should be revised to Instruments and Methods. There should be at least a table that provides an overview of the used instrumentation. The authors only mention auxiliary measurements with sun photometer and in situ measurements when they are already discussing results in Section 3.

We added a description of all used instrumentation and methods in Section 2.

It is not acceptable to use papers in preparation as references. Nothing is known about the status of these papers

We removed the papers in preparation as references but we kept the announcement that papers dealing with the same topic are in preparation.

The authors should consider restructuring the paper. It seems more straight-forward to first discuss the measured optical properties and later describe the subsequently retrieved parameters. This means that all optical properties should be addressed before Figure 4 is discussed.

We agree with this reviewer that a restructuring of the paper would be more straight-forward and followed his suggestion to first discuss the optical properties and then the subsequently retrieved parameters.

Greater care is necessary with respect to the investigated height range. The authors loosely vary between the terms convective marine boundary layer, convective boundary layer and just boundary layer. Are these meant to be the same things? Later they also discuss the transition layer and the Saharan air layer. It might be worthwhile to properly define all these layers in the example provided in Figure 2.

We are more consistent now.

Please make sure that the same tense is used throughout the paper.

We revised the paper to check the tense.

Statements of good and very good agreement need to be quantified.

We replaced these statements by more precise statements.

Minor points:

• Check the co-authors' affiliations. I believe it's Leibniz Institute.

We changed that.

• p1,l13: 80% seems like a normal value for RH in marine environment.

Indeed, 80% is a normal value for RH in marine environment. We mentioned that value as it justifies the use of optical properties for moist sea salt. We removed this statement in the abstract but mention this in the text.

• p1,l20: Are the measurements just used to support modelling efforts or rather to validate them?

Indeed, the measurements are also used to validate modelling efforts. We changed the text accordingly.

• p2,l11: Please elaborate on the point of efficient downward mixing.

We believe that the high values in the particle linear depolarization ratio in the layer below the well-defined Saharan Air Layer is already an indication that dust removal processes started to mix the dust out of the SAL down to the ground. We added this to the text.

p3,Section 2.2: More background is needed on how the conversion factors have been obtained. Did you apply any constraints for retrieving marine conversion factors from AERONET measurements at Barbados? Why are the factors almost identical for marine aerosol and mineral dust?

We provide now more information how the conversion factors are calculated.

To the question of the almost identical values: For large particles the aerosol extinction coefficient is mainly dominated by the size of the particles. As both, marine aerosols and mineral dust, are large particle types in the same size range also their conversion factor from extinction to volume should be almost the same.

• p4,l4: Does this mean that you use the gradient method to find the top height of the CMBL? Do you use the first gradient or the strongest gradient? Please provide more information.

The gradient method was applied to derive the top height of the CMBL which was defined as height range of the strongest gradient. Furthermore we used the change of the change of the intensive optical properties to strengthen our result. We changed the text to be more precise there.

• p4,Section 3.2: More details are needed regarding the analysis of the lidar measurements. You could provide those in an Instruments section: What is the averaging time of the lidar measurements? Were the lidar measurements performed during day or night? How did you analyze the data? Which lidar ratio has been used to derive the backscatter profiles?

We added a subsection in the 'Instrumentation and Method' section to describe the lidar system, analyzes of the data and specific information on the used data.

• p5,l12: Could the differences in lidar and sounding be the result of the two hours time delay between the two?

We do not believe that the missing capping inversion in the radiosonde at the CMBL top height derived from the gradient method is due to a two hour shift between both measurements. We

rather think that there was no strong capping inversion on that day. This would also explain the little difference in the intensive lidar quantities below the CMBL top height and above.

• p6,Figure 3: What is the general time difference between the lidar measurements and the soundings?

Typically the soundings were launched during the lidar measurement sessions, thus no or only little time difference is found in general. We added a subsection in the section 'Instruments and Method' which includes this information.

• p7,l3: Please elaborate what is meant with intensive lidar quantities for the unfamiliar reader.

Intensive lidar quantities are only dependent on the type of the observed aerosol or aerosol mixture. The intensive lidar quantities are not dependent on the amount of aerosols. We added a description in the text.

• p7,l12: I don't believe that this paper is the best reference on sea spray production.

We use this paper here as the authors conducted an empirical study of the relation between sea salt production and wind speed. We use their thresholds in this study.

• p8,Figure 5: Add mean/median/sd to the figure. Improve the scale in lidar ratio, i.e. 0 to 50 sr.

We show now mean, stdev, median and error of the mean in this figure and improved the lidar ratio scale from 0 to 50 sr.

• p10,l10: More details are needed for the in situ measurements used in the closure study. Which instruments are involved? How have those measurements been transformed to mass concentration? What is meant with "match in time"? Such criteria need to be provided in the paper.

We added a subsection in the 'Instrumentation and Method' section to provide information on the in-situ measurements and their analysis.

Anonymous Referee #2

We thank this Reviewer for his careful reading of the manuscript and for his suggestions to help us improve the paper.

The answers are given in a direct response (bold, italic).

The authors describe a case study of Saharan dust observed over the Caribbean with a dual wavelength lidar. In their paper, the authors describe time series of LIDAR (CIMEL and POLIS) measurements to highlight a study case (10 July 2013) and vertical profiles of this study case. They also provide a closure study based on the comparison of LIDAR retrieved parameters and in-situ measurements. This manuscript is of interest for the scientific community but need major revisions before submission to ACP.

MAJOR COMMENTS :

The scientific objectives of the study are limited to "provide detailed BL characterization as part of the vertical aerosol structure over Barbados during SALTRACE" as it play a significant role in the synergy between ground based, airborne and column integrated measurements. Could you state clearly how your results will help to link all these measurements? Could you also state if and how those results may be applied to different measurement campaign?

We changed the text to provide more infromation.

This paper is referring to LIDAR (POLIS and CIMEL), in-situ and radio-soundings measurements. There is no description of the used instruments, which is mandatory. Also every all the algorithms to correct the data, if existing, must be described in one specific section.

We included this information in the 'Instrumentation and Method' section.

Figure 4 : From the dust mass concentration shown in this figure, one can see that the variability is not important from day to day. The dust mass concentration is on average 40ug/cm3. Two outliers can be distinguished at 70and 100ug/cm3. That would have been really interesting to show the lidar profile for these two cases when dust are obviously mixed with sea salt.

We decided to not show another case study as we already showed a case with large dust contribution in the boundary layer. We included now the values from the case study in Figure 4 (now Figure 5).

Looking closely to the values for the study case (10/07/2013) the values are always below 40ug/cm3 and increasing throughout the day. Now from the profiles shown in Figure 2 the average mass concentration of dust within the CMBL is about 110ug/cm-3. This strong difference makes questionable the quality of the data used in Figure 2 or in Figure 4.

The reviewer is right that the value shown in Figure 2 is missing in Figure 4 (now Figure 5) as we used only synchronized lidar and radiosonde measurements for consistency of the analysis shown in Figure 3 and (now) Figure 5.

MINOR COMMENTS :

Could you provide a map to show the location where SALTRACE took place ?

Instead of showing a map of the SALTRACE location we referenced the SALTRACE overview paper in BAMS providing all necessary information about the SALTRACE campaign.

Although, Denjean et al 2015 found (based on model results) that optical properties of one dust plume particles were not modified during their transport over Atlantic, many studies have shown differences in the dust size distributions, in the dust morphology, and also on the dust optical properties including dust polarization (Bréon et al. 2013). Why you are stating that here ? Is it related to your choice of a mean depolarization ratio of 0.30 ? If yes then you should lead the reader into it cause I don't see the point here. Also, Burton et al. (2015), using HSRL measurements, highlight a dust particulate depolarization ratio of 0.32 over the Caribbean islands. You should spend more energy on why you choose 0.30.

We refered to the work of Denjean et al 2015 to justify that we do not consider changes in the particle depolarization ratio due to the high relative humidity. We thus took a mean value for the linear particle depolarization ratio of dust of 0.3 found during former studies (e.g.Freudenthaler et al., 2009; Liu et al., 2008, Groß et al., 2011) which is in good agreement with the values we found during the same campaign within the Saharan air layer over Barbados from our measurements (Groß et al., 2015). We tried to this more clear in the text.

P3, L8 Remains not remains

We changed that.

