Reply to the referee's comments

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

In the following, the referee's 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.

Comments by referee #1

General comments:

This article presents an observational characterization of four cases of Saharan dust affecting the southwest Germany towards validating a dust transport model ICON-ART. This topic of high relevance to ACP. The in situ observations provide unique capability of characterizing the temporal evolution, vertical distribution, size distribution, and optical properties of dust and their mixture with other aerosol species. However, I feel the current study does not fully take advantage of the observational capability. There are gaps between what the authors aim to do and what they have indeed accomplished. The presentation needs improvement too. Therefore, I recommend returning the manuscript back to the authors for a major revision.

R: We thank the reviewer for the constructive comments. In the revised manuscript, we have substantially expanded both the observational analysis and the model evaluation to better exploit the unique observational capabilities of the measurements and to strengthen the validation of ICON-ART.

First, we introduce a multi-resolution evaluation of ICON-ART using simulations at 26 km, 13 km, 2 km, and 1 km resolution. The results demonstrate that kilometer-scale simulations provide added value in representing dust-layer stratification and vertical gradients, which cannot be fully captured by the coarser simulations. To our knowledge, such a detailed evaluation of the resolution dependence of Saharan dust transport using this combination of observations and ICON-ART simulations has not previously been presented. (section 3.3)

Second, we introduced a comparison between two forecast strategies: a continuous 5-day forecast experiment (EXP-5d) and a daily re-initialized experiment (RI-EXP-1d). The new analysis demonstrates that daily re-initialization improves the representation of the observed dust-layer evolution by reducing the accumulation of meteorological forecast errors. This improvement is particularly evident in the convection-permitting simulations (2 km and 1 km), which produce less dust in the elevated layer and a more realistic vertical dust distribution. The convection-permitting simulations exhibit stronger resolved downdrafts, suggesting enhanced downward transport of dust from the free troposphere into the boundary layer. These results highlight the combined importance of accurate meteorological initialization and convection-permitting resolution for reproducing the vertical evolution of long-range transported Saharan dust. (Section 3.3)

Third, the combination of ground-based lidar observations and CALIPSO measurements provides complementary constraints on the vertical structure and optical properties of the Saharan dust plume. While the ground-based lidar at 355 nm shows that ICON-ART generally overestimates the dust backscatter coefficient, the CALIPSO observations at 532 nm show substantially better agreement with the simulations. This wavelength-dependent model performance, together with the consistency between the two independent observing systems, suggests that the remaining discrepancies are more likely related to uncertainties in the simulated dust particle size distribution and optical properties than to observational limitations. In particular, the underestimation of coarse particles and overestimation of intermediate-sized particles in ICON-ART may lead to an excessively strong wavelength dependence of the simulated backscatter coefficient. (Section 3.3, Figure 12 and 13)

Fourth, We have added a new evaluation of the simulated dust AOD against AERONET coarse-mode AOD using observations from 17 stations within the innermost model domain. The comparison covers both EXP-5d and RI-EXP-1d at horizontal grid spacings of 26, 13, 2, and 1 km. The results show that daily re-initialization improves the correlation and brings the regression slope closer to unity, whereas the AOD statistics vary only slightly with grid spacing. This suggests that the remaining discrepancies are primarily related to uncertainties in coarse-particle mass, size distribution, and associated optical properties rather than to horizontal resolution alone. (Section 3.3, Figure 14)

Fifth, we added a detailed analysis of aerosol mass size distributions measured by the Fidas 200 optical particle spectrometer and compared them with the simulated dust size distributions. The comparison with aerosol particle size measurements reveals a systematic bias in the simulated size distributions. ICON-ART consistently overestimates the mass concentration of particles with diameters between approximately 0.5 and 2 μm while underestimating particles larger than 2 μm. The persistence of this bias in both the EXP-5d and RI-EXP-1d experiments suggests that it is primarily related to the representation of size-dependent dust transport and removal processes rather than meteorological initialization. In particular, the underestimation of coarse particles indicates that large dust particles are removed too efficiently during long-range transport, likely because of excessive sedimentation and deposition. A similar conclusion was reached by Ratcliffe et al. (2025), who showed that additional processes counteracting the rapid sedimentation of coarse dust particles are required for climate models to reproduce observations. These size-dependent biases are also likely to contribute to the remaining discrepancies in the simulated optical properties and vertical dust structure. (Section 3.3, Figure 15 and S9)

