Manuscript title: Characterization of Saharan and Middle Eastern Dust Aerosols and Their Associated Shortwave Direct Radiative Effects over Cyprus

Dear Editor and Reviewers,

We sincerely thank the Editor and both Reviewers for their careful evaluation of our manuscript and for their constructive comments and suggestions. We have carefully considered all comments and substantially revised the manuscript accordingly. The revisions have improved the scientific clarity, methodological description, statistical robustness, presentation, and overall consistency of the manuscript.

For clarity, the comments from each reviewer are reproduced below, followed by our point-by-point responses. Reviewer comments are shown in black, while our responses are shown in red.

Response to the Editor

Editor comment:

As Editor, I would like to thank the lead author and all the co-authors for this excellent study and for the considerable work that has gone into this manuscript.

I would also like to thank the reviewers for their precise, detailed, and constructive reports, which provide the authors with clear guidance towards concrete improvements to the manuscript.

Finally, I would like to thank the authors once again for their detailed and comprehensive responses to the reviewers' comments.

In their responses, the authors mention a revised version of the manuscript. However, this revised version has not yet been uploaded. I would therefore kindly ask the authors to upload it as soon as possible.

In addition, before submitting the revised version of the manuscript, I would suggest that the authors add a glossary table explaining all the numerous acronyms used throughout the manuscript. Such a table would be a valuable aid for readers and would greatly facilitate their understanding of the publication.

Many thanks in advance, and best wishes to the authors for this final stage of the revision process

Response:

We sincerely thank the Editor for the kind and encouraging comments and for the careful handling of our manuscript. We also appreciate the acknowledgment of the reviewers' constructive contributions and of the revisions undertaken in response to their comments.

Following the Editor's suggestion, we have also added a glossary table to the revised manuscript, providing definitions of the numerous abbreviations and acronyms used throughout the study.

Response to Reviewer #1

We thank the reviewer for the careful evaluation of our manuscript and for the constructive comments and suggestions, which helped is improve its scientific clarity, and presentation.

In response, we revised the manuscript extensively. Several sections have been rewritten to improve readability, scientific clarity, and the overall flow of the paper. We expanded the descriptions of the observational datasets, aerosol classification methodology, HYSPLIT trajectory analysis, radiative transfer model configuration, and clarified the statistical and temporal representativeness of the results.

Most importantly, we revised the analysis of the shortwave direct radiative effects (DREs) to and account for the influence of solar zenith angle (SZA). Monthly DRE and direct radiative forcing efficiency (DRFE) values are now calculated using also observations within a common SZA interval of 60° ± 4°, thereby reducing the influence of seasonal solar geometry on comparisons among monthly DRE values. An additional analysis of the dependence of DRE on SZA is provided in the Supplement. We also revised the methodology, Results, Discussion, and Conclusions accordingly.

The paper "Characterization of Dust Aerosol Source Types and Associated Shortwave Direct Radiative Effects Over Cyprus: A Seven-Year Study" by Georgia Charalampous and coauthors presents seven (2025-2022) years of columnar aerosol properties from the Agia Marina Xyliatou station, remote site in central Cyprus, used to derive the impact of dust transported from the Saharan and the Middle East deserts on the aerosol load and on the dust direct radiative effects.

The dust source regions are identified by the use of the airmass backtrajectories computed from the HYSPLIT dispersion model, while the optical properties of dust are isolated by comparing the aerosol classification based on aerosol optical depth (AOD) at 440 nm and the Ångström exponent (AE) (AERONET Dubovik method) and the one based on the lidar ratio and the particle linear depolarization ratio (lidar depolarization method), using the measurements from the Limassol station. An important feature of the Middle Eastern dust is the difficulty to isolate pure dust particles, due to the contamination by fine pollution during transport.

After the description of the intra-annual variability of the dust optical properties, the dust radiative effects (DRE) at the surface, at the top of the atmosphere (TOA), and in the atmosphere, are computed for the two different source regions, taking advantage of the solar irradiance measurements performed at Agia Marina Xyliatou.

Finally, the attenuation of the global horizontal irradiance (GHI) due to dust is computed to assess the effects on the solar energy production.

General comments

The article highlights the aerosol property measurements from the AMX site, which is strategically located to compare the optical properties of dust from the Sahara and from the Middle Eastern deserts.

The dataset is generally well presented, as is the data selection and the classification of dust cases from the Sahara and the Middle East regions.

The description of the instruments and measurements used in the manuscript could be improved by including some missing information, as well as that relating to the RTM input data. Furthermore, some details are missing regarding the data analysis, which I believe are important for understanding the results. All comments are described in the Specific comments section.

My main concern is the calculation and comparison of the monthly averages of the DRE, which is dependent on the solar zenith angle (SZA). The authors do not mention this dependence, and it seems that, in calculating the monthly averages, they take into account all the estimates of the instantaneous DRE in the month regardless of the SZA value. This could lead to a bias in the results and distort the subsequent conclusions.

I therefore ask the lead author and co-authors to pay attention to this aspect and to present a study that shows the consistency of the results.

For this reason, I suggest major revisions in order to publish the work.

We thank the reviewer for the careful and constructive assessment. We have substantially revised the manuscript to address the concern regarding the dependence of shortwave DRE on solar zenith angle. In particular, we recalculated the source-resolved DRE at a fixed SZA of 60°± 4°, additionally examined the results within common SZA intervals, and revised the monthly statistics so that they are calculated from daily rather than instantaneous means. We also expanded the descriptions of the radiation measurements, AERONET sampling, HYSPLIT trajectory procedure and radiative-transfer configuration, and now report the sample sizes underlying the principal comparisons.

Specific comments

Line 206: the description of the GDAS dataset in the link provides 23 instead of 55 vertical layers. Moreover, the GDAS dataset with 0.5°x0.5° seems to be available only until 2019 in the online version of the HYSPLIT trajectory model.

Thank you for this valuable comment. We agree that the original description of the meteorological input dataset was outdated and could lead to confusion. We have revised Section 2.3.1 to accurately describe the meteorological fields used in the HYSPLIT simulations. Specifically, GDAS 0.5° meteorological fields were used for the period up to June 2019, while GFS 0.25° meteorological fields were used from June 2019 to 2022, consistent with the datasets available through the NOAA HYSPLIT archive. The incorrect reference to 55 vertical layers has been removed, and the corresponding NOAA archive reference has been updated accordingly. We have also clarified the trajectory initialization procedure for cases with and without lidar observations.