Dust volume and mass conversion: You use a conversion factor of 0.65.10-6 m. According to previous studies large aerosols do not reach the Caribbean coast (Maring et al. 2003). So this factor should not remain the same over the dust source and after few days of transport. Could you precise if the Gasteiger study was referring to fresh or aged dust ? Moreover it appears difficult to compare a factor obtained from measurements over the source (SAMUM) to a factor obtained after transport (SALTRACE). How did you calculate this factor ? It seems that you use the aerosol volume from AERONET measurements (integrated over the column) and an extinction coefficient from the LIDAR (at which altitude ?). What are the errors associated with this coefficient (AERONET volume errors + Lidar ratio errors + density errors)? Did you perform a closure with the AOD from AERONET and the AOD from your LIDAR data ?

From the measurements of size distribution we do not confirm that no large particles reach the Caribbean coast (see Weinzierl et al., 2016, van der Does et al., 2016). Analyses of the conversion factors from sunphotometer measurements confirm that the value does not change significantly during transport and that the conversion factor derived with the method described in Gasteiger et al. is still valid for long-range transported Saharan dust although the reference ensemble of Gasteiger et al. is referring to dust near the source region (measurements performed in Morocco). The conversion factor derived with the method described by Gasteiger et al. is the ratio of volume to extinction. The value from sunphotometer is also derived by first calculating the volume, the extinction, and the ratio of both using the aerosol mixture retrieved by the AERONET inversion algorithm for the calculation. We provide now an improved description of the method. For detailed information about the methods we included the references to the corresponding publications.

This factor is depending on the altitude, right ? Bigger SS at the surface, dust mixed with SS and pure dust over those layers.

We believe that in the convective marine boundary layer, which is characterized by mixing processes, we do not have to take any height dependency of the particle properties or conversion factors into account, especially not in the height ranges we are able to observe with our lidar system. Maybe this is different in the lowermost meters above ground, but we miss these height ranges with our observations.

You choose to use a density of 2.5g/cm3 assuming that dust are mixed with sulphate. Earlier you state that dust chemistry was not changing during the transport. If there is any sulphate on a dust particle, even a little bit, then the dust becomes hygroscopic (Roberts et al., 2001) and the optical properties are not the same than pure dust. You need to clarify this point

Measurements of the chemical properties of dust near the source region (Kaaden et al., 2009) and over Barbados (Kandler et al., in preparation) show that there is always a portion of sulfate externally mixed (Weinzierl et al., 2009) in the Saharan air layer. Thus, the statement that we do not see changes in the chemistry also includes that we do not see changes in this external mixture and that the dust particles are not coated with the sulfate at the end of the long-range transport across the Atlantic Ocean.

You need to show the data that provide you enough information to chose 0.65 .10-6 m for dust and 0.66 .10-6 m for sea salt particles.

We decided to not show all the measurements of the measurement period from 2007 to 2015. These measurements are freely available on the AERONET webpage and can be reviewed there.

Could you provide the extinction profile retrieved for the 10 July 2013 study case ?

We included the extinction coefficient profile in the case study.

P6 L4 You say that dust particles contribute to 100% of the total aerosol volume so why is there no pure dust in Table 2 ?

Table 2 only includes measurements within the CMBL while the dust contribution of 100% refers to height ranges above 1.6 km in the shown case study.

From what I understand, you used the wind speed to say that SS can be generated at the surface, the wind directions to say that wind are mainly coming from East / North- East, and the relative humidity is always larger than 60% and in average 80%. Does that need to be plotted ?

This information is already shown in Figure 3.

What can we learn based on your CMBL height retrievals ? You say that some cases are not well retrieved by the LIDAR and you say why. Is there a solution to avoid those mistakes with this kind of LIDAR ?

We do not think that you can avoid these mistakes. However what we show and also state in the text is that if the gradient is so small that it would lead to this kind of mistake, then the intense optical properties do not change significantly between the lower layer and the layer above.

Figure 5 : Could you change the scale of the Lidar ratio plot ? The values are between 15-35 and your scale is between 0-100. What are the green and blue dots represent?

We changed the scale for the lidar ratio to values from 0 to 50 sr. We clearly indicate the meaning of the different symbols in the figure caption.

Section 3.6 : What kind of in-situ measurement did you use ?

The description of the in-situ measurements is now added in Section 2.

- The correction you apply to these unknown in situ data is based on OPAC desert mixture and assuming 10um particles reach the barbadoes. What is this correction about? You cannot use a correction factor that please you without explaining the reader what you exactly did. - You are only looking to data that 'match in time'. What does that mean ? Is it a window of an hour, 10 minutes? - This closure doesn't conveniently take into account the larger values of dust concentration. In the figure caption remove the second 'dust'

For the derivation of this correction factor we use the OPAC desert mixture and calculate the aerosol volume of this mixture for upper cut-off radii of 5 and 10 micrometer. We calculate the ratio between both volumes, assuming that a cut-off radius of 10 micrometer is valid for dust reaching Barbados and a cut-off radius of 5 micrometer is valid for the instrument. This factor is about 1.25 and is applied to the PM10 measurements to calculate the ambient dust volume. However, as the uncertainty about the size distribution of dust after long-range transport is large, we consider an uncertainty of +-0.25 which also covers the case that no aerosol with r > 5 micrometer reaches Barbados.

The summary is not giving any conclusions or any clue to better improve the relation between ground base and remote sensing measurements. You should be careful in the summary and say that you were able with this case to link ground based measurements to remote sensing measurement but that for other cases it might not be as easy to achieve. You also need to tell the reader why you were able to do it (mixing condition with the BL, Just two type of particles etc.

We reworked the Summary.

Anonymous Referee #3

We thank this Reviewer for his careful reading of the manuscript and for his suggestions to help us improve the paper.

The answers are given in a direct response (bold, italic).

General comments

The paper presents a case study related to SALTRACE campaign addressed to the characterization of the boundary layer with the presence of a mix of aerosol (dust and maritime) in the Caribbean area during a Saharan dust transport. It deals with a very interesting topic for the scientific community involved in atmospheric research because it provides information that can be merged with other results coming from other papers produced for the same campaign, obtaining a large and exhaustive overview and interpretation of the atmospheric observations in a particular site and in several kinds of conditions. This gives the paper a value even if it is not particularly original.

The paper seems to be written with no sufficient detail in the discussions and justifications. Improvement and more care should be requested in English language, being present several English grammar typos errors.

We changed the manuscript considering the suggestions of this Reviewer. We modified the Summary and included a Section to discuss the results. We also checked on grammar typos errors.

Specific comments

Some general considerations

In order to give the paper more completeness and to allow a better understanding of the observations, the authors should link (and cite) a previous paper: "S. Groß, V. Freudenthaler, K. Schepanski, C. Toledano, A. Schäfler, A. Ansmann, and B. Weinzierl, Optical properties of long-range transported Saharan dust over Barbados as measured by dual-wavelength depolarization Raman lidar measurements, Atmos. Chem. Phys., 15, 11067–11080, 2015, www.atmos-che-phys.net/15/11067/2015/, doi:10.5194/acp-15-11067-2015", where most of the authors are the same, the lidar system is the same and also the measurement period is the same. In the present paper the authors address the study to a different day, characterized by a dominance of marine aerosols.

As suggested by this reviewer we linked and cited the previous paper in this work.

There are several references to papers in preparation for the same special issue. In my opinion, this is possible if some aspects presented will be furtherly analyzed and discussed in those, but this is strange if the results of those papers are used (e.g. Groß et al 2015, Haarig et al., Marinou et al.) before the corresponding peer review processes. In principle, the results or conclusions of those papers could also be rejected. This paper should have its own self-consistence and therefore the results of those other papers should be introduced in a different way, otherwise the paper should be accepted after the others will be accepted for publication.

We agree that the paper has to be self-consistent and thus we replaced the papers in preparation by peer-reviewed published papers

where a link to former or other work is needed. However we kept the announcement that papers dealing with the same topic are in preparation for this special issue.

In detail

Page 2, Lines 11-12: The authors write: "This strong increase at the top of the cloud-topped or cloud-less CMBL is to our opinion a clearly sign for an efficient..." The conclusion should be better discussed by the authors.

We believe that the high values in the particle linear depolarization ratio in the layer below the well-defined Saharan Air Layer is already an indication that dust removal processes started to mix the dust out of the SAL down to the ground. We added this to the text.

Page 3, Line 6: The authors justify the assumption about the two component mixture of marine aerosols and mineral dust with "coordinated in-situ measurements". Which kind of measurements?