We therefore believe that the revised manuscript contributes not only to model evaluation but also to a better understanding of the processes controlling Saharan dust transport, vertical redistribution, and observational detectability over Europe. We have revised the abstract, introduction, discussion, and conclusions to better emphasize these scientific findings and improve the clarity of the manuscript's main messages.

Specific comments:

1. While the authors have claimed, e.g. in the title of the manuscript, that the dust characterized by in situ observation in southwest Germany originated from Sahara, it has not been explicitly shown that these plumes indeed came from Sahara. The supplementary figures show potential connectivity between the dust observed in Germany with antecedent Saharan dust emission from MODIS AOD. But to directly demonstrate the dust source, the authors may need to conduct back trajectory analysis for each of these cases, show the dust trajectory on top of the MODIS AOD maps, and move these maps to the main article.

R: Thank you for this important comment. We agree that the original manuscript did not sufficiently demonstrate the Saharan origin of the observed dust plumes. To address this concern, we have moved the back-trajectory analysis from the Supplementary Material to the main manuscript and expanded the discussion accordingly. For each dust event, backward trajectories were calculated and are now presented in the main text. The trajectories consistently trace the sampled air masses back to North African source regions and show transport pathways across the Mediterranean towards southwestern Germany. To further support the source attribution, we also examined MODIS aerosol optical depth (AOD) observations, which reveal enhanced aerosol loading over the Saharan source regions and along the transport pathway. The corresponding MODIS AOD maps are provided in the Supplementary Material. The combined evidence from the backward trajectories and MODIS observations provides strong support that the observed aerosol plumes originated from Saharan dust outbreaks. These additions strengthen the source attribution and the overall conclusions of the study. Corresponding revisions have been made in Section 3 and Figure 1 of the revised manuscript.

To investigate the dominant physical processes controlling Saharan dust transport over Western Europe, Four representative meteorological scenarios are analyzed combining remote sensing, in situ measurements, and ICON-ART model calculations. The transport of the four SALs were first investigated by the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model. The hourly seven-day backward trajectories were calculated during Saharan dust periods for altitudes from 500 to 7500 m with an interval of 1000 m based on the HYSPLIT model. The frequency of these trajectories at two altitudes levels (Low altitude: 500 m & High altitude: 1500 m - 7500 m) is shown in Figure 1. The reasons for classifying these trajectories into two groups is that the trajectories at an altitude of 500 m are related to the transport of aerosol within the boundary layer while the high-altitude (1500 - 7500 m) ones are related to the long-distance transport in the free troposphere. The frequency map of high altitude trajectories shown at the bottom of Figure 1 indicates that most of the trajectories originated from north Africa (Sahara Desert) as expected. However, the places of origin are different at low-altitude for these 4 Saharan dust cases. In case 1, most of the air parcel trajectories originated over the Atlantic Ocean, indicating that sea salt aerosols were likely transported over a long distance from the ocean to the study area by prevailing winds. During case 2, most of the low-altitude trajectories also originated from north Africa (Sahara Desert), which is the reason why the Saharan dust particles could be measured by ground in situ instruments during this case. During case 3 and case 4, the low-altitude trajectories are of local origin, which is related to the transport of local aerosol.