Section 2.2: A paragraph should be dedicated to solar irradiance instruments and measurements, instead of providing the information under Section 2.2.3 which is devoted to the description of the PollyXT system. Among the missing information, the time step of the solar irradiance measurements should be specified, since it has a role in the estimation of the cloud-free intervals and in the calculation of the dust DRE.

We agree that the description of the surface solar radiation instrumentation should be presented separately from the PollyXT instrumentation. We have therefore reorganized Section 2.2 by introducing a dedicated subsection (2.2.2) describing the solar irradiance measurements, including the instrumentation, calibration and quality-control procedures, and the native measurement time step. We also clarify that these measurements used for the cloud-screening procedure and the radiative transfer model validation.

Section 2.2.1: the time step of the AERONET measurements should be made explicit, as well as the wavelengths of the Cimel CE348NE. On the AERONET web site I see that some channels are missing in some periods.

We would like to thank the reviewer for his comment. We have expanded Section 2.2.1 (lines 140 – 143) to specify the measurement wavelengths and temporal sampling of the Cimel CE348NE sun–sky photometer operated at AMX. Direct-sun observations are nominally performed at approximately 15 min intervals during daylight, with each observation consisting of a triplet of measurements. However, effective temporal sampling is irregular because measurements may be unavailable or subsequently excluded owing to cloud screening, sky-radiance measurement sequences, instrument downtime or quality-control procedures.

Section 2.3.2: the authors should argument the choice of the radiative transfer model (RTM) input parameters. Why did they select the AOD only from two wavelengths, instead of using at least four (440, 675, 870, and 1020 nm) that are available for the entire period? This would improve the description of the spectral AOD variations and the effect on the GHI simulation.

I guess that the AOD is extrapolated below 440 nm and above 675 nm by the AE and interpolated within the 440-675 nm interval, but I suggest explaining it in the text.

Thank you for this valuable comment. We revised Section 2.3.2 and Table 1 to clarify the treatment of spectral aerosol optical depth in the radiative transfer simulations. The AERONET-reported Ångström exponent at 440–870 nm was not used directly. Instead, the Ångström coefficients α and β, were derived from the measured AOD values at 440 and 675 nm and supplied to libRadtran using the aerosol_angstrom parameterization. libRadtran then calculated the spectral AOD at the model wavelength grid over the simulated wavelength range of 289–3000 nm.

In this parameterisation, aerosol optical depth is represented as,

$$\tau(\lambda) = \beta\lambda^{-\alpha},$$

where wavelength is expressed in micrometres. For each observation, the coefficients were calculated as

$$\alpha = -\frac{\ln(\tau_{440}/\tau_{675})}{\ln(0.44/0.675)} = \frac{\ln(\tau_{440}/\tau_{675})}{\ln(0.675/0.44)}.$$

and

$$\beta = \tau_{440}(0.44)^{\alpha},$$

which is equivalent to:

$$\beta = \tau_{675}(0.675)^{\alpha}.$$

Because wavelength is expressed in micrometres, β represents the AOD implied by the fitted power law at 1 μm. These two parameters were supplied to libRadtran, which calculated the spectral AOD continuously over the simulated shortwave wavelength range. Thus, the 440 and 675 nm measurements were not used as interpolation nodes; rather, they were used to derive the two parameters defining the spectral Ångström relationship.

We agree that using additional wavelengths could provide a more detailed description of spectral curvature when departures from a single Ångström power law occur. However, the adopted two-wavelength parameterization reproduced the cloud-free ground-based GHI measurements very well, with approximately 87% of simulations within ±5% and 96% within ±10% of the observations. We therefore retained the existing simulations while clarifying the exact implementation and its validation in the revised manuscript. We also corrected Table 1 .

Which atmospheric profiles are used?

We have revised Section 2.3.2 to explicitly describe the atmospheric profiles used in the radiative transfer simulations. Specifically, we now state that the AFGL Midlatitude Winter and AFGL Midlatitude Summer atmospheric profiles were adopted for December–February and March–November, respectively.

I can not find any information about the SZA interval or time step for the RTM simulations for the purpose of the validation of the model performance in reproducing the cloud-free GHI measurements. Are model simulations carried out for each cloud-free irradiance measurement or for specific SZA values?

We clarified that radiative transfer simulations were performed for each individual AERONET observation using the corresponding date, time, and geographical location (also added to Table 1). Consequently, the solar zenith angle was calculated internally by libRadtran for every simulation rather than being prescribed over a fixed interval. Finally, we clarified that the simulated irradiances used for the validation were temporally matched with the nearest cloud-free ground-based irradiance measurements within a ±15-minute time window.

Table 1: please explain the sentence "440 nm and 675 nm, treated as wavelength independent within each interval", which is not clear.

We agree that the previous wording was unclear. The table has been revised to clarify that the single-scattering albedo (SSA) and asymmetry parameter (ASY) were calculated as the arithmetic mean of the AERONET values at 440 and 675 nm and were applied as spectrally constant aerosol properties throughout each radiative transfer simulation. The previous phrase referring to "wavelength independent within each interval" has therefore been removed.

Section 2.4.3: the DRE at the surface is calculated for both the downwelling and the net radiation. Which of the two is then evaluated for the successive analysis?

Thank you for pointing this out. We agree that the original wording was ambiguous. Although both downwelling and net surface shortwave fluxes were calculated during the radiative transfer simulations, all analyses presented in this manuscript are based on the net surface DRE, as defined by Equation (5). We have revised Section 2.4.3 to explicitly state that the results presented throughout the manuscript refer to the net surface shortwave radiation.