For this assumption we used airborne in-situ measurements of microphysical and chemical composition of the observed aerosols. We added this in the text.

Section 2.1. The authors assume several values for linear depolarization ratio for dust and marine aerosols, lidar ratio. Did they try to have support from direct measurements to these assumptions? For example, in my opinion, with reference to the paper I cited before (Point 1), why in this paper the authors do not use a similar optical characterization?

This reviewer is right that we should link the previous paper to this work to justify our assumptions of the used values for the linear

depolarization ratio of dust and marine aerosols. We measured these values during the SALTRACE campaign and the values are described in detail in Groß et al., 2015. We now refer to this optical haracterization of the different aerosol types to make clear that the values used for the type separation are based on direct measurements at Barbados.

Section 2.2: It is not clear to me how, from the reference ensemble of Gesteiger et al (2011) at 532 nm, the value 0.68x10-6m is obtained. But, in general, this is applicable also to the several values of v/alpha. The assumptions are introduced in a very fast way, without justifications. I think, a discussion, even if minimum, should be given to give the paper a self-consistence.

The v/alpha value is calculated for the reference ensemble by first calculating the volume of the mixture and then the extinction coefficient of the mixture as described by Gasteiger et al.

Page 4, Line 15: Did the authors tried a comparison using Raman measurements? According to the paper I cited at the beginning (Point 1), POLIS is also equipped with Raman channels. How the backscatter in fig 2a are calculated? Why Raman measurements have been not used to characterize the layers like in the previous paper (see Point 1)?

POLIS is indeed equipped with Raman channels and we used these measurements for the optical characterization of the different aerosols and aerosols layers as was shown in the previous paper mentioned by this reviewer (Point 1). We also characterized the intensive optical lidar properties in the boundary layer as shown in Fig. 5 (now Fig. 4) and Table 1. The shown case study was performed during daytime where no Raman measurements were performed. As the aerosol type separation is based on depolarization measurements, the backscatter

value and depolarization ratio measurements are the most important values. We derived them with the Fernald/Klett algorithm as is now described in the 'Instrumentation and Method' section. We chose this case study as the measurements were performed during aircraft overflights over the ground-based station and the date was chosen as one of the 'golden cases.' Thus this case study might be useful for further analyzes. We tried to better link to the previous study.

Page 9, Table 1: It is not clear to me the case 24 June – 10 July. What does this indication mean: dust and marine (marine dominated), but without marine cases.

'dust and marine (marine dominated)' refers to a mixture of dust and marine aerosols which optical properties dominated by the marine aerosols in this mixture.

Page 10, Line 2: Which is the distance between the measurement site and the Ragged Point? Is this comparison significant?

The distance between Ragged Point and the lidar measurement site is about 40 km. To check the significance of comparisons between both sites we looked on aircraft in-situ and sunphotometer measurements of total AOD and Angström Exponent.

Page 10, Line 8: Which is the meaning of the factor 1.25? How is it obtained?

For the derivation of this correction factor we use the OPAC desert mixture and calculate the aerosol volume of this mixture for upper cut-off radii of 5 and 10 micrometer. We calculate the ratio between both volumes, assuming that a cut-off radius of 10 micrometer is valid for dust reaching Barbados and a cut-off radius of 5 micrometer is valid

for the instrument. This factor is about 1.25 and is applied to the PM10 measurements to calculate the ambient dust volume. However, as the uncertainty about the size distribution of dust after long-range transport is large, we consider an uncertainty of +-0.25 which also covers the case that no aerosol with r > 5 micrometer reaches Barbados.

Page 10, Lines 9 and 10: What does it mean “we assume an uncertainty of. . .”. How this estimation has been obtained?

See previous comment.

Page 10: The comment to the results of Fig. 6 is really very short. In general, these should be better discussed.

We extended the discussion.

Page 11, Summary: I image that the conclusions are referred to the 10 July case study. The authors does not report this. Moreover, I do not see correspondence between the values reported for PLDR in the Summary and those reported in table 1. Again, in the last line, which is the distance from the eastern part of the island? In general, the summary should be more clear and should give the idea of the importance of the reached goals.

We completely modified the summary to make it more clear and to give and idea of the reached goals.

Technical corrections

Page 1, Line 5: change “information of the CMBL” into “information on the CMBL”

We changed that.

Page 2, Line 21: change “information of the boundary layer” into “information on the boundary layer”

We changed that.

Page 2, Line 24: change “ground-base” into “ground-based”

We changed that.

Page 2, Line 26: change “located at the area” into “located in the area”.

We corrected that.

Page 3 Lines 6-8: Specify that the content of the sentence has been demonstrated when aerosols are transported across the Atlantic in summertime, otherwise it seems valid in general.

We tried to limit the validity of this statement by mentioning that it is valid for this study. However we agree with this Reviewer that a wrong assumption of general validity has to be avoided. Therefore we modified the text to make clear that this two-type assumption is only valid during dust long-range transport across the Atlantic Ocean as it was found for this study.

Page 7, Lines 3 and 5: change “on top the CMBL” into “on top of the CMBL”. Page 7, Line 3: change “found, that” into “found that”. Remove the comma.

We corrected that.

Page 8, Line 9: the authors write “AOD >= 0.4 nm”. They missed the wavelength between “0.4” and “nm”

We corrected that.

Zusammenfassung
22.07.2016 14:11:46

Es bestehen Unterschiede zwischen den Dokumenten.

Neues Dokument:
SALTRACE-BL-R1.4
19 Seiten (481 KB)
22.07.2016 14:11:41
Zum Anzeigen der Ergebnisse verwendet.

Altes Dokument:
SALTRACE-BL-V1.4
14 Seiten (471 KB)
22.07.2016 14:11:41

Beginn: Erste Änderung auf Seite 1.

Es wurden keine Seiten gelöscht

Wie ist dieser Bericht zu lesen

Highlight zeigt eine Änderung an.
~~Gelöscht~~ zeigt gelöschten Inhalt an.
zeigt an, dass Seiten geändert wurden.
zeigt an, dass Seiten verschoben wurden.

Saharan dust contribution to the Caribbean summertime boundary layer - A lidar study during SALTRACE

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Abstract. Dual-wavelength lidar measurements with the small lidar system POLIS of the Ludwig-Maximilians-Universität München were performed during the SALTRACE experiment at Barbados in June and July 2013. Based on high-accuracy measurements of the linear depolarization ratio down to about 200 m above ground level, the dust volume fraction and the dust mass concentration within the convective marine boundary layer can be derived. Additional information from radiosonde launches at the ground-based measurement site provide independent information on the convective marine boundary layer height and the meteorological situation within the convective marine boundary layer. We investigate the lidar-derived optical properties, the lidar ratio and the particle linear depolarization ratio at 355 and 532 nm and find mean values of 0.04 (stdev 0.03) and 0.05 (stdev 0.04) at 355 and 532 nm, respectively, for the particle linear depolarization ratio, and (26 $\pm$ 5) sr for the lidar ratio at 355 and 532 nm. For the concentration of dust in the convective marine boundary layer we find that most values were between 20 and 50 $\mu g/m^3$. On most days the dust contribution to total aerosol volume was about 30–40%. Comparing the dust contribution to the column-integrated sun-photometer measurements we see a correlation between high dust contribution, high total aerosol optical depth and a low Angström exponent, and of low dust contribution with low total aerosol optical depth.

1 Introduction

Saharan dust is one of the primary components of the global aerosol load (Forster and et al., 2007; Haywood and Boucher, 2000) with an estimated annual emission of more than 1000 Mt (Duce et al., 1991). Saharan dust can be transported over several thousand kilometers (Goudie and Middleton, 2001; Liu et al., 2008), influencing the Earth's energy budget on its way (Tegen et al., 1997). Turbulent downward mixing of dust in the convective marine boundary layer (CMBL) over the tropical Atlantic is assumed to be an efficient dust removal process. To support modeling efforts to simulate dust long-range transport and removal processes accurately and to validate the model output, a high-quality vertically resolved characterization of the optical and microphysical particle properties in the convective marine boundary layer and in the main dust layer (Saharan Air

Layer, SAL) is essential. SAL properties found during SALTRACE have already been presented by Groß et al. (2015), here we present the properties for the CMBL. Further papers will be presented in the framework of this SALTRACE special issue that will also partly deal with the removal of dust by turbulent downward mixing (Rittmeister et al., in preparation; Marinou et al., in preparation).

