Reply to the Referees' comments

Referee #1 comments:

We thank the referee for the useful comments, which helped us to improve the quality of our manuscript.

In the following, the referees' comments are given in black.

Our point-to-point replies are marked by "R" and are in blue.

Changes to the manuscript text are in green.

General remarks:

The study deals with the description of a long-range Saharan dust plume that affected the Central Europe in April 2018 and captured by ground-based instruments (lidars, sunphotometer) operating at Kalrsruhe (Germany). Moreover, an evaluation of the ICON-ART transport model is performed. I think that several modifications on the manuscript are needed in order to be acceptable for publication in AMT. For instance, it has not been clear by the authors which is the added value of the current study with respect to previous similar analyses. Likewise, an intercomparison of the obtained findings with those reported in past studies is missing. A critical point which must be clear to the reader is to highlight the purpose of the current study. There are parts in which different retrieval methods (raman vs klett) are compared, different observational geometries (vertical point vs off-zenith vertical profiles) are discussed, different remote sensing techniques (active vs passive) are employed and dust numerical simulations are evaluated against ground-based measurements. But it is not clear what is the exact proposition from this exercise (e.g., to deploy similar instrumentation for desert dust studies?). Even though the amount of data/techniques sounds impressive, the way that they are presented is confusing to my opinion. As you will see in my comments below it is required a restructure of the paper sections. Finally, please consider to improve the English writing throughout the manuscript.

R: It is our aim to demonstrate how useful multiple angle lidar measurements can be in addition to vertical lidar and sun photometer data and what kind of understanding of the aerosol properties can be achieved by combining the different measurement techniques. In addition, we want to understand the quality of the dust plume predictions with one of the state of the art transport models, the ICON-ART model, by comparison with these observational data. To point this out, we have added information about similar previous studies to the introduction and modified its final part as follows:

"The major objective is to quantify the uncertainties of different measurement and retrieval methods including a demonstration how useful multi angle lidar measurements can be in addition to vertical lidar and sun photometer data and what kind of understanding of the aerosol properties can be achieved by combining the different measurement techniques. Furthermore, we want to understand the quality of the dust plume predictions with one of the state of the art transport models, the ICON-ART model, by comparison with these observational data. This paper is organized as follows. Section 2 describes the remote sensing methods and the model simulations done with ICON-ART. Details of our dust observations and its properties are discussed in section 3 including a comparison of the different remote sensing methods as well as how they compare to the model predictions. In the final section we provide some conclusions from this."

Minor edits:

1. Lines 12-13: Provide the wavelength

   R: The wavelength of our lidar is 355 nm, and we have added this information to the abstract of the manuscript.

   The related text has changed into:

   "The lidar measurements at a wavelength of 355 nm show that the dust particles had backscatter coefficients of 0.86 ± 0.14 Mm^{-1} sr^{-1}, an extinction coefficient of 40 ± 0.8 Mm^{-1}, a lidar ratio of 46 ± 5 sr, and a linear particle depolarization ratio of 0.33 ± 0.07."

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2. Lines 34-35: Could you please explain better this sentence? Which are the problems for CALIOP to depict the vertical structure of dust layers?

   R: We think it is fair to say that their capabilities to retrieve dust plume structures is limited especially compared to ground based active remote sensing methods.

   "However, their data still has limitations compared to ground based active remote sensing methods e.g. concerning characterisation of the structures of dust plumes especially for low aerosol particle concentrations (Ma et al., 2018)."

3. Line 47: Replace "Recently, synergy analysis methods…" with "Recently, synergistic approaches/methods…".

   R: We have changed this in the revised manuscript.

4. Lines 54-56: Rephrase and explain better this sentence.

   R: We have changed this sentence into:

   "However, the complex configuration of some of these systems, as well as the relatively weak intensities of vibrational Raman scattering, impeded the widespread use of these technologies or limit them to night-time measurements."

5. Lines 74-77: Check also the SDS-WAS in which several regional models provide short-term dust forecasts over the NAMEE domain.

   R: We agree that it is useful to add information on the SDS-WAS program at this point and modified the text as follows:

   "Various models like CAMS (O'Sullivan et al., 2020), WRF/Chem (Kang et al., 2011) , EMAC (Gläser et al., 2012) , COSMO-ART (Deetz et al., 2016;Vogel et al., 75 2014) and ICOsahedral Nonhydrostatic model - Aerosols and Reactive Trace gases (ICON-ART) (Rieger et al., 2017; Gasch et al., 2017; Hoshyaripour et al., 2019) have been used to predict mineral dust plumes. A systematic validation of ICON-ART is beyond the scope of this study and has been done in previous works (Rieger et al., 2017; Gasch et al., 2017; Hoshyaripour et al., 2019). However, a multi model forecast comparison is beyond the scope of this study but is available by the Sand and Dust Storm Warning Advisory and Assessment System (SDS-WAS) (https://sds-was.aemet.es/forecast-products/dust-forecasts/forecast-comparison, last access September 22, 2021), a program of the World Meteorological Organisation (WMO)"

6. Lines 90-91: Not only ASD but SSA is also retrieved. Please make the appropriate corrections in this sentence.

   R: We have modified this sentence as follows:

   "Besides, a sun photometer (CE-318, CIMEL, Holben, et al., 1998) provides wavelength-dependent aerosol optical depth (AOD), AE, and via inversion the aerosol size distributions (ASD), and SSA."