The authors say (lines 283-284) that "The corresponding instantaneous DREs were then derived and subsequently averaged to obtain monthly mean values". How do they average the instantaneous DRE values? This is a key point since the DRE, either at the surface and at TOA, has a clear SZA dependence (see, e.g., Balmes and Fu, The diurnally-averaged aerosol direct radiative effect and the use of the daytime-mean and insolation-weighted-mean solar zenith angles, J. Quantitat. Spectr. and Rad. Transfer, 257, 2020, doi:10.1016/j.jqsrt.2020.107363; Wu et al., Aerosol direct radiative effects at the ARM SGP and TWP sites: Clear skies, J. Geophys. Res. Atmospheres, 126, e2020JD033663, 2021, doi:10.1029/2020JD033663; di Sarra et al., Surface shortwave radiative forcing of different aerosol types in the Mediterranean, Geophys. Res. Lett., 35, L02714, 2008, doi:10.1029/2007GL032395). Since AERONET measurements are not continuous throughout the day and, even more so, those in dusty conditions are not, the dust DRE can be estimated only for some SZAs. Furthermore, daytime SZA values vary throughout the year, so in summer the DRE can be calculated for low SZAs that are not reached in other seasons. How did the authors account for this dependence when calculating monthly averages? Averaging all instantaneous DRE values (calculated for variable SZAs) means that seasonal DREs cannot be compared. To overcome this problem, I suggest calculating the DRE for fixed SZAs. There will be SZA values (e.g., 60°) for which the DRE can be calculated throughout the year, and monthly and seasonal averages can then be computed and compared.

We thank the reviewer for this valuable comment. We agree that the instantaneous DRE depends on solar zenith angle and that this should be considered when comparing monthly and seasonal values. Following the reviewer's suggestion, we have added an additional analysis using a common solar zenith angle interval (60° ± 4°), which is available throughout the year. The methodology has been revised accordingly (Section 2.4.3), and the corresponding results have been added to the manuscript (new Figure 8). We also performed several additional diagnostic analyses (shown below), including the dependence of the instantaneous surface DRE on SZA, normalized surface attenuation, and comparisons between the complete dataset and the fixed-SZA subset. These analyses show that the fixed-SZA approach produces very similar seasonal behaviour to the complete dataset, confirming that the principal conclusions are robust with respect to solar geometry, while the complete dataset provides more comprehensive statistics because it retains all available dust observationsComparison with the complete dataset. We compared the monthly DREs derived from the complete dataset (SZA ≤ 65°) with those obtained at the fixed SZA. Although the fixed-SZA approach reduces the number of available dust observations in several months, the seasonal behaviour and the overall conclusions remain very similar, indicating that our results are robust with respect to solar geometry.

Investigation of the SZA dependence. To better understand the reviewer's concern, we further examined the dependence of the instantaneous DRE on SZA using several diagnostic analyses (shown below). These include:

- monthly DREs calculated for different SZA intervals,
- comparison between the complete dataset and the fixed-SZA analysis,
- scatterplots of instantaneous surface DRE versus SZA,
- normalized (relative) surface attenuation,

These analyses show that, for the SZA range considered in this study (≤65°), the absolute surface DRE exhibits only a relatively weak dependence on SZA, whereas the relative attenuation (expressed as the percentage reduction with respect to the no-aerosol surface net irradiance) increases gradually with increasing SZA. For completeness, we include below the additional diagnostic figures.

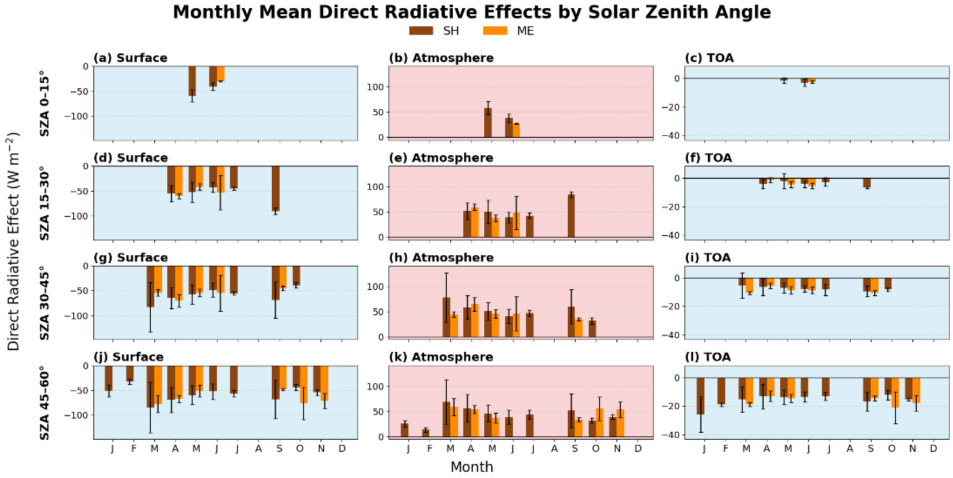


Figure R1.1: Monthly mean shortwave direct radiative effects (DREs) at the surface (left column), within the atmosphere (middle column), and at the top of the atmosphere (TOA) (right column) for Saharan (SH) and Middle Eastern (ME) dust, calculated separately for four solar zenith angle (SZA) intervals: 0–15°, 15–30°, 30–45°, and 45–60°. Bars represent monthly mean DRE values derived from daily averages, while error bars denote ±1 standard deviation. The figure illustrates the dependence of the DRE magnitude on solar zenith angle and demonstrates that, although the absolute magnitude varies with SZA, the overall seasonal behaviour and the relative differences between the two dust source regions remain consistent.

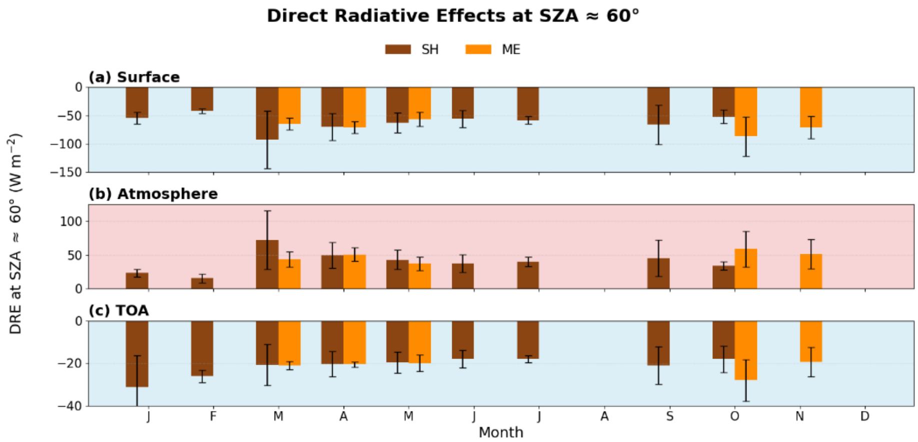


Figure R1.2: Monthly mean shortwave direct radiative effects (DRE, W m^{-2}) at SZA = 60° ± 4° over AMX (2015–2022) under clear-sky conditions for (a) surface, (b) atmosphere and (c) TOA. Saharan dust is shown in brown and Middle Eastern dust in orange. Bars represent monthly mean values and error bars denote ±1 standard deviation. Background colours denote cooling (blue) and warming (red) effects.