Typically, the cloud-topped convective boundary layer in the trade-wind-dominated tropics consists of the so-called sub-cloud layer, which is identical with the convective marine boundary layer in the absence of cloud formation and usually reaches to 500-1000 m height, and the cloud layer (Siebert et al., 2013). Moist convection can lead to a considerable increase of the overall depth of the convectively active height range. Over Barbados, cloud top heights were frequently observed from 1500-2500 m. In the convectively active zone, the observed particle linear depolarization is usually low (<0.1) and rapidly increases to typical values >0.2 in the base of the elevated mineral dust layer (Groß et al. 2015, Haarig et al., in preparation for this special issue). This strong increase at the top of the cloud-topped or cloud-less CMBL can be interpreted as a clear sign for an efficient downward mixing of dust at the interface between the CMBL and the elevated SAL as it indicates large amount of dust below the well-defined SAL. Dust trapped in the CMBL will then be comparably quickly transported down to the ocean or land surface and deposited.

As concluded from observations of long-range transported dust with the space-borne lidar system CALIOP (Liu et al., 2008), the CMBL depth is low close to western Africa in summer and increases with distance from Africa. This finding is in agreement with shipborne lidar observations in May 2013 (Kanitz et al., 2014). Frequent cloud formation in the marine boundary layer change the thermodynamic conditions in the range from about 700 to 1500-2000 m towards a less stable air stratification such that subsequent cloud formation is facilitated and clouds may reach higher altitudes.

In this work we present information on the CMBL and the dust contribution within the CMBL over Barbados in June and July 2013. This information is based on ground-based lidar measurements with the depolarization and Raman lidar system POLIS (Freudenthaler et al., 2015; Groß et al., 2015) of the Ludwig-Maximilians-Universität, München, performed in cooperation with the Deutsches Zentrum für Luft- und Raumfahrt (DLR), and on radiosonde measurements (launched typically twice a day) over the Barbados ground-based site performed by the Leibnitz-Insitut of tropospheric research (TROPOS), Leipzig. The measurements were conducted in the framework of the Saharan Aerosol Long-range Transport and Cloud-interaction Experiment (SALTRACE, Weinzierl et al. 2016). The measurement site was located in the area of the Caribbean Institute of Meteorology and Hydrology (CIMH) at Husbands (13.14° N, 59.62° W, 100 m), on the south-western part of Barbados.

The general properties discussed in this paper include height, wind direction and wind speed within the boundary layer. The lidar derived properties include the mean lidar ratio and mean particle depolarization ratio within the CMBL at 355 nm and 532 nm, and the retrieved dust volume fraction and dust concentration within the CMBL. The aim of this paper is to provide a detailed characterization of the CMBL as part of the vertical aerosol distribution over Barbados during SALTRACE. The characterization of the whole atmospheric column by vertical profiles of its properties, and a characterization of the different layers within is important as it enables to link ground-based dust measurements, airborne measurements, and column-integrated measurements e.g. with sun-photometers.

This paper is structured as follows; in Section 2 measurements, instrumentation, and methodology are briefly described, in Sections 3 and Section 4 the results are presented and discussed, and Section 5 concludes this work.

2 Instruments and Method

2.1 SALTRACE

The presented study is based on measurements during the Saharan Aerosol Long-range Transport and Aerosol-Cloud-Interaction Experiment (SALTRACE). Measurements were performed at Barbados in June and July 2013. SALTRACE was designed as closure experiment combining airborne and ground-based in-situ and remote sensing measurements with long-term observations and modeling efforts. For a detailed description of the SALTRACE project see Weinzierl et al. (2016).

2.2 POLIS lidar system

The lidar measurements used in this study were performed with the small six-channel dual-wavelength depolarization and Raman lidar system POLIS which was developed and build by the Meteorological Institute of the Ludwig-Maximilians-Universität, München (Groß et al., 2015; Freudenthaler et al., 2015). POLIS measures simultaneously the co-and cross-polarized laser return at 355 and 532 nm, during night-time additional measurements of the N_2-Raman shifted returns at 387 and 607 nm are performed. POLIS has a full overlap at about 200–250 m (depending on system configuration) allowing studies close to the lidar system (i.e. in the boundary layer). The raw data resolution of the POLIS measurements is 3.75 m along-side and typically 10 s in time. Night-time measurements were used to derive the extinction coefficient and the lidar ratio based on the Raman approach described by Ansmann et al. (1992). The typical resolution for the analysis of the Raman measurements is 1–2 h in time and about 200 m along-side. The retrieved lidar ratio was then used for a Fernald/Klett-analysis (Klett, 1985; Fernald, 1984) of the elastic channels to derive extinction coefficient, backscatter coefficient and depolarization ratio with much better vertical and temporal resolution than possible from the inelastic Raman channels. The vertical and temporal resolution of the measurements used for this study are about 155 m and about 30 minutes. In single cases measurement periods of about 1 h are used. For this study we used, when available, one day-time and one night-time measurement per day, coordinated with radiosonde ascents at the lidar site. For a general description of measurements and analysis see Groß et al. (2015).

2.3 CIMEL

Two AERONET sunphotometer (site name: Barbados_SALTRACE) were co-located with the ground-based lidar POLIS. Direct Sun observations were performed every 3 minutes (high frequency acquisition mode of the Cimel sunphotometers). They provide aerosol optical depth at 8 spectral channels in the wavelength range 340-1640nm. The multi-angle and multi-spectral measurements of sky radiance (almucantar and principal plane geometries, measured once every hour) are used to derive a set of optical and microphysical aerosol properties by means of inversion algorithms: volume particle size distribution, complex refractive index, single scattering albedo and fraction of spherical particles. For further details on the instrument, calibration procedures and data products, see Holben et al. (1998), Dubovik and King (2000), and Dubovik et al. (2006).

2.4 Radiosondes

During SALTRACE radiosondes were launched typically twice a day along with the lidar measurements; one during the morning sessions (14–15 UTC) and one during the evening session (23–1 UTC). The radiosondes recorded temperature, air pressure, relative humidity, wind speed and wind direction. Altogether 56 radiosondes were launched during SALTRACE.

2.5 In-situ measurements

In-situ dust mass concentrations were determined at the field station Ragged point (see Prospero and Mayol-Bracero 2013). For the SALTRACE campaign the station was equipped with additional instrumentation for dust characterization.

Aerosols were sampled through an aerosol PM10 inlet on top of a mast 17 m above ground. The aerosol laden air was drawn with a flow rate of 16.6 l/min through a 3/4 inch stainless steel tube. At the base of the mast the flow was split and directed to different instruments. Before the measurements, the aerosol was dried to a relative humidity of about 40% using Nafion membranes. Instruments for investigating properties of cloud condensation nuclei are described in Kristensen et al. (2016). Instruments for measuring optical properties were placed in an outside cabinet under the mast to avoid sampling line losses for super-micrometer particles. Particle light scattering coefficients were measured with a Nephelometer (Aurora4000m, Ecotech Pty Ltd., Australia) and light absorption coefficients were measured with a Spectral Optical Absorption Photometer (SOAP, Müller et al. 2011). Additionally, an Aerodynamic Particle Sizer (APS-3321, TSI) for measuring the particle number size distribution for sub-micrometer particles and a Scanning Mobility Particle Sizer (SMPS, Wiedensohler et al. (2012)) for measuring the sub-micrometer particle number size distribution were used.

The total particle mass concentration is derived from the particle number size distribution measured with APS and SMPS. To convert the aerodynamic particle number size distribution to a volume equivalent number size distribution for dust particles we chose a dynamic shape factor of 1.17 and a density of 2.45 g/cm^3 . The method and the values for the dynamic shape factor and density are discussed in Niedermeier et al. (2014). For cases with high dust concentrations (dust mass concentration > 20 $\mu g/m^3$), the total mass concentration from the particle number size distribution was found to be lower by 14% compared to the dust mass concentration from optical absorption. Niedermeier et al. (2014) pointed out, that the determination of the dust mass concentration from optical absorption depends on the choice of the mass absorption coefficient, specifically on the relative abundance of the strongly absorption iron oxides. The mass absorption coefficient used in this study was derived from the SAMUM-I campaign for Saharan desert dust with an relative iron abundance of 1% (Kandler et al., 2009). This can explain differences between the two methods qualitatively, a detailed error discussion of the methods is beyond the scope of this paper.