7. Line 114: It is strange that for the first time in the manuscript you are referring to Figure S3. Also it is missing a short description about this comparison.

   R: We agree that it is strange to show Fig.S3 first in the manuscripts. And we also think that the comparison between our data analysis procedure and Single Calculus Chain (SCC) code (EARLINET) is necessary if we want to use our own data analysis procedure. All these things are obvious, so we think Fig. S2 did not bring too much information in the manuscripts. Therefore, we would like to delete Fig S2 and related description.

8. Results and discussion: It would be useful to add a section describing the factors driving the emission and transport of the Saharan dust plume towards central Europe. Such analysis should include model outputs (e.g., meteorology, dust) as well as ground-based observations (these have been already provided but not in an appropriate place) and satellite retrievals thus providing a complete overview.

   R: The factors driving the emission and transport of the Saharan dust plume towards central Europe are of course of great interest but not really in the focus of our study which is discussing different ground based remote sensing methods and how they compare with one transport model as pointed out above. However, we have added some more information on the main factors relevant for emission and transport of Saharan dust towards central Europe and discuss them in the context of our comparison of model results with observations in Karlsruhe in section 3 as they may have some influence on the model performance. The added sentence is as follow:

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"In early April 2018, a far southward reaching upper-level trough associated with a large low-pressure complex in the western North Atlantic lad to a cold front with strong surface winds and dust emission in the Northern Sahara in Morocco and Algeria. The dust was transported northward into the western Mediterranean where it entered a warm conveyor belt that effectively lifted the dust and transported it towards central Europe. "

9. Figure 1:

Which is the off-zenith angle for the KASCAL aerosol profiles?

R: We have added the off-zenith angle for KASCAL aerosols profiles in the right figure. We did measured with KASCAL 0°, 60° off zenith angle (90° and 30° elevation angle) and we add this information in the manuscript .

"The scanning lidar was operated doing vertical and slant measurements at 90° and 30° elevation angle alternatingly with integration times for each observation angle of 300 s."

Use common colorbar for the three curtain plots in order to facilitate a visual intercomparison among them.

R: We have changed the colorbar of Figure 1 into a common colorbar.

It would be interesting to make a quantitative comparison (e.g. bias) between the curtain plots. To realize, you have to regrid the altitude-time plots and project them in a common grid.

R: For this purpose we have included the ICON-ART data in the middle panel as contour lines over the lidar data demonstrating that the model predicts the dust plume arrival time and structure quite well. For a quantitative comparison we have plotted the backscatter coefficients for one time interval separately. We think that this allows a good comparison of the backscatter coefficients.

I suggest to remove the black curves from the middle plot. I don't see why they are useful and in some cases it is hard to distinguish them (packing). Moreover, the labels are missing.

R: We have reduced the line thickness of the black curve representing the model result in the middle plot to improve the visibility. We consider it useful to demonstrate the agreement regarding dust plume arrival time and structure.

How you have selected the timeframe for the backscatter plot (right figure)?

R: We choose a period without clouds and a distinct dust layer for this comparison. We indicate this period in Figure 1 now. The modified Figure 1 and caption are given below:

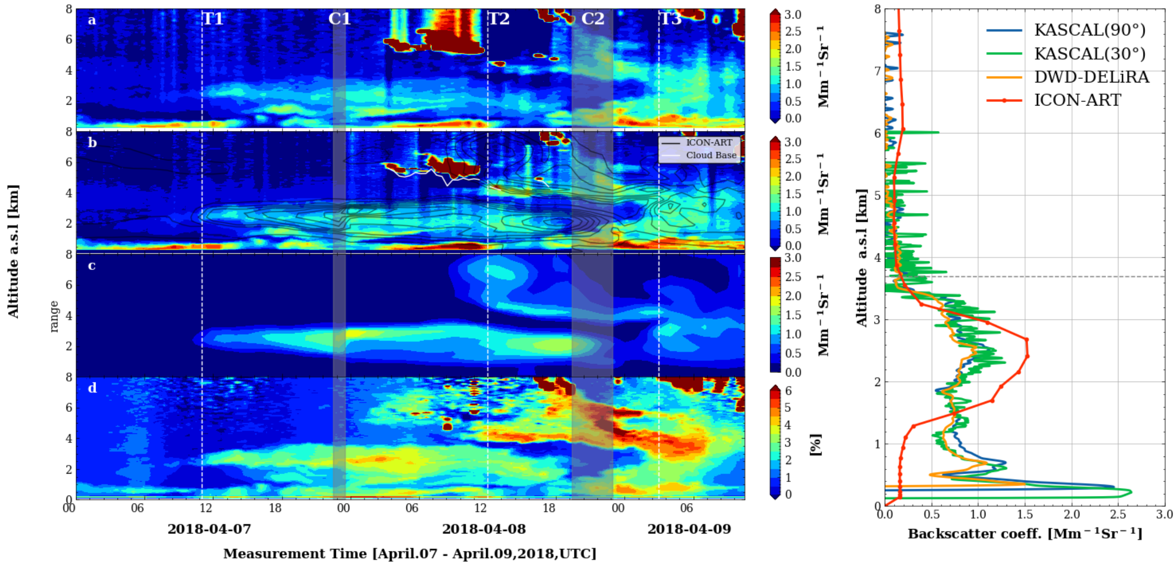

Figure 1: Time series of backscatter coefficients from KASCAL measurements (a) and from DWD-DELiRA measurements with ICON-ART results shown as black contour lines (b) as well as ICON-ART backscatter coefficients (c) and linear volume depolarization ratios from KASCAL measurements (d) from April 7th to 9th, 2018. Please note that the model data only includes the Saharan dust while the lidar data shows also other aerosol particles and clouds. The profiles of backscatter coefficients measured by the two lidars from 22:30 to 23:30 and predicted by ICON-ART for 23:00 on April 7th, 2018 (indicated as C1 in the contour plots) are shown on the right side of this figure. The vertical dashed lines in the

contour plots indicate dust arrival (T1), second dust layer appeared (T2), and the two dust layers merged (T3). C1 and C2 represent time periods used for a more detailed data analysis.

How the backscatter coefficient by the model has been calculated?

R: Mineral dust in ICON-ART is represented by three lognormal modes with mass median diameters of 1.5, 6.7 and 14.2 µm, and standard deviations of 1.7, 1.6 and 1.5, respectively. The output of the ICON-ART model is mass concentrations of these three modes. The mass backscatter cross section (m^2/g) is provided by Meng et al. (2010) . We have added this information in section 2.2 of the revised manuscript as follows.

"For this study, the altitude dependent backscatter coefficients and column AODs were used to compare ICON-ART calculations to the results from lidar and sun photometer measurements based on the three lognormal dust size distributions in ICON-ART and the mass backscatter cross sections, mass extinction cross sections provided by Meng et al. (2010) ."

Why the modelled backscatter coefficient is so much overestimated?

R: Besides potential overestimation in particle mass or size, we consider a main reason the assumption that the dust particles are spherical to calculate the backscatter coefficients from the dust mass size distributions. As we discussion section 3.2, the AOD from model calculation is systematically lower than from sun photometer measurements as their bias is wavelength dependent and increased with decreasing wavelength towards the UV regions. This is potentially related to an underestimation of the number of small particles as shown by Hoshyaripour et al., (2019). Therefore, the overestimation of backscatter coefficients is most likely not due to overestimated particle numbers.

Fig. 2 of Hoshyaripour et al., (2019) shows the scattering phase function at wavelengths of 532 nm and 1064 nm for spherical (SPH) and non-spherical (NSP) particles for the three lognormal modes. The spherical particles have larger backscatter coefficients (at 180°) than non-spherical particles. This is the reason that the backscatter coefficients are so much overestimated. The physical meaning behind is phenomenon is that for spherical particles also surface waves can contribute to the backscatter, hence causing larger backscatter coefficients for spherical particles (Hovenac and Lock, 1992).

In the revised manuscript, we show now the mass backscatter coefficient for non-spherical particle parameters as provided by Meng et al. (2010). The revised modelled backscatter coefficients can be seen in the revised Fig.1. After using parameters for non-spherical particles, the predicted backscatter coefficient is generally on average larger by only a factor of 1.01 ± 0.56 compared to the lidar measurements at wavelength of 355 nm.

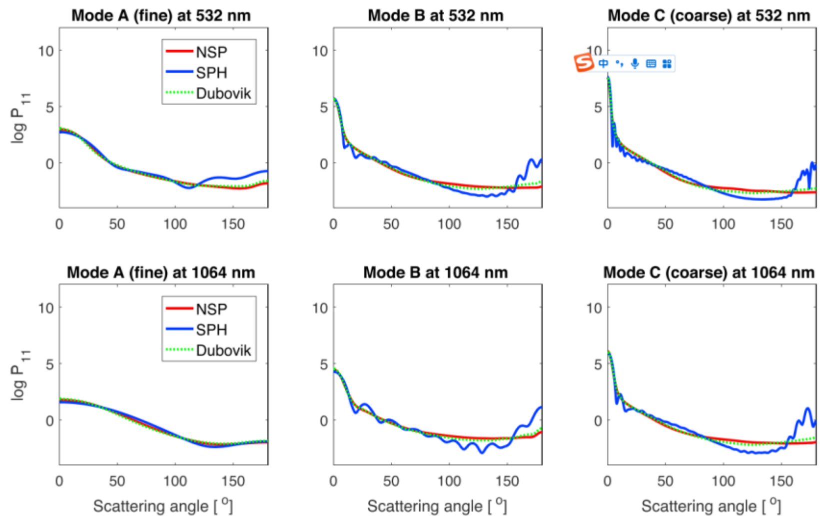

Figure 2. Scattering phase function at wavelengths 532 and 1,064 nm for SPH (blue) and NSP (red) particles in all three size modes. Dashed green line is based on the spheroid shape distribution proposed by Dubovik et al. (2006). SPH = spherical; NSP = non-spherical (from Hoshyaripour et al., (2019)).