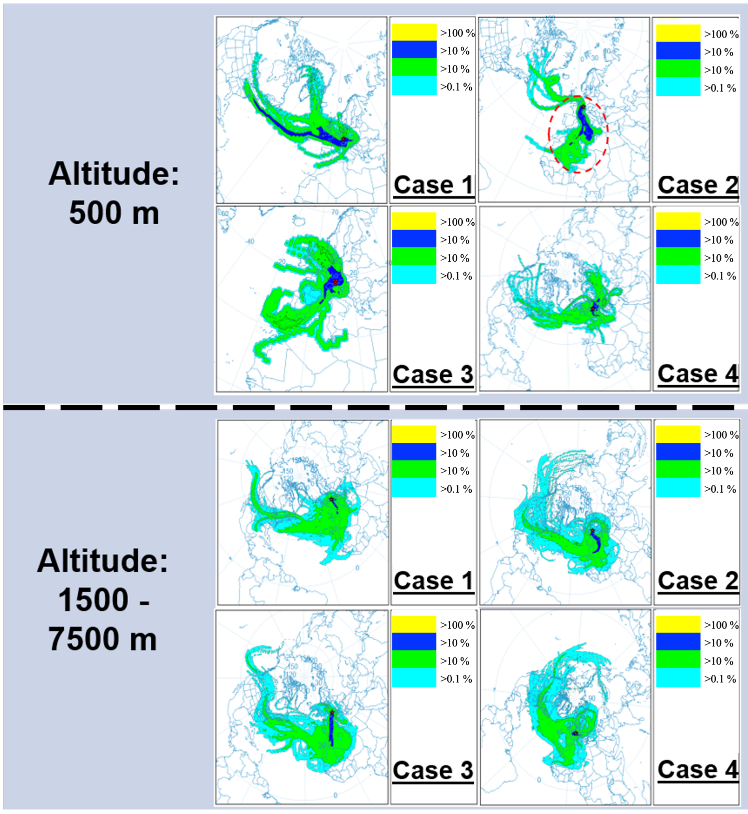

Figure 1: Frequency of trajectories at two altitude levels (500 m and 1500 - 7500 m) during four Saharan dust case periods based on back trajectories calculated by the HYbrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model. (The case IDs are labeled in Table 1)

2. While the authors stated that the major objective of this study was to "assess the performance of dust prediction for ICON-ART, to identify model improvements, and to better understand dust properties during these dust events benefiting from the advanced instruments", the model assessment is indeed quite qualitative from my reading of the current manuscript:

(i) The model turns off gaseous and other aerosol species, whereas the observations contain a fully mixing scenario. The authors processed the observational data to obtain a dust signal, e.g. by equation (1); this processing may introduce uncertainty for model evaluation per se. I'm not complaining about the use of equation (1) but thinking that it would be optimal if the model turns on full chemistry. Under the full chemistry set up, the authors can truly characterize the ageing and mixing of Saharan dust using their advanced instrumentation.

R: Thank you for this important comment. We agree that a full-chemistry simulation including gaseous species and other aerosol components would provide a more comprehensive framework for investigating aerosol ageing and mixing processes during Saharan dust transport events. However, the objective of the present study is to evaluate the capability of ICON-ART in reproducing the transport and vertical distribution of mineral dust using a dust-only model configuration. We agree that the omission of aerosol ageing, coating, and interactions with other aerosol species represents a limitation of the dust-only ICON-ART configuration. These processes can modify particle size, hygroscopicity, and optical properties during long-range transport and therefore influence the agreement with observations. This procedure allows us to isolate the optical contribution of mineral dust from the mixed aerosol environment and therefore provides a quantity that is directly comparable to the dust-only output from ICON-ART. While uncertainties associated with the dust separation method remain, the use of Eq. (1) substantially reduces the inconsistency between the observations and the dust-only model configuration. This procedure allows us to isolate the optical contribution of mineral dust from the mixed aerosol environment and therefore provides a quantity that is directly comparable to the dust-only output from ICON-ART. While uncertainties associated with the dust separation method remain, the use of Eq. (1) substantially reduces the inconsistency between the observations and the dust-only model configuration. To avoid potential misunderstanding, we have clarified this point in the revised manuscript and explicitly stated that the model evaluation focuses on the mineral dust component rather than the total aerosol mixture. We have also expanded the discussion of the uncertainties associated with the dust retrieval methodology and the limitations arising from the dust-only simulation setup. Future work using the full aerosol and chemistry configuration of ICON-ART would allow a more comprehensive investigation of aerosol ageing and mixing processes.