2.6 Aerosol type separation

From the profiles of the particle linear depolarization ratio δ_p and particle backscatter coefficient β_p measured at 532 nm we determine the dust backscatter coefficient β_d following the procedure described by Tesche et al. (2009a); Groß et al. (2011a) and Ansmann et al. (2011). This method is based on the work of Shimizu et al. (2004) assuming a two component mixture with known particle depolarization ratio of the two components as indicated by coordinated aircraft in-situ measurements (Weinzierl et al., 2016). As input parameters for the aerosol type separation we use the mean dust linear depolarization ratio δ_d of 0.30 as found from the former field campaigns during the Saharan Mineral Dust Experiment (SAMUM) (Freudenthaler et al., 2009; Groß et al., 2011b). We also include measurements over Barbados during the SALTRACE experiment focusing on the general situation during the campaign and on the optical properties of long-range transported Saharan dust (Groß et al., 2015). For marine (non-dust) aerosols we use a mean linear depolarization ratio δ_{nd} of 0.02 for relative humidity values $\geq$45% (Groß et al., 2011b, 2015). The dust α_d and marine extinction coefficient α_{nd} are calculated according to $\alpha = \beta \cdot S$ with a dust lidar ratio S_d of 55 sr (Tesche et al., 2009b; Groß et al., 2015) and a marine lidar ratio S_{nd} of 20 sr (Groß et al., 2015) at 532 nm.

2.7 Dust volume and mass conversion

In a next step the volume concentration of both particle types is derived using a conversion factor from extinction to volume concentration v/α. This conversion factor strongly depends on the microphysical properties of the aerosol type, in particular on the size distribution. To derive v/α and to study the potential differences in the conversion factor v/α for fresh and long-range transported dust, v/α was derived from SAMUM and SALTRACE-AERONET measurements during pure dust periods. The conversion factors are derived from AERONET aerosol mixture retrieved by the AERONET inversion algorithm (Mamouri and Ansmann, 2016) which is then used to derive the volume and extinction of this aerosol mixture to finally derive v/α. For the dust conversion factor well-defined dust outbreaks observed over Morocco, Cape Verde and Barbados with aerosol optical depth (AOD) > 0.2 at 500 nm and Angström Exponent (AE) < 0.2 (Barbados) and < 0.4 (Cape Verde and Morocco) are considered. The AERONET-derived conversion factors show a constant value of v/α=0.65$\cdot 10^{-6}$ m for measurements close to the source and over Barbados. In this study we adopt this value for the conversion. To derive the conversion factor for marine aerosols AERONET measurements at Barbados from 2007–2015 were analyzed. Altogether about 100 observations which were defined as pure marine (AOD < 0.07 at 500 nm and AE between 0.25 and 0.6) were found, resulting in a marine conversion factor v/α=0.66$\cdot 10^{-6}$ m. The conversion factors for dust and marine aerosols are similar because the size distribution of both aerosol types are rather similar. The dust volume fraction can then easily be calculated from the ratio of the dust volume concentration to the total volume concentration. The dust mass concentration is calculated from the dust volume concentration by multiplication with the particle density, which we assumed to be 2.5 g/cm^3 based on the fact, that in most cases a mixtures of coarse and fine mode particles (Ansmann et al., 2011; Mamouri and Ansmann, 2014) and sulfate particles (Kaaden et al., 2009) was found in the Saharan dust layer.

2.8 CMBL height identification

We infer the height of the CMBL from the radiosonde measurements. As turbulent convection in the boundary layer causes constant values of the potential temperature and mixing ratio (Hooper and Eloranta, 1986; Kaimal et al., 1976), we use these properties as indicators for the CMBL height. Furthermore we use temperature information derived from the radiosonde ascents, as the boundary layer is mostly capped by an inversion layer (Carson, 1973). Independently we derived the CMBL height from the optical properties measured by our lidar system. Aerosol concentration and thus the aerosol backscatter coefficient show a gradient on top of the boundary layer (Boers et al., 1984; Hooper and Eloranta, 1986). We use the strongest gradient to determine the CMBL height. Furthermore we also use the measured intensive lidar quantities like the linear particle depolarization ratio to strengthen our result.

3 Results

3.1 General measurement situation

The main measurement period for closure studies during SALTRACE was from 20 June to 12 July 2013. During this time the aerosol situation above Barbados was characterized by an aerosol optical depth (AOD) which mainly ranged between about 0.2 and 0.4 almost wavelength-independent for the CIMEL measurements at 340, 500 and 1020 nm (Fig. 1). The Angström Exponent (AE) was typically 0.2 or lower. On some days, however, the aerosol load over Barbados was substantially lower, with AOD values well below 0.2. Those low AOD values were connected with higher AE of about 0.5–0.7. On 7 July 2013 the AE was even as high as 1.1. Five episodes with high AOD values (up to 0.6) were observed.

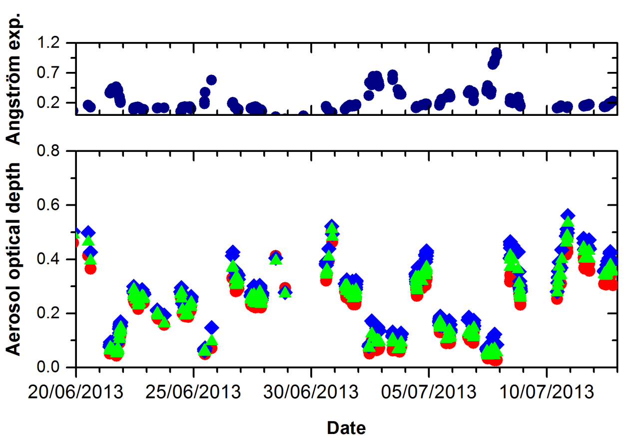

Figure 1. Angström Exponent between 440 and 870 nm (upper panel) and the Aerosol optical depth at 340 (blue), 500 (green) and 1020 nm (red) derived from AERONET-CIMEL sun-photometer measurements at the Caribbean Institute for Meteorology and Hydrology, Barbados (data: Barbados_SALTRACE) from 20 June to 13 July 2013

3.2 Case study – 10 July 2013

A multi-layer aerosol structure was observed over Barbados during SALTRACE in June and July 2013 (Groß et al., 2015). Figure 2 provides an overview of the situation on 10 July 2013 based on aerosol lidar observation at 532 nm with POLIS. The general structure of the shown profiles is representative for most of the SALTRACE measurements. From the volume and particle linear depolarization ratio (Fig. 2b) two aerosol regimes are clearly visible; in the lowermost 1.5 km the particle depolarization ratio is around or even below 0.1, indicating that dust has only a minor contribution to the aerosol mixture. Above about 1.6 km the volume and particle linear depolarization ratio is clearly higher with values of about 0.14 to 0.18 for the volume linear depolarization ratio and 0.28 to 0.3 for the particle linear depolarization ratio. The separation of the two aerosol regimes is also visible in the radiosonde measurements launched at 17:49 UTC (Fig. 2e,f) showing a temperature inversion between about 1.6 and 1.8 km height together with a change in relative humidity, mixing ratio, potential temperature and wind speed (not shown).