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We have added this explanation to section 3.2 of the revised manuscript:

"In order to consider effects of particle shape on dust optical properties in ICON-ART (Hoshyaripour et al. (2019)) parameterisations provided by Meng et al. (2010) are used. Fig. S6 shows the backscatter coefficients of two lidar measurements and two model calculations using spherical (SPH) and non-spherical (NSP) particle parameterisations, respectively. This figure shows that the ICON-ART model would overestimate backscatter coefficients by a factor 2.6 ± 1.1 at a wavelength of 355 nm if assuming spherical particles to calculate backscatter coefficients. The reason for backscatter coefficients are so much overestimated for SPH particles is that the spherical particles have larger backscatter coefficients (at 180°) than non-spherical particles as shown in Fig.2 of Hoshyaripour et al. (2019). The physical meaning behind this phenomenon is that for spherical particles surface waves can contribute to the backscatter, hence causing larger backscatter coefficients for spherical particles (Hovenac and Lock, 1992). The vertical profiles of backscatter coefficient from two lidar measurements and two ICON-ART modes are shown in Fig. S7 for two selected periods as indicated C1 and C2 in Fig. 1. Comparing Fig. S6 and Fig.S7, we found that ICON-ART can predict dust layer structures quite well for most of the time of this event but also shows substantial differences with lidar measurements figure e.g. for the time period C2 (cf. Figure S7 right). The coarse mode AOD of the sun photometer and ICON-ART results for spherical and non-spherical particle models are shown in Fig. S5. All AOD values follow a similar trend but the model results are higher by a factor of 1.25 ± 0.21 for NSP particles and 1.14 ± 0.18 for SPH particles at a wavelength of 550 nm."

The Fig. S5, Fig S6, Fig S7 in the supplement have been updated:

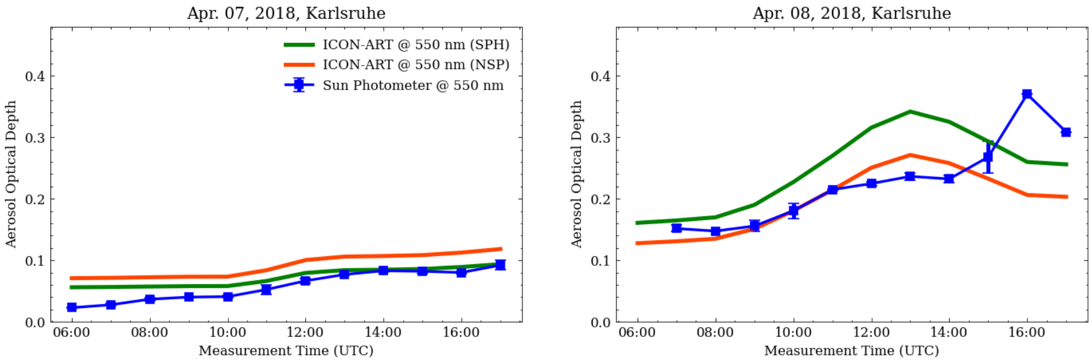

Figure S5: AOD from the sun photometer (coarse mode) and ICON-ART for both SPH and NSP particles model simulation for 7th and 8th of April for 1hour temporal resolution. SPH = spherical; NSP = non-spherical.