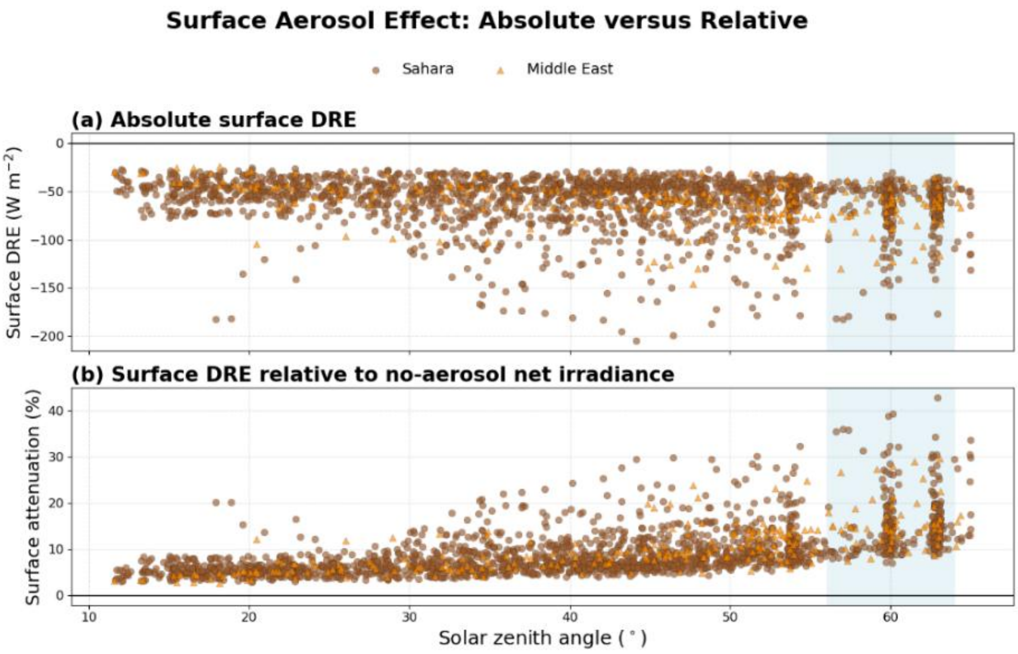


Figure R1.3: Dependence of the instantaneous surface aerosol direct radiative effect (DRE) on solar zenith angle (SZA) for all dust observations (SZA ≤ 65°). (a) Absolute surface DRE (W m⁻²) as a function of SZA for Saharan (circles) and Middle Eastern (triangles) dust events. (b) The corresponding relative surface attenuation, expressed as the percentage reduction in net surface irradiance with respect to the aerosol-free case $[(Net_{aer} - Net_{no\ aer})/Net_{no\ aer} \times 100]$. The shaded region indicates the common solar zenith angle interval (60° ± 4°) used for the fixed-SZA sensitivity analysis. While the absolute surface DRE shows only a modest dependence on SZA, the relative attenuation increases with increasing SZA owing to the longer atmospheric optical path.

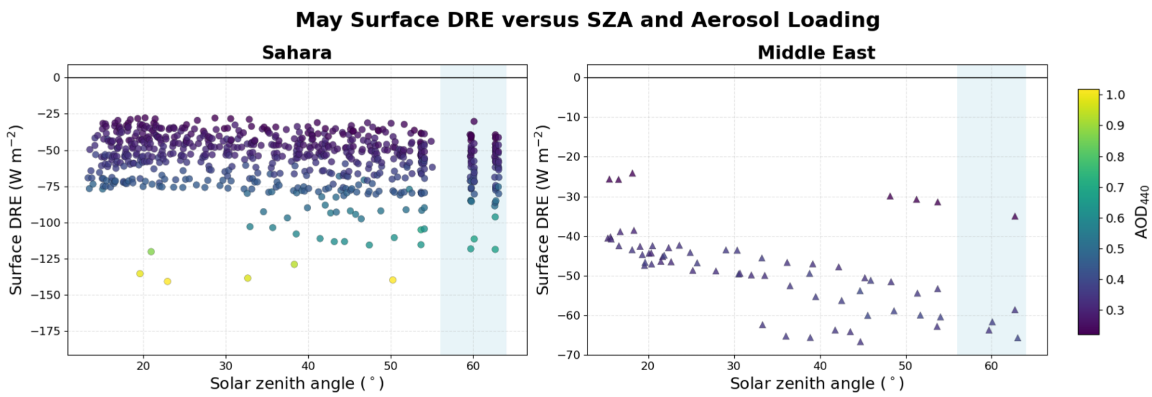


Figure R1.4: Instantaneous surface direct radiative effect (DRE) as a function of solar zenith angle (SZA) for May dust events. Saharan (circles) and Middle Eastern (triangles) dust observations are shown separately. Marker colours indicate the aerosol optical depth at 440 nm (AOD_{440}). The shaded region denotes the common solar zenith angle interval (60° ± 4°) used for the fixed-SZA sensitivity analysis. The absolute surface DRE exhibits only a weak dependence on SZA within the examined range, with the magnitude of the radiative effect being primarily controlled by aerosol loading (AOD), while the fixed-SZA subset provides a consistent basis for comparing radiative effects independent of seasonal changes in solar geometry.