Tesche et al. (2009) proposed a method to separate the total backscatter coefficient into a dust part and a non-dust part using the following equation:

$$\beta_{\lambda,d} = \beta_{\lambda,p} \frac{(\delta_{\lambda,p} - \delta_{\lambda,nd})(1 + \delta_{\lambda,d})}{(\delta_{\lambda,d} - \delta_{\lambda,nd})(1 + \delta_{\lambda,p})} \tag{1}$$

Where $\beta_{\lambda,d}$ is the pure dust backscatter coefficient, $\beta_{\lambda,p}$ is the total particle backscatter coefficient, $\delta_{\lambda,p}$ is the total particle depolarization ratio, $\delta_{\lambda,nd}$ is the particle depolarization ratio of non-dust particles, $\delta_{\lambda,d}$ is the particle depolarization ratio of the pure dust plume. In this equation, $\beta_{\lambda,p}$ and $\delta_{\lambda,p}$ can be retrieved from lidar measurement.

(ii) If the authors insist using the dust-only set up, they have to clearly state that in the method section. Under this circumstance, the authors have to restrict their goal to validating the meteorology, dust transport pathway, and vertical and size distribution at the observational site. If this is the case, the authors need to expand their validation of the meteorology using three-dimensional data, probably from ERA5, that covers the source to the observation site.

R: We thank the reviewer for this valuable suggestion and agree that the objectives of the study should be consistent with the model configuration. In the revised manuscript, we have refined the scope of the study and now explicitly state that the evaluation focuses on the meteorological conditions controlling dust transport, the transport pathways from North Africa to southwestern Germany, and the resulting vertical and size distributions of mineral dust at the observation site. To strengthen the model evaluation, we have substantially expanded the validation of the simulated dust transport and meteorological conditions. Specifically, we added backward trajectory analyses for all dust events, incorporated independent CALIPSO observations to evaluate the simulated vertical dust structure, compared two forecast strategies (EXP-5d and RI-EXP-1d) to assess the impact of meteorological initialization, and included multi-resolution simulations (26, 13, 2, and 1 km) to investigate the influence of model resolution on dust transport and vertical redistribution. In addition, we expanded the discussion of the meteorological forcing and its role in controlling the long-range transport of Saharan dust. These revisions better align the study objectives with the capabilities of the dust-only model configuration and provide a more comprehensive evaluation of the simulated transport pathways, vertical dust structure, and surface size distributions.

3. The ICON-ART model overestimated wet removal in Case 3, any idea why? Does it relate to the simulated distribution bias in precipitation and cloud? Or the vertical distribution of dust? Can you use real data to demonstrate the reason? I think this is an interesting finding to dive deeper into.

R: Thank you for this interesting comment. We would like to clarify that in the original manuscript we did not explicitly conclude that ICON-ART overestimated wet removal in Case 3. Figure 7 shows that the observed aerosol concentration decreased during the drizzle and precipitation periods, indicating wet removal in the observations. However, the available comparison does not provide sufficient evidence to quantitatively demonstrate that the model overestimated wet removal. The discrepancy between ICON-ART and the in-situ PM measurements in Case 3 is likely influenced by several factors. First, the model grid point used for the comparison is approximately 40 km away from the measurement site, which can introduce substantial differences under the convective and cloudy conditions of this case. Second, cloud and precipitation fields are spatially heterogeneous, so small displacement errors in simulated precipitation or clouds can strongly affect the comparison at a single station. Third, the vertical overlap between dust, clouds, and precipitation may influence the efficiency of wet scavenging, but this cannot be fully quantified with the available observations. We have revised the manuscript to avoid over-interpreting the wet-removal process and added a more cautious discussion of the possible roles of precipitation, cloud distribution, and dust vertical structure in Case 3.