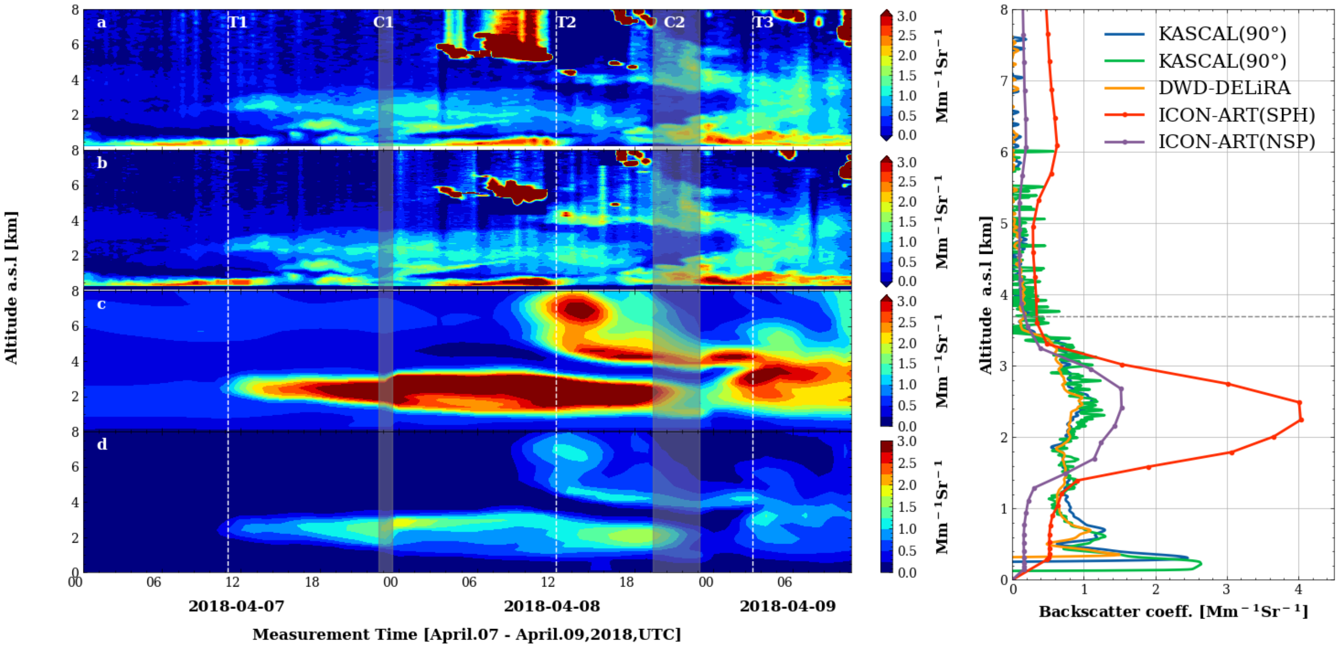

Figure S6: Time series of backscatter coefficients from KASCAL measurements (a) and from DWD-DELiRA measurements with ICON-ART results shown as black contour lines (b) as well as ICON-ART results for SPH particles (c) and as ICON-ART results for NSP particles from April 7th to 9th, 2018. Please note that the model data only includes the Saharan dust while the lidar data shows also other aerosol particles and clouds. The profiles of backscatter coefficients measured by the two lidars from 22:30 to 23:30 and predicted by ICON-ART for 23:00 on April 7th, 2018 (indicated as C1 in the contour plots) are shown on the right side of this figure. The vertical dashed lines in the contour plots indicate dust arrival (T1), second dust layer appeared (T2), and the two dust layers merged (T3). C1 and C2 represent time periods used for a more detailed data analysis. SPH = spherical; NSP = non-spherical.

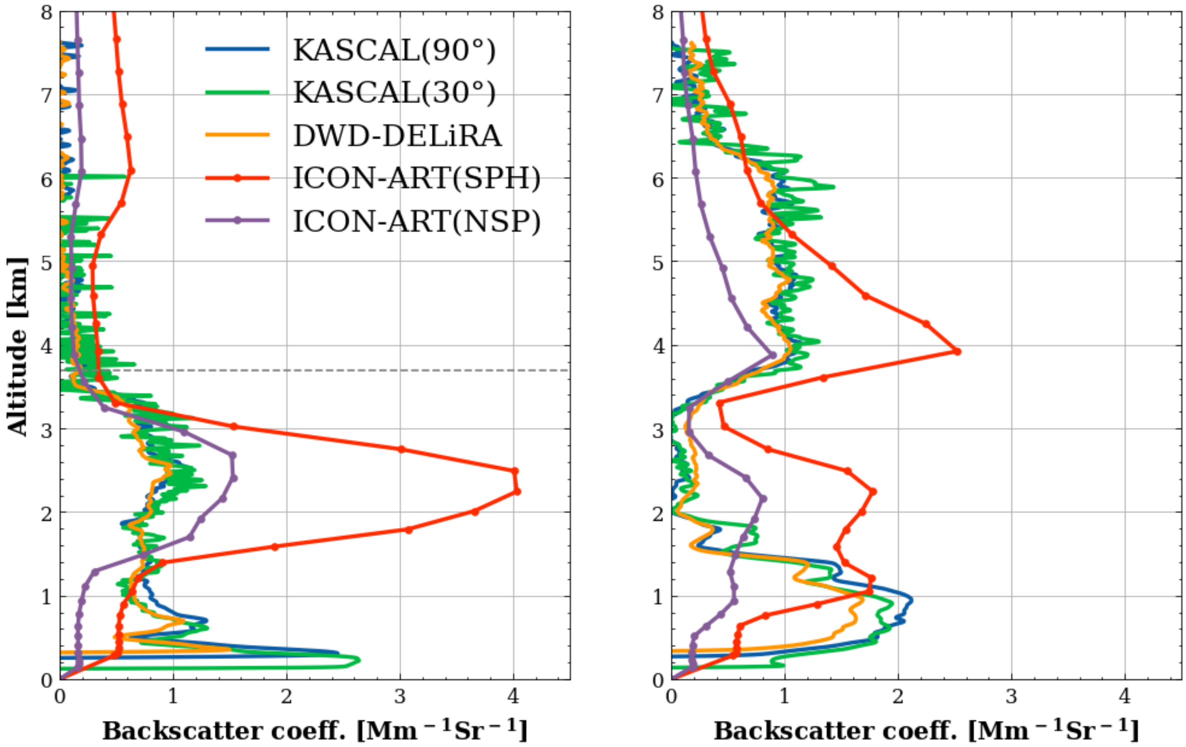

Figure S7 Profiles of backscatter coefficient from KASCAL (both vertical and slant direction), DWD-DEliRA measurements as well as ICON-ART model simulation for two typical cases indicated C1 and C2 in Fig. 1. SPH = spherical; NSP = non-spherical.

10. Lines 196 – 199: There is a contradiction between these two sentences. Do you mean the extinction coefficients, their

uncertainties or both? According to Table S2, the variation of the alpha values is very small among the window types/lengths whereas the uncertainty (standard deviation) decreases for increasing window lengths.