Based on these analyses, we retained the original climatological DRE results (which maximize the available observations) in the manuscript, but added the new fixed-SZA analysis to explicitly demonstrate that the seasonal conclusions are not an artifact of varying solar zenith angle.

Section 3.2: It is not clear to how many dust AERONET measurements the calculation of the backtrajectories with the HYSPLIT model is applied. For example, if a measurement is classified as dust-dominated and the next one (expected to be close in time, let's say after 15 minutes) is also classified as dust, do you run the model for both?

This is not realistic, even because of the temporal resolution of the GDAS meteorological field. Since the origin of each case is also cross-checked with MODIS images, I guess that few cases per day can be considered.

The same applies to the cases classified as dust from the LD and AD, which are 37. Are these instantaneous measurements?

Thank you for this important comment that help us clarify the methodology used. The HYSPLIT backward trajectory analysis was not performed for every individual AERONET observation. Instead, representative trajectories were calculated for approximately 2–3 representative times per dust day, selected to capture the temporal evolution of the dust episode while remaining consistent with the temporal resolution of the meteorological input fields. The corresponding AERONET observations belonging to the same dust event were then assigned the same source classification. MODIS true-colour imagery was used as an additional consistency check of the transport pathway and source region. We have clarified this procedure in the revised manuscript. We also clarify that the 37 LD–AD cases correspond to 37 coincident AERONET–lidar comparison cases, i.e., individual cases for which simultaneous observations from both instruments were available.

Section 3.3: When the authors talk about a “dust day”, what exactly do they mean? Is there a minimum number of instantaneous measurements identified as dust during a day for it to be classified as a “dust day”? Similarly, how is the AOD at 440 nm monthly climatology calculated? From Table 2 I understand if one dust day is present in the month than it is included in the climatology. In the case of the month of March, for the one case of Middle East dust the standard deviation represents the variability of the instantaneous measurements in a single day, while in the case of dust from the Saharan dust the standard deviation represents the variability of the daily measurements of the 15 days, that may have been occurred in different years. Are the authors sure that these data can be effectively compared?

We thank the reviewer for this valuable observation. We agree that calculating monthly climatologies directly from all instantaneous observations may overweight dust days with a large number of measurements. Therefore, the analysis has been revised. A dust day is now defined as a day with at least one valid dust observation satisfying the selection criteria. When multiple observations were available during the same day, the aerosol optical properties and radiative effects were first averaged to obtain representative daily values. The monthly climatologies were subsequently calculated from these daily means, ensuring that each dust day contributes equally to the monthly statistics. The error bars (see figure below) now represent the standard deviation among the daily mean values contributing to each month, rather than the variability among all instantaneous observations. For months represented by a single dust day, no standard deviation across days can be calculated; these values are therefore shown without an error bar and are interpreted as individual event values rather than statistically robust monthly climatological estimates. The manuscript, Figure 5 and Table 3 and discussion have been updated accordingly.

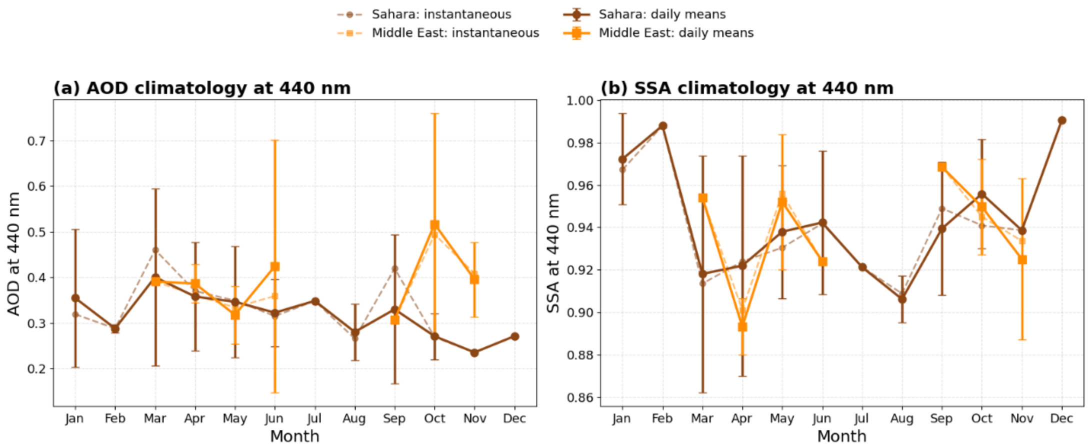


Figure R1.5: Monthly climatology of (a) aerosol optical depth at 440 nm (AOD_{440}) and (b) single-scattering albedo at 440 nm (SSA_{440}) for Saharan and Middle Eastern dust. Solid lines show monthly statistics calculated from daily mean values, while dashed lines represent the corresponding statistics derived from all instantaneous observations. Error

bars denote ±1 standard deviation. The comparison illustrates the influence of averaging methodology on the monthly climatologies by reducing the disproportionate weighting of dust days with multiple observations.

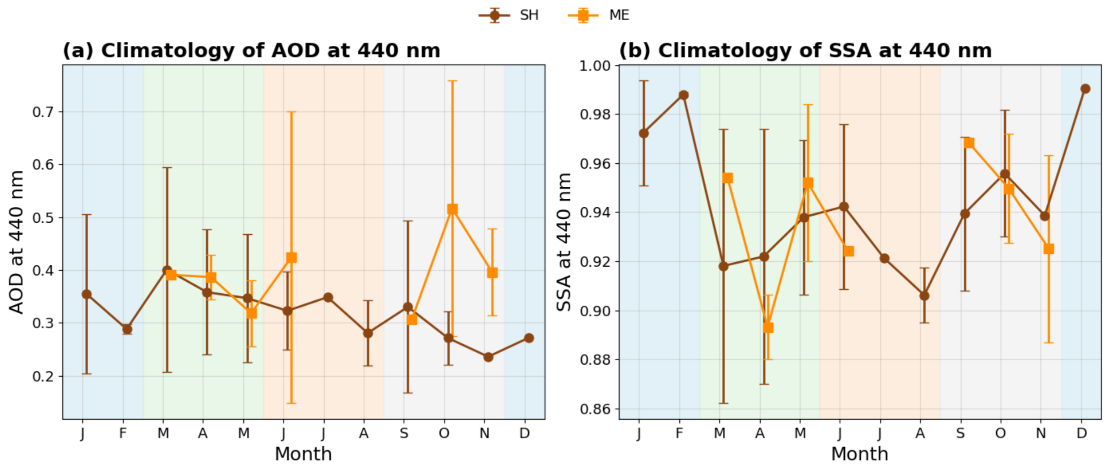


Figure R1.6: The intra-annual variability of monthly average aerosol optical properties (a) AOD at 440nm, and (b) SSA at 440nm for different dust origins (SH-brown and ME-orange). Error bars represent ±1 standard deviation (±1σ). Seasons are indicated by background colours: light blue for DJF, light green for MAM, light orange for JJA, and light grey for SON.