The discrepancy between the observed and simulated surface dust concentrations during Case 3 should therefore not be attributed solely to wet removal. Because this case was affected by clouds and precipitation, the comparison is sensitive to spatial displacement errors in the simulated cloud and precipitation fields, especially given the approximately 40 km distance between the model sampling location and the measurement site. In addition, the vertical overlap between dust, clouds, and precipitation may influence the simulated removal efficiency. However, the present observations do not allow a quantitative attribution of the model–observation difference to wet scavenging alone.

4. The discussion section is overly general, i.e. any model-data comparison work could attribute the discrepancies to these factors. Could you point to your results when discussing about each factor. For example, how did you reach the conclusion that "plume-boundary layer interaction and aerosol mixing play a dominant role"? Do you have evidence from your analysis?

Thank you for this valuable comment. We agree that the original discussion was to general and that several of the proposed explanations were not sufficiently linked to the results presented in the manuscript.
In the revised manuscript, we have substantially revised the Discussion section and explicitly connected each

identified source of model–observation discrepancy to the corresponding observational and modeling results. Rather than attributing the differences to generic factors, we now discuss the mechanisms supported by our analyses. Specifically, we use the comparison between the continuous forecast experiment (EXP-5d) and the daily re-initialized experiment (RI-EXP-1d) to demonstrate the impact of meteorological initialization on dust transport and vertical redistribution. We further use the newly added multi-resolution simulations (26 km, 13 km, 2 km, and 1 km) to assess the influence of model resolution on the representation of dust-layer stratification and vertical structure. In addition, the comparison with aerosol particle size measurements is used to identify systematic biases in the simulated dust size distributions and to discuss uncertainties associated with dust emission, sedimentation, and deposition processes.

We agree that statements such as "plume–boundary layer interaction and aerosol mixing play a dominant role" were not sufficiently supported by the original analyses. Therefore, we have removed or reformulated such statements and replaced them with discussions directly supported by the observational evidence and model results presented in this study.

The revised discussion now reads:

The comparison of observations with ICON-ART simulations for four Saharan dust events and two sensitivity experiments provides insight into the main sources of model-observation discrepancies. Three main findings emerge. First, the large-scale transport pathway and plume arrival time are reproduced consistently across all model resolutions and meteorological initialization strategies, with a mean arrival-time difference of approximately 20 min even at 20 km horizontal resolution. Second, the aerosol loading and vertical distribution of dust are strongly influenced by both horizontal resolution and meteorological initialization, with the best agreement achieved only when both are improved simultaneously. Third, the particle size distribution and some systematic features of the optical properties remain largely unchanged across all experiments, suggesting that these persistent discrepancies originate from the aerosol representation rather than from the transport itself.