R: To avoid misunderstandings we have reformulated these sentences as follows:

"From this table, we can find that the mean values of extinction coefficients for different filter types and filter lengths remain almost constant. In contrast, their uncertainties vary from around 35 to 5 Mm^{-1} with window lengths from 82.5 m to 1207.5 m for different types of filters."

11. Figure 2: Please provide a better explanation in the caption.

R: We have changed the caption to: "Figure 2: Extinction coefficients (a) and backscatter coefficients (c) from elastic and Raman retrieval methods are shown on the left. On the right Raman extinction coefficients (b) and elastic backscatter coefficients (d) are given for different optical paths for measurements in the time from 19:21 to 22:47 (UTC) on April, 8th, 2018. (Two vertical paths are from DWD-DELiRA and KASCAL and one slant path is from KASCAL)."

12. Figure 3: Can you provide an explanation for the differences of the lidar ratio (LR) for the dust layer (4-6 km) found between slant and vertical angles?

R: For the analysis of the slant and vertical measurements, we had to choose different reference values at different reference heights. These reference values have of course uncertainties and the choice of them might not have been optimal. Within the uncertainties, the backscatter coefficients differ slightly (left figure) but the extinction coefficients (right figure) were almost identical which in turn leads mathematically to slightly different lidar ratios. The Raman backscatter coefficients and extinction coefficients for both vertical and slant measurements are shown in Fig. 3.

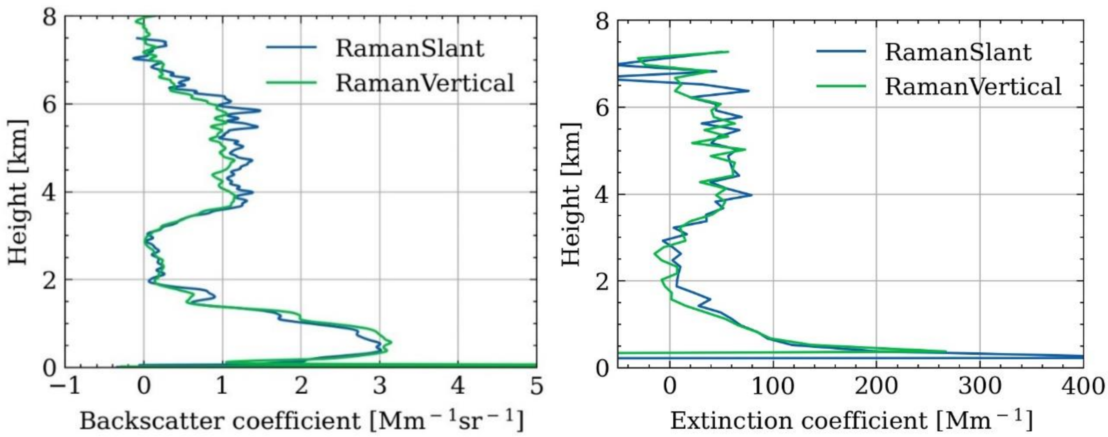

Figure 3. Profiles of backscatter coefficients and extinction coefficients retrieved from Raman channels in the time from 19:21 to 22:47 (UTC) on April, 8th, 2018.

13. Line 226: Replace "retrieved" with "retrieve".

R: We have changed this in the revised manuscript.

14. Line 231: Why you have used LR=55sr and not 50sr?

R: In this case we wanted to use a typical literature value for Saharan dust (e.g. LR = 55 sr) to achieve a kind of independent analysis.

15. Lines 235-236: Can you provide a short description about the collocation approach that you have followed?

R: The observations were done closely collocated as described in section 2.1.

16. Line 238: Why the AE is assumed equal to 1?

R: We have revised this analysis using the mean AE from the sun photometer in the wavelength range between 340 nm and 380 nm. These results in the following update: "However, the average AOD retrieved from the lidar data for two days is systematically lower by 0.041 ± 0.022 than that from the sun photometer after wavelength conversion to 340 nm. The AE used in this wavelength conversion is 0.471, which is calculated from sun photometer at wavelengths of 340 nm and 380 nm. The average stratospheric AOD of for the years 2018-2019 in Northern Hemisphere was 0.01 at 340 nm (Kloss et al., 2020). Hence, the averaged AOD measured by the sun photometer is still larger by 0.031 ± 0.022 than the AOD from the lidar measurement even considering stratospheric AOD. This bias may due to an inappropriate assumption of constant backscatter coefficients in the overlap region of the lidar. Such an uncertainty of AOD corresponds to an uncertainty in backscatter coefficients of 4.1 ± 2.9 Mm^{-1} sr^{-1} in the overlap region"