Section 3.4: see comment on Section 2.3.2. How many model-measurement comparisons are made that provide the statistics in Figure 7 and Table 4?

We thank the reviewer for pointing this out. The number of collocated model–measurement comparisons was not explicitly reported in the original manuscript. We have now added this information to Section 3.4, Figure 6, and Table 4. The validation statistics are based on 550 comparisons for Saharan dust cases and 78 comparisons for Middle Eastern dust cases, corresponding to 628 comparisons in total.

Figure 7: those cases for which the percent difference between modelled and measured GHI is larger than 10% (or, better, lower than -10%) the DRE should be not be evaluated since the model is not capable of reproducing the measured irradiances, thus it is plausible that even the dust-free simulation may be unrealistic and so the DRE. Did the authors take this aspect into account?

We thank the reviewer for this valuable suggestion. To assess the robustness of our results, we performed a sensitivity analysis by repeating the complete surface DRE analysis after excluding all collocated cases for which the absolute difference between the modelled and measured GHI exceeded ±10%. We then compared the overall surface DRE, the monthly mean DRE values, the daily-mean DRE statistics, and the DRE–AOD correlations with those obtained from the original analysis. The overall mean surface DRE changed only marginally, from −56.70 to −55.29 W m^{-2} for Saharan dust (2.49%) and from −60.68 to −60.28 W m^{-2} for Middle Eastern dust (0.66%). The DRE–AOD correlations remained essentially unchanged, with the Pearson correlation coefficient changing from −0.9128 to −0.9198 for Saharan dust and from −0.9420 to −0.9450 for Middle Eastern dust. Most monthly mean DRE values were unaffected. The largest difference was observed for Saharan dust in March, where the monthly mean changed from −106.97 to −89.44 W m^{-2} after excluding four observations. However, when monthly values were calculated from daily mean DRE, thereby avoiding disproportionate weighting of days with multiple observations, the corresponding March mean changed only from −91.13 to −88.46 W m^{-2} (2.93%). These results demonstrate that the sensitivity to the ±10% filtering criterion is minimal and that the principal conclusions of the study remain robust.

Section 3.5: here the authors re-assess the methodology followed to compute the average monthly DRE "The DREs were initially calculated at the instantaneous level, using the corresponding aerosol optical properties and solar geometry, and were subsequently averaged to derive monthly mean values". As the DRE is SZA-dependent, the authors should state if and how this dependence is included when computing the monthly averages. If the SZA dependence does not affect the results, a specific analysis should be provided. An alternative way of comparing the DRE in different months is to do it for fixed SZA values.

We thank the reviewer for this important comment. We agree that the shortwave DRE depends on SZA and that this should be explicitly assessed. In the original analysis, the DRE was calculated for each instantaneous observation using the corresponding aerosol optical properties and solar geometry and subsequently averaged by month. To evaluate the potential influence of SZA on the monthly climatologies, we performed an additional sensitivity analysis.

First, the monthly DRE climatologies were recalculated separately for four SZA intervals (0–15°, 15–30°, 30–45°, and 45–60°) (Figure R1.1). These results show that, although the absolute DRE exhibits some dependence on SZA, the seasonal evolution and the relative differences between Saharan and Middle Eastern dust remain consistent across the different SZA ranges. In addition, following the reviewer's recommendation, we repeated the monthly analysis using only observations acquired within a common solar zenith angle interval (60° ± 4°), thereby allowing direct comparison between months under nearly identical illumination conditions (new Figure 8 in the revised manuscript). The fixed-SZA analysis preserves the principal conclusions of the study: dust produces cooling at the surface and TOA and heating within the atmosphere for both source regions, with the strongest Saharan radiative effects occurring during spring and the strongest Middle Eastern effects during autumn. To further investigate the influence of SZA, we also examined the dependence of the instantaneous surface DRE on SZA, the corresponding relative attenuation with respect to the no-aerosol surface net irradiance, and the simulated surface net irradiances under aerosol and aerosol-free conditions (Figures R1.3–R1.4). These complementary analyses show that, within the SZA range considered in this study (SZA ≤ 65°), the absolute surface DRE exhibits only a relatively modest dependence on SZA, whereas the relative attenuation increases gradually with increasing SZA because of the longer atmospheric optical path. Consequently, the fixed-SZA analysis leads to essentially the same seasonal interpretation as the complete dataset, demonstrating that the reported climatological patterns are robust with respect to solar geometry.

Lines 648-649: the sentence “Months with limited sample size (e.g., December for Saharan dust) should be interpreted with caution, as the corresponding monthly means are not statistically robust” here is probably referred to the surface albedo value, which is assumed to be constant, and also wavelength-independent, throughout the period and along the seasons. More generally, this sentence should be associated with the results that describe the monthly averages of the various parameters examined (AOD at 440 nm, AE, SSA, DRE) precisely because the properties of dust from the Sahara and the Middle East are compared for a number of cases that differ from a source to another.

We agree that the limitation associated with small sample sizes is not specific to the DRE analysis but applies to all monthly climatologies presented in the manuscript, including AOD at 440 nm, Ångström exponent, SSA and DRE. We have therefore moved and expanded this statement to the beginning of the monthly climatology results section, where it now applies generally to all monthly comparisons. In addition, we explicitly note that the number of dust cases differs between Saharan and Middle Eastern dust, particularly during months with infrequent dust events, and that monthly statistics based on a limited number of dust days should therefore be interpreted with caution.