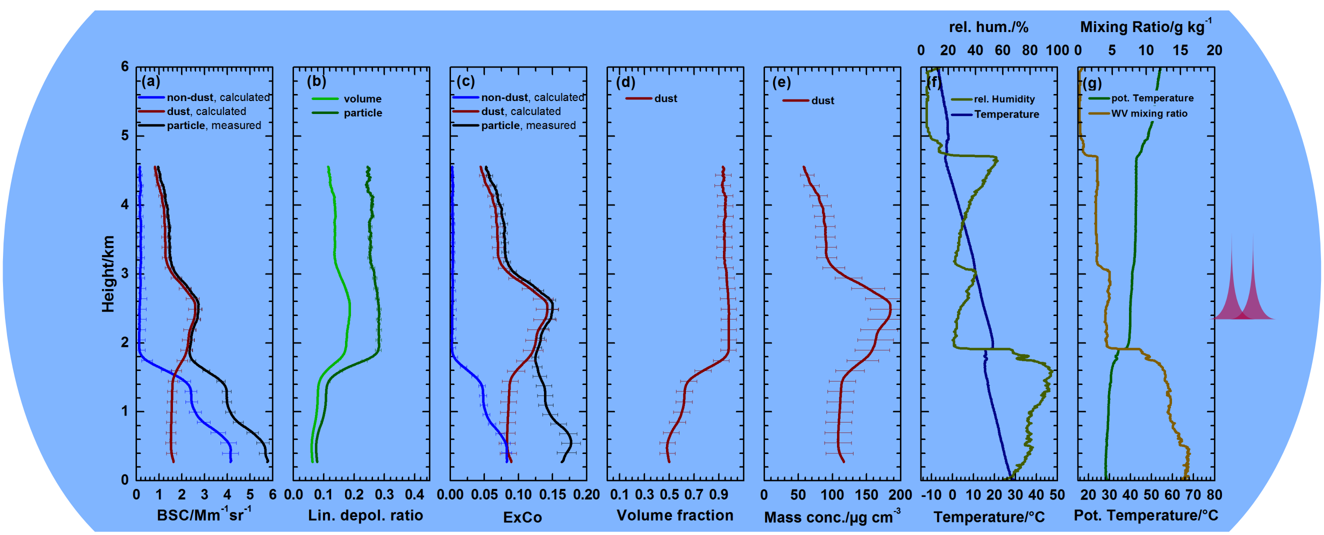

Figure 2. (a) Separation of dust (red) and non-dust (blue) particle backscatter coefficient (BSC) at 532 nm from total particle backscatter coefficent (black) at 532 nm, (b) measured volume (light green) and particle (dark green) linear depolarization ratio at 532 nm, (c) dust (red) and non-dust (blue) extinction coefficient at 532 nm and the total particle extinction coefficient (black) at 532 nm derived from POLIS lidar measurements, (d) dust volume fraction, (e) dust concentration derived from POLIS measurements at Barbados on 10 July 2013 at 20 UTC, (f) temperature (dark blue) and relative humidity (dark yellow) profiles, and (g) profiles of potential temperature (dark green) and water vapor mixing ratio (orange) derived from radiosonde measurements started on 10 July 2013 at 17:49 UTC. Error bars give the systematical uncertainties resulting from measurement uncertainties and uncertainties in the lidar specific input parameters.

According to the criteria for CMBL height identification with lidar (Boers et al., 1984; Hooper and Eloranta, 1986) the CMBL height on 10 July 2013 was at about 500 m. Lidar measurements show a strong gradient in the aerosol backscatter coefficient (Fig. 2a) at about 500 m. CMBL height detection from radiosonde measurements at 17:49 UTC is not that distinctive;

only the water vapor mixing ratio shows slight changes. The capping inversion in the temperature profile and the change in the potential temperature on top of the CMBL (at about 500 m altitude) were missing or not pronounced. Also the measured volume and particle linear depolarization ratio (Fig. 2b) within the CMBL showed only slight differences compared to the values found in the transition layer between the CMBL and the Saharan air layer. The CMBL was characterized by a constant value of the potential temperature of about 28°C and a constant water vapor mixing ratio of about 16 g/kg. The relative humidity within the boundary layer increased with height from about 65 to 80%. The wind in the boundary layer (not shown) came from easterly directions with a mean wind speed around 7 m/s. The aerosol optical depth within the boundary layer is about 0.1 at 532 nm, and the mean volume and particle depolarization ratio at 532 nm are about 0.06 and 0.08, respectively.

Following the procedure described in Section 2.7 the volume fraction of dust is derived (Fig. 2d). Above about 1.6 km dust contributes to almost 100% to the total aerosol volume while below 1.5 km height the dust contribution is only 70% or less. In the CMBL (lowermost 0.5 km) the dust volume fraction is even less than 60%. For the dust concentration (Fig. 2e) we find a rather constant value of about 110 μg/m^3 in the lowest 1.5 km. Above a height of 1.5 km the profile of the dust concentration generally follows the profile of the backscatter coefficient (Fig. 2a) and the extinction coefficient (Fig. 2c) with a maximum in dust concentration of about 190 μg/m^3 between 1.4 and 1.6 km height.

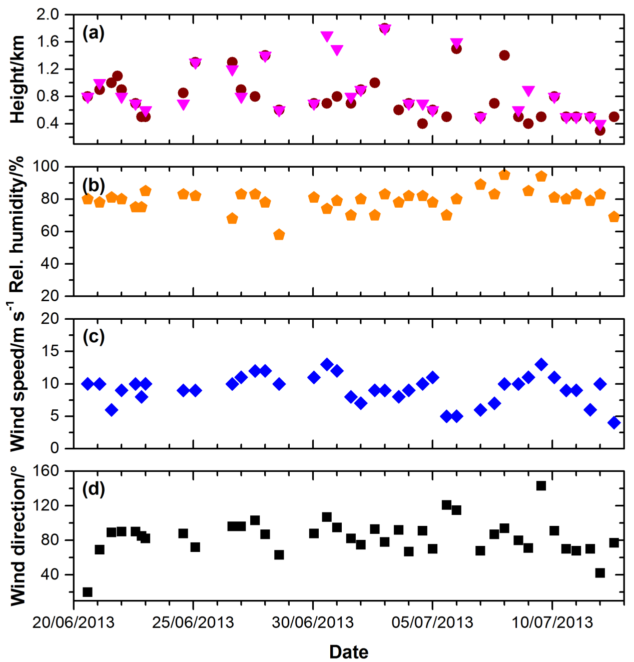

Figure 3. (a) CMBL height derived from radiosonde measurements (brown dots) and lidar measurements (magenta rectangles), (b) mean relative humidity within the CMBL derived from radiosonde measurements, (c) mean wind speed in the CMBL measured with radiosonde, and (d) mean wind direction in the CMBL derived from radiosonde measurements.

3.3 CMBL height and conditions during SALTRACE

As described in Section 2.8 the CMBL height is derived from radiosonde and lidar measurements (Fig. 3a). The CMBL top above our measurement site during SALTRACE is mainly between 0.5 and 0.9 km, in some cases the boundary layer reaches up to 1.8 km. The CMBL height derived from radiosondes and lidar mostly agree within 100 m, however in a few cases the CMBL height derived from lidar measurements is higher than the CMBL height derived from radiosondes. In those cases the CMBL height from radiosondes is mainly based on observed changes in the mixing ratio, we do not see a profound change in the potential temperature nor a capping inversion layer on top of the CMBL. However we do see a pronounced temperature inversion and change in the potential temperature in those cases within the height ranges of the lidar-derived CMBL heights. We frequently found pronounced changes of the intensive lidar quantities (i.e. quantities that only depend on the observed aerosol type or mixture but not on its amount) on top of the CMBL in connection with strong capping inversions and changes in potential temperature on top of the CMBL. The differences of the intensive optical properties between CMBL and transition layer was not as pronounced in situations where the capping inversion on top of the CMBL was absent and changes in potential temperature were small. Those later situations occurred mainly during the daytime.

During SALTRACE the relative humidity within the CMBL was quite high with values around 80%. Only on a few days the relative humidity within the boundary layer was lower, but never below 60% (Fig. 3b). The mean wind speed within the CMBL over Barbados during SALTRACE was predominantly between 8 and 12 $\mathrm{m/s}$ (Fig. 3c) which are optimal conditions for the production of sea salt particles (Gong, 2003; Knippertz et al., 2011). Between 5 July and 7 July 2013 and during individual days between 20 June and 23 June 2013 the wind speed was lower with values around 6 $\mathrm{m/s}$, but those values are still above the empirically derived threshold for sea-salt aerosol production of 5.5 $\mathrm{m/s}$ (Knippertz et al., 2011). Only on the last days of our measurements the wind speed is lower than this empirical value.

From our measurements we assume that sea salt particles at Barbados exist only below about 1500 to 2000 m, most likely advected to our measurement site by strong onshore easterly winds. The wind direction within the CMBL derived from radiosondes (Fig. 3d) was mainly East to North-East, except for very few cases when the wind came from either northern or southern directions.