17. Lines 250 – 251: What are we expecting in the case of oriented dust particles? Please provide also some relevant references.
R: A preferential orientation of non-spherical particles relative to the propagation direction of the incident light may result in significantly higher (or lower) effective scattering cross-sections by orders of magnitude (Geier and Arienti, 2014), hence causing different depolarization for different elevation angles(Asano, 1983). Recently Kahnert et al., (2020) provided an overview of dust particle linear depolarisation values and a model approach describing the backscatter depolarisation ratio of mineral dust particles. We have added both references to the revised manuscript.
18. Lines 261 – 269: I think that this part should be moved to the new section presenting an overview of the studied dust outbreak by means of numerical simulations, satellite observations and ground-based retrievals (see comment 8). Improve also the part of the text between lines 266 and 269.
R: Following our answer to comment 8 and considering that the information on the single scattering albedo of Saharan dust belongs to the description of the characteristic properties of the Saharan dust particles, we didn't move this part but modified the text between lines 266 and 269 as follows:
"The single scattering albedos (SSA) determined for the wavelengths between 439 and 1018 nm range between 0.88 and 0.96 and agree quite well with data from previous observations (cf. table S2)."
19. Section 3.2: At the end of the main body of the manuscript you are discussing the results of Figure 1 which is quite strange. To my opinion, the Results section should be restructured as follows:
   Description of the dust outbreak (lidars, AERONET, model)
   R: Following our answer to comment 8, we have reformulated the text in the section 3. And used the dash line and label to describe the dust event clearer. In addition, the discussion related to the ICON-ART model has moved to section 3.2. The sentence in this section has changed into:
   "As can be seen in these figures, the plume arrived in Karlsruhe at 11:00 on April 7th (dash line T1), and lasted about 3 days. Initially, this dust layer showed a maximum in backscatter at an altitude of 2.5 km which subsequently also reached lower altitudes. At 12:00 UTC, April 8th, another dust layer which lies between 5.0 -11.0 km arrived at the observation station (dash line T2). Then the dust layer started sinking and overlapped with the lower dust layer at around 3:00 am of April 9th (dash line T3). A cloud with a base at 4.5 km appearing at 11:00 (UTC) of April 9th made it difficult to retrieve the backscatter coefficients for the aerosol particles below. Hence, the backscatter coefficients of the lidar measurements are not shown for this period. In addition, two periods (C1 and C2) are highlighted for which we have done a more detailed analysis.
   Keep Section 3.1 after removing Figure 4 and the relevant discussion (these should be transferred to the model evaluation)
   Model evaluation discussing also the comparison between lidars and sunphotometer
   R: We consider it necessary for the discussion of the particle characteristics determined from observations to have Fig. 4 with the AOD information in section 3.1. We could remove the model results from Fig. 4 to clearly separate the observations from the model results. However, we think it is better to have them in Fig. 4 for the comparison between modelled and observed AOD following in section 3.2. To better distinguish model results and observations we modified Fig. 4 showing the ICON-ART results as dashed lines. Furthermore, we have added the following sentence to the text:
   "The hourly AODs from the sun photometer, the vertical lidar (DWD-DELiRA) and the ICON-ART model are shown in Fig. 4. Please note that the model result will be discussed in detail only in section 3.2. All these three methods

show a similar trend with AODs increasing from around 0.13 to 0.45 during these two days."

The modified Fig.4 is as follows:

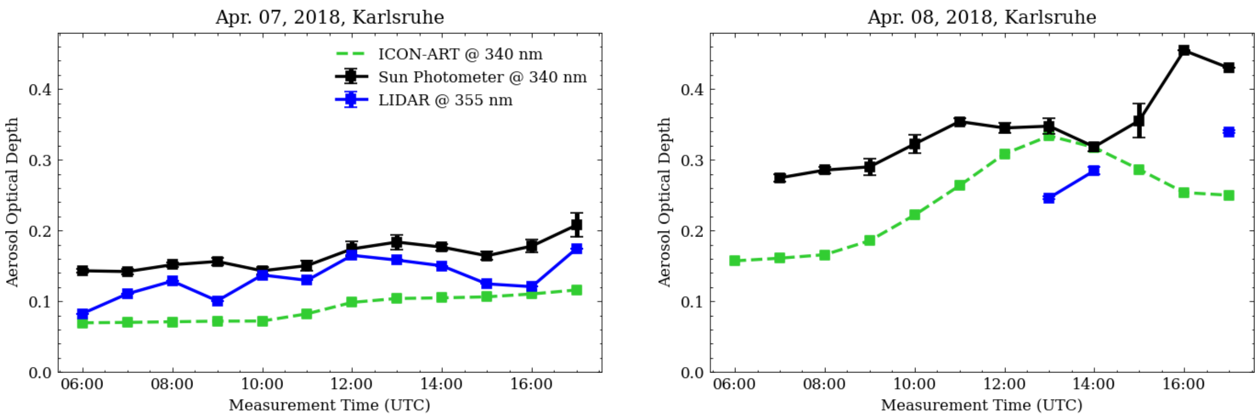

Figure 1: AOD from lidars (blue circles) and sun photometer (black squares) on 7th and 8th of April for 1 hour temporal resolution. ICON-ART results are shown for comparison (dashed green line) and will be discussed in section 3.2.

20. Line 284: I would be more cautious with this statement!

    R: We have modified the sentence in the revised manuscript as follows:

    "Although the lidar data shows more details of the dust plume structures, the agreement with the model is quite good considering the relatively coarse spatial resolution used in this model run."

21. Lines 289 – 290: Why are you ignoring the potential model deficiencies?

    R: It isn't our intention to ignore any potential differences and we modified this sentence in the revised manuscript as follows:

    "However, the modelled AODs are systematically lower than those from the sun photometer. Fig. S6 shows the time series of coarse particle mode AOD for sun photometer and modelled AOD, which shows that the modelled AOD values agree well with coarse particle AOD of the sun photometer at a wavelength of 550 nm. Hence, the reason of underestimating AOD by the model shown in Fig. 7 is partially due to the fact that the modelled AOD only includes the Saharan dust plume and the sun photometer also the boundary layer aerosol."