Technical corrections

Line 97: SSR is not introduced, use GHI. The suggested correction has been implemented.

Lines 122-124: the verb is missing from this sentence. Use the same number of decimals for the coordinates of the two sites. Thank you for pointing this out. The manuscript has been revised accordingly.

Line 136: add “during” before “the last 10 years”. Thank you.

Line 145: add “spectral”. The suggested correction has been implemented.

Line 180: diffuse horizontal irradiance (DHI). This has been corrected in the revised manuscript.

Line 314: I suggest “3.1 Aerosol Classification”. Thank you for the suggestion.

Lines 323-324: the sentence “It should be noted that the statistics presented as all points correspond to the total number of individual AERONET measurements during the study period” is not clear. The manuscript has been revised.

Lines 325-328: the sentence should be moved further on where the SON season is mentioned again (from line 331). Yes, thank you.

Lines 339-340: the sentence “Figure 2(iv) table of this classification by showing…” should be revised. This has been corrected in the revised manuscript.

Lines 359-360: use only one decimal. Thank you, we changed this.

Figure 3: the meteorological dataset indicated in the HYSPLIT plots report “GFSG”. Is it different from GDAS? We rewrote the 2.3.1 part.

Lines 380-383: this part better in Section

We thank the reviewer for this suggestion. We agree that this information is methodological and is more appropriately placed in Section 2.2.2 (now 2.2.3), where the PollyXT lidar system and the retrieval methodology are described. The corresponding text has therefore been moved to that section.

Lines 393-397: there are some repetitions. This has been corrected in the revised manuscript.

Line 431: how did the authors chose the FMF threshold of 0.4?

Thank you for this comment. We have clarified the rationale for selecting the FMF threshold of 0.4. The chosen threshold is consistent with previous studies (Gobbi et al., 2007; Logothetis et al., 2020; Rogozovsky et al., 2024) and is also supported by the bimodal FMF distribution observed in our dataset, where FMF ≈ 0.4 corresponds to the transition between coarse-mode-dominated mineral dust and mixed aerosol populations. This explanation has been added to Section 2.4.2.

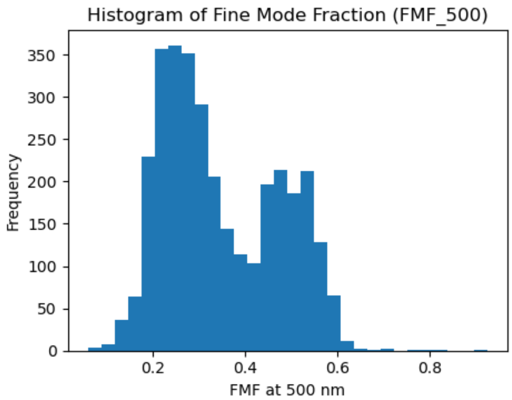


Figure R1.7: Histogram of the fine-mode fraction at 500 nm (FMF_{500}) for all aerosol observations used in this study. The bimodal distribution indicates two distinct aerosol populations, with a transition around FMF ≈ 0.4, supporting the use of FMF < 0.4 as the threshold for identifying coarse-mode-dominated mineral dust events.

Line 440: here the number of Saharan and Middle East dust cases (199 and 33) appear for the first time. I suggest to indicate these numbers also in Section 3.1. Thank you for the suggestion, we added these numbers in Section 3.2

Line 458: review the sentence “and this is associated with enhanced AOD values associated with increased…”. Thank you for pointing this out.

Line 462: maybe is “year-to-year” instead of “month-to-month”? We thank the reviewer for this observation. We agree that "year-to-year" (or interannual) variability is more appropriate in the context of a monthly climatology. The text has been revised accordingly.

Line 504: it seems to me that the central radius is more around 2 µm, and not 1-2 µm. The suggested correction has been implemented.

Lines 514-516: the sentence “For a more compact and quantitative comparison of particle size between the two origins, because it summarizes the combined influence of the peak position and the coarse/fine partitioning” needs to be revised. Thank you for this one.

Line 548: “DRE” instead of “ARE”. Thank you for pointing this out. The manuscript has been revised accordingly.

Lines 621-622: this should be better detectable in the DRE efficiency. Thank you.

Line 659-660: the sentence “The DRFE within the atmosphere (Fig. 10b) remains positive throughout the year as DRE is also positive” can be simplified. This has been corrected in the revised manuscript.

Line 676: include a sentence for the choice of the SSA classes. Thank you we added that.

Table 5: I suggest to include the AE values in the table. Thank you, we added that

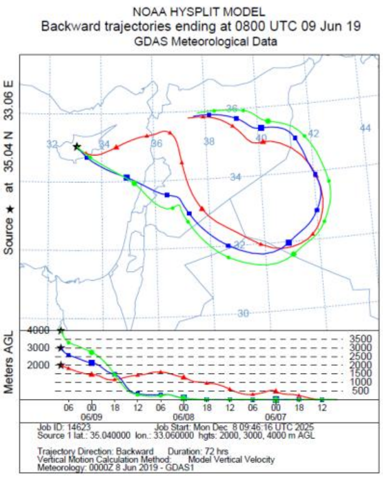
Line 706: include the standard deviation also for the ME dust cases. Thank you for pointing this out.

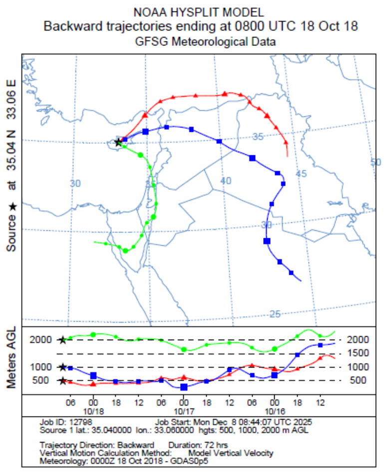
Line 708: The reference to Figure 11 is incorrect, I guess is Figure 14. Yes we corrected this one.