3.4 Optical properties within the CMBL

Aside from the last dust event during the SALTRACE campaign, the CMBL during SALTRACE was characterized by low values of the particle linear depolarization ratio and the lidar ratio ranging between 0.01–0.08 and 15–31 sr at 355 and 532 nm (Fig. 4). These values are in good agreement with the findings of Murayama et al. (1999), who found mean values of the particle linear depolarization ratio at 532 nm of 0.01 and 0.1 in a marine boundary layer without and with dust influence. They related the lower values to pure marine aerosols whereas they assumed a contribution of dust for the higher values. Similar to Murayama et al. (1999) and Groß et al. (2011b, a) we assign values of the particle linear depolarization ratio of 0.01–0.03 (mean value 0.02) at 355 and 532 nm to marine aerosols, which is in good agreement to the findings of Sakai et al. (2010), who found values of 0.01 for sea-salt droplets from laboratory chamber measurements at 532 nm. The corresponding values

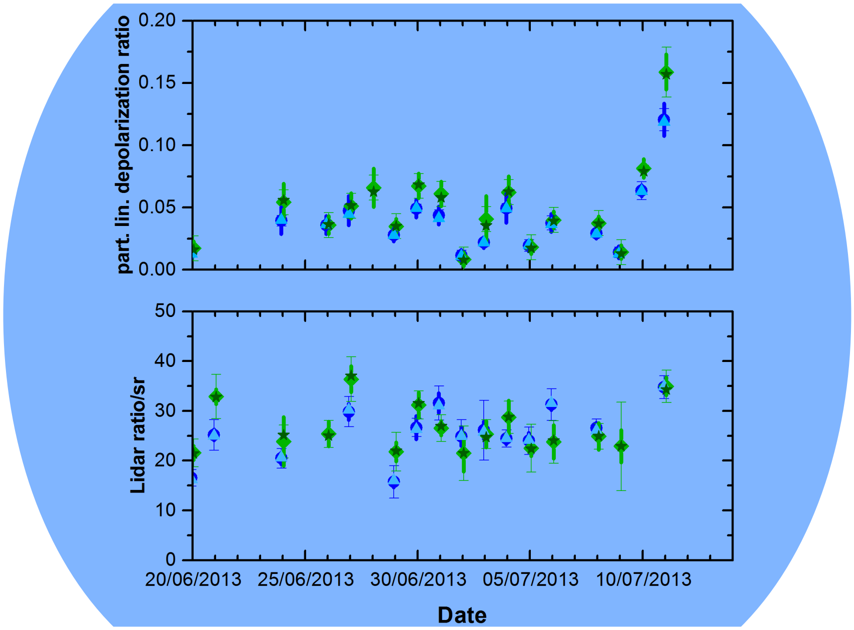

Figure 4. Mean values, median, standard deviation of the mean and mean systematic error of the particle linear depolarization ratio (upper panel) and the lidar ratio (lower panel) at 355 and 532 nm measured with POLIS within the convective marine boundary layer. Blue dots and green diamonds show the mean values at 355 and 532 nm, light blue triangles and dark green stars show the median values at 355 and 532 nm, thick lines show the standard deviation of the mean, and the thin error bars denote the mean systematic errors.

of the lidar ratio for the marine aerosol cases are 16–24 sr with mean values of 20 ± 3 at 355 nm and of 22 ± 5 at 532 nm. These values are also in good agreement to previous findings from theoretical studies (Ackermann, 1998) and measurements (Groß et al., 2011b, a). During the last measurement day the mean value of the lidar ratio within the CMBL is about 35 sr independent of wavelength. The particle linear depolarization ratio shows mean values of about 0.12 at 355 nm and of about 0.16 at 532 nm, indicating a larger fraction of mineral dust (Murayama et al., 1999; Groß et al., 2011b). The overall values of the particle linear depolarization ratio are wavelength independent with mean values of 0.04 ± 0.03 at 355 nm and 0.05 ± 0.04 at 532 nm (±-values give the standard deviation of the mean). The overall mean value of the lidar ratio within the boundary layer is 26 ± 5 sr at 355 and 532 nm (±-values give the standard deviation of the mean).

According to former findings (e.g. Ackermann 1998; Sakai et al. 2010; Murayama et al. 1999; Groß et al. 2011b, a) and lidar based aerosol classification schemes (Groß et al., 2011b; Burton et al., 2012; Groß et al., 2013) we find four days during the whole SALTRACE measurement period with a pure marine CMBL, one day with dust dominated dust-marine mixture within the CMBL. On all the other days we assign to polluted marine-dominated mixture within the CMBL. The results of the optical properties within the CMBL during SALTRACE are summarized in Table 1.

Table 1. Mean values of the lidar ratio and particle linear depolarization ratio (PLDR) including the mean systematic errors (±) for different aerosol types and their dominant time periods. *±-values for the overall mean values indicate the standard deviation of the mean.

Dominant type	Date	PLDR		Lidar ratio/sr	
		355 nm	532 nm	355 nm	532 nm
marine	20, 29 June 2, 5, 9 July	0.02 ± 0.01	0.02 ± 0.01	20 ± 3	22 ± 5
dust and marine (marine-dominated)	24 June - 10 July without 2, 5, 9 July	0.04 ± 0.01	0.05 ± 0.01	27 ± 3	28 ± 3
dust and marine (dust-dominated)	11 July	0.12 ± 0.01	0.15 ± 0.02	35 ± 3	35 ± 3
overall		0.04 ± 0.03	0.05 ± 0.04	26 ± 5	26 ± 5

Figure 5. Dust volume fraction (upper panel) and dust mass concentration (lower panel) within the CMBL over Barbados derived from POLIS lidar measurements. Error bars give the systematical uncertainties resulting from measurement uncertainties and uncertainties in the lidar specific input parameters.

3.5 Dust contribution in the CMBL

Figure 5 shows the mean dust volume fraction and the mean dust mass concentration within the CMBL retrieved from our lidar measurements. The dust volume fraction within the CMBL shows values between 0.01 and 0.65. For the majority of days we find values between about 0.3 and about 0.4. The dust mass concentration within the CMBL ranges between 2 and 100 $\mu g/m^3$ with most frequent values found between 20 and 50 $\mu g/m^3$. High dust mass concentrations are derived at the end of the campaign when the wind speed in the boundary layer was low. Thus we conclude that low wind in the CMBL may provide optimal conditions for dust downward mixing. Comparing the dust volume fraction and dust mass concentration within the CMBL with total AOD at 500 nm and AE (between 440 and 870 nm) for the complete atmospheric column derived from sun-photometer measurements (Fig. 1), one can see that days with low dust volume fraction and low dust mass concentration within the CMBL are found for days with column integrated AOD ≤ 0.1 at 500 nm and corresponding AE ≥ 0.4. The highest values of the dust volume fraction and the dust mass concentration are found for days with high AOD ≥ 0.4 at 500 nm and corresponding low AE of ≤ 0.2.

3.6 Closure

To validate the lidar derived dust contribution (i.e. dust volume fraction and dust mass concentration), we compared the lidar derived dust mass concentration with synchronized ground-based in-situ measurements of dust concentration at Ragged Point (Kristensen et al., 2016; Müller et al., in preparation for this special issue) at the eastern coast of Barbados (see Fig. 6).

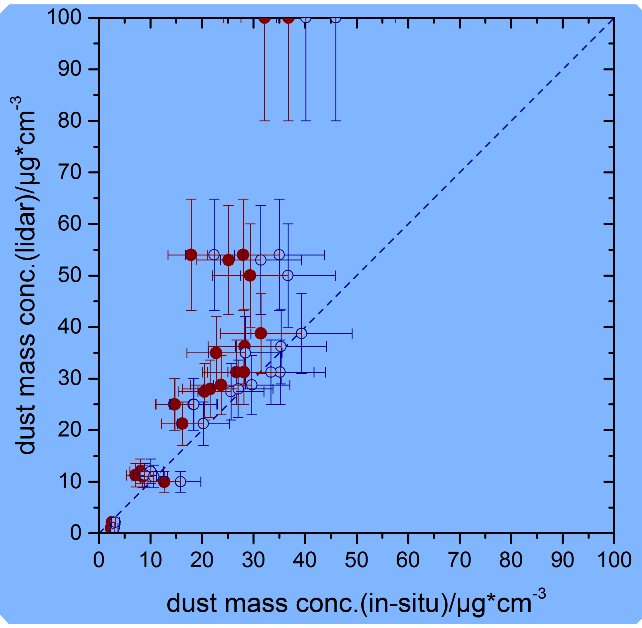

Figure 6. Dust mass concentration derived from lidar analysis versus dust mass concentration measured in-situ at Ragged Point (red dots). Only measurements that match in time (i.e. the lidar measurements were performed within or with temporal overlap to the sampling period of the in-situ measurements) are plotted. Additionally the in-situ vs. lidar derived dust mass concentration is plotted including a correction of the in-situ measurements (multiplied by a factor of 1.25) due to the nominal cut-off of the PM10 measurements (blue circles). Error bars for the lidar derived dust mass concentration give the systematic uncertainties resulting from measurement uncertainties and lidar specific input parameters. Error bars for the in-situ derived dust mass concentration result from the nominal cut-off and the assumed dust mass which thus can not be covered by the in-situ measurements. The dashed line gives the one-to-one line.