22. Lines 296 – 297: This sentence needs a better explanation.

    R: Indeed this aspect deserves a better explanation. Therefore, we have added the following text:

    "In order to consider effects of particle shape on dust optical properties in ICON-ART (Hoshyaripour et al. (2019)), parameterisations provided by Meng et al. (2010) are used. Fig. S6 shows the backscatter coefficients of two lidar measurements and two model calculations using spherical (SPH) and non-spherical (NSP) particle parameterisations, respectively. This figure shows that the ICON-ART model would overestimate backscatter coefficients by a factor 2.6 ± 1.1 at a wavelength of 355 nm if assuming spherical particles to calculate backscatter coefficients. The reason for backscatter coefficients are so much overestimated for SPH particles is that the spherical particles have larger backscatter coefficients (at 180°) than non-spherical particles as shown in Fig.2 of Hoshyaripour et al. (2019). The physical meaning behind this phenomenon is that for spherical particles surface waves can contribute to the backscatter, hence causing larger backscatter coefficients for spherical particles (Hovenac and Lock, 1992). The vertical profiles of backscatter coefficient from two lidar measurements and two ICON-ART modes are shown in Fig. S7 for two selected periods as indicated C1 and C2 in Fig. 1. Comparing Fig. S6 and Fig.S7, we found that ICON-ART can predict dust layer structures quite well for most of the time of this event but also shows substantial differences with lidar measurements figure e.g. for the time period C2 (cf. Figure S7 right). The coarse mode AOD of the sun photometer and ICON-ART results for spherical and non-spherical particle models are shown in Fig. S5. All AOD values follow a similar trend but the model results are higher by a factor of 1.25 ± 0.21 for NSP particles and 1.14 ± 0.18 for SPH particles at a wavelength of 550 nm. "

23. Conclusions: You should rewrite the whole section since it is not appropriate in its current state. You have to mention briefly the overarching goal of your work, then to highlight the main scientific outcomes and finally to propose how the performed analysis can be expanded.

    R: We have modified the conclusions section to include these topics.

    "The objectives of this work were to compare different measurements and retrieval methods including multi angle lidar measurements and sun photometer data and to demonstrate which aerosol properties can be determined by combining the different measurement techniques. Furthermore, we wanted to understand the quality of the dust plume predictions with the ICON-ART model by comparison with the observations. The evolution and the properties of a Saharan dust plume were characterized for two and a half days combining data from a scanning lidar, a vertical lidar, and a sun photometer. The comprehensive dataset from different methods could characterize the dust plume in different ways, thus providing additional information for further analysis.

    The multi angle lidar measurements enabled us to retrieving lidar ratios and extinction coefficients independently, which were comparable to Raman based retrievals. The comparison of extinction and backscatter coefficients for different retrieval methods was used to quantify uncertainties of the different methods and the impact of different denoise filters on extinction coefficients from Raman scattering lidar signals. The consistency among three different lidar laser beam paths reflects the high quality of the measurements as well as the retrieval algorithms. Vertical and slant volume and particle depolarization ratio measurements contain information on shape and partially orientation of dust particles. Comparison between lidar and sun photometer measurements has proven useful to study the dust optical properties like aerosol optical depth and to obtain information about lidar parameters like the lidar ratio. Wavelength-dependent optical parameters and microphysics of dust particles provided by the sun photometer indicated larger particles over the observation station for this dust event. Comparison between lidar measurements, sun photometer and ICON-ART predictions shows a quite good agreement for dust arrival time, dust layer height, and structure, backscatter coefficients, and AODs. The model results are on average larger by factor of 1.01 ± 0.56 for backscatter coefficients at wavelength of 355 nm and 1.25 ± 0.21 at wavelength of 550 nm for AODs. However, the model can overestimate the observed backscatter coefficients by a factor of 2.62 ± 1.14 at wavelength of 355 nm if assuming spherical particles. This demonstrates how crucial it is to use an appropriate parameterisation for the dust particle optics. Despite the relatively good agreement between model predictions and observations for this Saharan dust plume at one location we can't draw the conclusion that this must generally be the case. Systematic comparisons for different meteorological conditions and at different locations are needed to substantiate the model validation and to facilitate a potential improvement of the model."

Additional references:

Asano, S.: Light scattering by horizontally oriented spheroidal particles, Appl. Opt., 22, 1390-1396, https://doi.org/10.1364/AO.22.001390, 1983.

Dubovik, O., Sinyuk, A., Lapyonok, T., Holben, B. N., Mishchenko, M., Yang, P., Eck, T. F., Volten, H., Muñoz, O., Veihelmann, B., van der Zande, W. J., Leon, J.-F., Sorokin, M., and Slutsker, I.: Application of spheroid models to account for aerosol particle nonsphericity in remote sensing of desert dust, J. Geophys. Res. Atmos., 111, https://doi.org/10.1029/2005JD006619, 2006.

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Reply to the Referees' comments

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Best regards,

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