The improvement in the simulated vertical dust structure is one of the main findings of this study. Compared with the continuous 5-day forecast (EXP-5d), the daily re-initialized forecast (RI-EXP-1d) increases the correlation between simulated and observed near-surface PM_{10} concentrations from $R = 0.65$–0.69 to $R = 0.86$–0.88 across all model resolutions, while reducing the RMSE by approximately one third. The RI-EXP-1d also increases the correlation between simulated and observed AOD from $R = 0.29$-0.31 to $R = 0.41$–0.42 (Table S1). These results show that daily re-initialized forecast provides better representation of both surface dust concentration and column-integrated aerosol concentration. This sensitivity to meteorological forcing agrees with previous studies showing that Saharan dust outbreaks contribute to short-range forecast uncertainty over Europe (Hermes et al., 2024) and that updated meteorological analyses improve aerosol forecast skill in operational forecasting systems (Benedetti et al., 2009). The improvement is not solely attributable to increased horizontal resolution. Similar improvements from EXP-5d to RI-EXP-1d are found at both coarse (26 and 13 km) and convection-permitting (2 and 1 km) resolutions, indicating that reducing accumulated meteorological forecast errors substantially improves the timing and duration of near-surface dust events. Higher resolution provides an additional benefit by resolving circulations and enhancing vertical exchange between the free troposphere and the boundary layer, resulting in sharper dust-layer boundaries and a reduced overestimation of elevated dust concentrations (Figure 10 and 12). These findings are consistent with previous studies demonstrating that convection-permitting simulations improve the representation of dust-related vertical transport processes associated with convective downdrafts and cold pools (Marsham et al., 2011; Heinold et al., 2013). However, higher resolution alone does not compensate for deficiencies in the meteorological forcing. In the EXP-5d simulations, the 1 and 2 km experiments underestimate the duration of the near-surface dust event more strongly than the coarser-resolution simulations because accumulated meteorological errors are more directly reflected in the better-resolved boundary-layer transport. These results demonstrate that meteorological initialization and horizontal resolution provide complementary improvements, with the best performance obtained when both are combined.

At first glance, the backscatter-profile statistics appear inconsistent with the improvements obtained for near-surface PM_{10}. The normalized mean bias of the lidar-model comparison is smaller for EXP-5d (5.9–6.5 %) than for RI-EXP-1d (38–50 %), whereas RMSE and correlation remain similar in both experiments ($R \approx 0.37$–0.41) (Table S1). This behaviour is most likely explained by compensating errors rather than improved model performance. The comparison with CALIPSO observations (Figure 13 and S8) shows that all simulations, including the 1 km RI-EXP-1d experiment, systematically overestimate backscatter above approximately 2.6 km. A continuous forecast may therefore produce a smaller overall bias if underestimation at one altitude compensates for overestimation elsewhere, without improving the vertical profile itself. This interpretation is supported by the nearly unchanged RMSE between EXP-5d and RI-EXP-1d. Similar limitations of profile-integrated bias metrics have been reported previously, and profile-resolved statistics are generally recommended for evaluating vertically resolved aerosol simulations (Binietoglou et al., 2015). Consequently, the backscatter results do not contradict the improvements in vertical dust transport but instead indicate that improved meteorological forcing and resolution improve the vertical redistribution of dust without correcting the persistent overestimation of elevated aerosol layers.

The overestimation of elevated dust layers forms part of a broader pattern that is largely unaffected by either model resolution or meteorological initialization. ICON-ART overestimates the backscatter coefficient at 355 nm (KASCAL) but show agreement with the backscatter coefficient at 532 nm (CALIPSO). This wavelength-dependent behaviour is consistent with ICON-ART underestimating the abundance of coarse particles while overestimating intermediate-sized particles. This interpretation is independently supported by the particle mass size distributions measured by the Fidas 200 (Figure 15 and S8). ICON-ART consistently overestimates particles between approximately 0.5 and 2 μm while underestimating particles larger than 2 μm, and these biases remain nearly unchanged in both EXP-5d and RI-EXP-1d. Since meteorological re-initialization substantially improves the timing and duration of surface dust events without affecting the particle size distribution, the remaining discrepancy likely reflects limitations in the representation of the emitted size distribution and the size-dependent removal of coarse particles, potentially through sedimentation and dry deposition during long-range transport. This interpretation is consistent with previous studies. Ratcliffe et al. (2025) showed that additional processes are required to maintain coarse dust during atmospheric transport, while Adebiyi and Kok (2020) demonstrated from a global synthesis of in-situ observations that current models remove coarse dust too efficiently. The present study extends these findings to long-range Saharan dust transport over Europe using both remote sensing and in-situ observations.