The dust concentration derived from both methods show good agreement for dust mass concentrations below about 40 $\mu g/m^3$. Dust mass concentrations derived from both methods below this value do not show significant differences. However, the lidar-derived dust concentration is on average about 3 $\mu g/m^3$ higher than the in-situ derived dust mass concentration. A linear fit considering all measurements with dust mass concentration below 40 $\mu g/m^3$ (including 17 measurement points) has a slope of 0.93. The good agreement of the derived dust mass concentration from lidar and in-situ measurements suggests that the method to derive dust mass concentration from lidar measurements works well.

For values above 40 $\mu g/m^3$ we do not see a good agreement between both methods. These larger dust mass concentrations derived from the lidar measurements at the western part of the island are not captured by the in-situ measurements. We found evidence that the PM10 inlet causes an underestimation of mass concentrations especially for high dust concentrations. A detailed analysis for SALTRACE data is not finished yet, but unpublished data indicate that mass concentrations could be underestimated by up to 50%. Corrections are considered to be uncertain since inlet efficiencies are not well characterized for the high wind speeds frequently found at Ragged Point. This underestimation would partly explain the differences found for mass concentrations above 40 $\mu g/m^3$. Furthermore, the ambient aerosol was sampled through a PM10 inlet (i.e. nominal cut-off at r=5μm) for the in-situ measurements (Kristensen et al., 2016). Thus a certain fraction of the ambient dust mass is likely not covered by the in-situ measurements. Using the OPAC desert mixture and assuming that particles up to r=10μm reach the Barbados measurement site (Weinzierl et al., 2016), we deduce that the mass concentration derived from the in-situ measurements needs to be multiplied by a factor of about 1.25 to get ambient mass concentration. However, as the coarse mode size distribution of transported dust is not well characterized, we assume an uncertainty of $\pm$0.25 for that factor. Taking this factor into account we not longer see a bias between the in-situ and lidar-derived dust mass concentration found for dust mass concentration higher than 40 $\mu g/m^3$.

4 Discussion

To characterize the optical properties of the convective marine boundary layer and the contribution of dust within the CMBL a number of input parameters had to be adopted to derive dust volume and dust mass concentration within the CMBL.

For the separation of the different aerosol types contributing to the aerosol mixture in the CMBL we assumed a two-component mixture. Comparisons with coordinated aircraft in-situ measurements of the microphysical and the chemical properties of the observed aerosols justify the assumption of a two-component mixture of marine aerosols and mineral dust for the period of long-range dust transport over the Atlantic Ocean during summertime (Weinzierl et al., 2016), as it was the case in this study. To derive the dust and marine backscatter and extinction coefficient the linear depolarization ratio and lidar ratio of dust and marine aerosols is needed. Those properties depend on the chemical and microphysical particle properties such as particle size and shape. These properties may change during long-range transport. The particle linear depolarization ratio as well as the lidar ratio of Saharan dust was studied during several field experiments. Freudenthaler et al. (2009) found a mean linear particle depolarization ratio of 0.31 $\pm$ 0.01 for fresh Saharan dust close to the source. This value does not change significantly for Saharan dust at the beginning of its long-range transport across (Groß et al., 2011a). Measurements of long-range transported Saharan dust over Europe (Wiegner et al., 2011), the Mid-West and the Caribbean (Burton et al., 2015) confirm a particle linear depolarization ratio of about 0.3 at 532 nm considering the systematic uncertainties of the lidar systems. Furthermore these optical properties of long-range transported Saharan dust were also seen with lidar measurements at Barbados during SALTRACE (Groß et al., 2015). The particle linear depolarization ratio ranged from 0.26 and 0.3 at 532 nm. Thus the adopted value of 0.3 $\pm$ 0.01 in this study is in good agreement to previous findings. The lidar ratio of long-range transported Saharan dust is also derived from SALTRACE measurements. A mean value of 55sr at 532 nm was found (Groß et al., 2015) which is also in good agreement to previous studies of Saharan dust lidar ratios (e.g. Tesche et al. (2011)). In this study we use a value of 55 sr to derive the dust extinction coefficient. Denjean et al. (2015) show that long-range transported dust does not show enhanced hygroscopicity and that the chemical composition of the dust remains rather unchanged. Therefore, we do not assume any effects caused by the high relative humidity within the CMBL. Furthermore the high relative humidity within the boundary layer indicates that we do not have to consider any dry marine aerosols within the boundary layer (Murayama et al., 1999; Sakai et al., 2010).

To determine the dust volume and the dust volume fraction the derived dust extinction coefficient has to be converted to dust volume. For this conversion we used a conversion factor derived from AERONET sunphotometer measurements. To confirm this conversion factor we compare it to the modeled conversion factor using the method described by Gasteiger et al. (2011). Assuming a reference ensemble to calculate the volume and extinction coefficient, the conversion factor is then the ratio between the derived volume and extinction. Gasteiger et al. (2011) used an ensemble which was consistent with lidar measurements of Saharan aerosol in Morocco during SAMUM-1. As the airborne in-situ measurements show no significant changes of the properties of long-range transported Saharan dust (Weinzierl et al., 2016) we assume that this reference ensemble is still valid for long-range transported Saharan dust. With the method described by Gasteiger et al. (2011) we found an extinction to volume conversion factor of $0.68 \cdot 10^{-6}\,\mathrm{m}$ for a wavelength of 532nm. This value is very similar to the one derived from sunphotometer measurements, confirming its validity for this study.

To further confirm our method and the derived results we compared the lidar derived dust mass concentration with coordinated in-situ measurements. For uncorrected in-situ dust mass concentrations we find that, aside from a negative bias of the in-situ measurement of about 3 $\mu g/m^3$, both methods agree well up to a dust mass concentration of about 40 $\mu g/m^3$. A correction factor taking into account the underrepresented size range of the dust size distribution from the in-situ measurements could compensate the bias in the in-situ measurements. The differences at larger values of the dust mass concentration can partly be explained by the underestimation of large dust mass concentration from PM10 measurements. However, the differences for very large values of around 100 $\mu g/m^3$ can not fully be explained by either the underestimation of the PM10 measurements or the correction due to the uncovered size range. Those high values were measured in conditions with low wind speed compared to the other days during this study. Thus it may be possible that effects during transport across Barbados, e.g. from turbulence over the island or island heat effects may be of importance for measurements at the downwind side of the island.

5 Conclusions

Different measurements and methods in different height ranges are often difficult to link and to compare directly. Especially different aerosol mixtures in different height ranges pose difficulties in the comparison of measurements. Lidar measurements are a valuable tool as they provide height resolved information over the entire atmospheric column. Furthermore, with the method applied in this study it is not only possible to characterize the different layers within the atmospheric column, but also to derive the contributions of the different aerosol types to aerosol mixtures. This is of importance to link e.g. measurements of one single aerosol type to measurements of the whole aerosol mixture, measurements of different height ranges, or measurements of single height ranges to measurements of the whole column. The measurements presented in this work can, in particular, be used to study the downward mixing of Saharan dust after long-range transport across the Atlantic Ocean or to study dust removal processes. The results derived here can also serve to validate dust transport models as they separate the dust contribution from the contribution of other aerosol types. Furthermore the results provide insight into dust removal processes as they provide a detailed characterization of the conditions within the CMBL during the SALTRACE measurement period.

Acknowledgements. The SALTRACE campaign was mainly funded by the Helmholtz Association, the Deutsches Zentrum für Luft- und Raumfahrt (DLR), the Ludwig-Maximilians-Universität München (LMU) and the Institut für Troposphärenforschung (TROPOS). This work project was partly founded by a DLR VO-R young investigator group, by the Deutsche Forschungsgemeinschaft (DFG) in the SPP (no. 1294/2) "Atmosphären- und Erdsystemforschung mit dem Forschungsflugzeug HALO" under contract no. KI1567/1-1, and the LMU Munichs Institutional Strategy LMUexcellent within the framework of the German Excellence Initiative. The lidar and sun-photometer measurements were performed at the site of the Caribbean Institute for Meteorology and Hydrology (CIMH). We thank CIMH for providing us with this measurement environment.

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