Wet deposition represents another potential source of uncertainty, particularly during Case 3. Observations show that moderate precipitation efficiently removed dust from the boundary layer. However, the present analysis does not allow a robust assessment of the wet deposition parameterization because the model evaluation point is located approximately 40 km from the observation site and precipitation was spatially heterogeneous. Consequently, differences between simulated and observed dust concentrations may partly reflect spatial displacement of precipitation rather than deficiencies in the wet removal scheme itself. Wet deposition should therefore be regarded as an important physical process that requires further investigation using more closely collocated precipitation observations.

Overall, the results indicate that further improvements in the simulation of long-range Saharan dust transport should focus on two largely independent aspects. Meteorological initialization together with convection-permitting resolution substantially improves the timing, vertical distribution, and surface concentrations of transported dust. In contrast, the persistent coarse-particle deficit and associated optical discrepancies remain largely insensitive to these improvements and instead reflect limitations in the current aerosol representation. Future model development should therefore focus on improving the the representation of the emitted coarse-particle size distribution and size-dependent sedimentation and deposition processes and on extending the aerosol representation to include ageing and mixing processes that modify aerosol optical properties.

5. The description of each case is overly descriptive and lengthy, with some statements unsupported by any observational evidence. For example, the synoptic weather conditions for Case 2 are extensively discussed without any figure of real data or reference. If the authors decide to take my earlier suggestion and expand the model validation to meteorology, please add quantitative analysis about meteorological condition in all cases. Otherwise, I suggest to reduce such descriptive text about each case.

R: Thank you for this valuable suggestion. We agree that the meteorological descriptions in the original manuscript were overly detailed and, in some cases, not sufficiently supported by observational evidence. Since the primary objective of this study is to evaluate the transport and vertical structure of Saharan dust rather than the meteorological simulation itself, we have substantially shortened the synoptic descriptions for all cases in the revised manuscript. Only the meteorological information directly relevant to the dust transport and interpretation of the observations has been retained. The focus of the Results section has been shifted from descriptive case narratives to the comparison between observations and ICON-ART simulations under different meteorological conditions. We believe that this revision improves both the clarity and scientific focus of the manuscript.

Technical corrections:

1. Figures 1, 3, 6, 8, 10, 11, 12: missing all or part of the panel index (a, b, ...).

R: We have added panel index for this Figures.

2. Contents that better fit the method section:

(i) separation of the total backscatter coefficient into a dust part and a non-dust part.

(ii) definition of the dust layer height.

R: We have moved this two parts into the method section.

3. The sentence on lines 255–257: "The volume size distribution ... has the highest concentration..." is confusing.

R: Thank you for pointing out it. We have changed this sentence as following:

The sun-photometer-retrieved aerosol volume concentration reached its maximum on 24 February 2021, whereas the surface aerosol mass concentration measured by Fidas200 peaked on 25 February 2021. The one-day difference likely reflects the different measurement principles and sampling volumes of the two instruments.

4. Contents that better fit the corresponding figure caption:

(i) The blue-shaded area ... (lines 421–422)

(ii) The boxplots ... (lines 429–431)

R: Thank you for your comments. We have moved this two parts into figure captions.

5. There is a typo of the word "calculation" in the abstract.

We have corrected this typo.

6. On line 60, double "also".

R: We have deleted one "also".

7. On line 83, MODIS is a satellite instrument rather than a satellite.

We have changed "MODIS satellite" to "MODIS"

References

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Tesche, M., Ansmann, A., Müller, D., Althausen, D., Engelmann, R., Freudenthaler, V., and Groß, S.: Vertically resolved separation of dust and smoke over Cape Verde using multiwavelength Raman and polarization lidars during Saharan Mineral Dust Experiment 2008, Journal of Geophysical Research: Atmospheres, 114, https://doi.org/10.1029/2009JD011862, _eprint: https://onlinelibrary.wiley.com/doi/pdf/10.1029/2009JD011862, 2009.