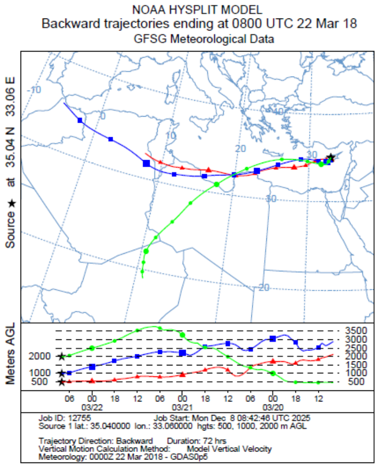
Lines 710 and 711: the correct surface DRE values are -167 and -127 Wm-2, respectively, and not -168 and -126 Wm-2. Thank you for pointing this out. The manuscript has been revised accordingly.

Line 736: the analysis of the airmass backtrajectories may add information, for example short-range transport may be associated with larger AOD values?

We revisited the HYSPLIT backward trajectories for the selected dust events to investigate whether transport distance could explain the observed AOD differences. The analysed cases do not show a clear relationship between transport length and AOD. In particular, the two Saharan events with the highest mean AOD values (0.95 and 0.89) are associated with long-range transport across North Africa, whereas the June 2019 Middle Eastern event, characterised by comparatively shorter and more regional transport, exhibits the lowest mean AOD (0.62). Therefore, our case studies do not provide evidence that shorter transport is systematically associated with larger AOD values, and we have not added such an interpretation to the manuscript.







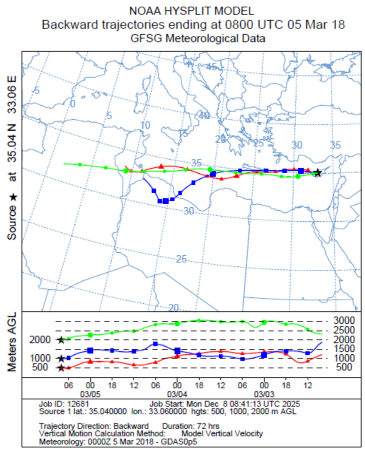


Figure R1.8: NOAA HYSPLIT 72-hour backward trajectories for the four representative dust case studies analysed in this work. The trajectories were re-examined in response to the reviewer's comment to assess whether transport distance could explain differences in aerosol optical depth (AOD). The selected case studies do not reveal a systematic relationship between transport length and AOD, indicating that higher aerosol loading cannot be attributed solely to shorter or longer transport pathways.

Line 742: I suggest the title “Attenuation of Global Horizontal Irradiance for Solar Energy Production”. Thank you for the suggestion.

Line 759: maybe “monthly” instead of “seasonal”. This has been corrected in the revised manuscript.

Section 4: when comparing the results of the present study with previous works, it should be specified if the reported data are instantaneous, daily, or monthly averages.

Thank you for this valuable suggestion. We have revised Section 4 to explicitly state the temporal representativeness of the results reported in both the present study and the cited literature. Specifically, we now clarify whether the reported quantities correspond to instantaneous values, daily or event-based averages, monthly means, or annual averages, as appropriate.

Line 834: change SSR with GHI. This has been corrected in the revised manuscript

Some typos are present.

Thank you again. The technical corrections and clarifications suggested by the reviewer have been addressed in the revised manuscript.

Response to Reviewer #2

We thank the reviewer for the careful evaluation of our manuscript and for the constructive comments and suggestions, which helped us improve its scientific clarity, statistical robustness, and presentation.

In response to the reviewer's recommendations, we have revised the manuscript extensively. Several sections have been rewritten to improve readability, scientific clarity, and the overall organization of the paper. We have expanded the descriptions of the datasets, aerosol classification methodology, radiative transfer simulations, and validation procedures, and have included additional statistical analyses and supplementary material where appropriate to improve the robustness and interpretation of the results, and added Supplementary Material, including the interannual variability of dust frequency and radiative effects, seasonal meteorological statistics, and additional supporting figures. We also carefully revised the manuscript to correct inconsistencies, improve figure organization, and ensure consistent terminology, formatting, and referencing throughout.

All reviewer comments have been carefully considered and addressed individually below.

This manuscript presents the characterization of radiative and optical properties of long range transported dust events originating from Sahara Desert (SA) and Middle East (ME) region at the Agia Marina Xyliatou station (AMX), Cyprus. The study combines the use of multiple remote sensing instruments (ground based and satellite) to identify dust events at the site from 2015 to 2022.

Analysis focuses on the detailed dust-source identification by utilizing HYSPLIT model backward airmass trajectories and two methods analyzing optical properties relationship – AERONET-Dubovik method (aerosol optical depth AOD440nm vs Ångström exponent AE440-870nm and LIDAR Depolarization-based method. The results of identified dust events were further confirmed by satellite measurements.

The identified dust events were investigated further (both sources separately), specifically their inter-annual variability, shortwave direct radiative effect (SW DRE) at different layers of the atmosphere, relationship between distinct optical properties as well as global horizontal irradiance (GHI) with implications for solar energy applications in the region.

General comments:

I see the strength of the manuscript in the effort to separate optical properties and radiative impacts of SA and ME originated dust events and validate outcomes by the combination of multiple reliable methods.

However, the title "Characterization of Dust Aerosol Source Types and Associated Shortwave Direct Radiative Effects Over Cyprus: A Seven-Year Study" can be a bit ~misleading. Although authors were analyzing seven-year long dataset, the work is missing the interannual variability of the events, which could provide valuable information on the change in frequency, intensity and occurrence of dust events together with their radiative impacts in medium-term period.

Thank you for this comment. To provide additional information on the representativeness of the study period, we obtained 10-minute meteorological observations from the nearby Xyliatos Dam station operated by the Cyprus Department of Meteorology. The dataset includes air temperature, relative humidity, wind speed and direction at 10 m, for September 2015–December 2022. Seasonal statistics of these variables have now been added as Table S1 in the Supplement. The corresponding description has also been included in the revised manuscript to better support the discussion of seasonal meteorological and solar-radiation conditions.

Moreover, authors focus on four specific episodic dust events in Section 3.7 Analysis of dust events. I strongly suggest changing the title or incorporate interannual variability study.

We agree that the original title could imply that interannual variability was a central component of the study. We have therefore revised the title to better reflect the principal scope of the manuscript, namely the source-dependent characterization of Saharan and Middle Eastern dust aerosols and their radiative impacts. The revised title is: "Characterization of Saharan and Middle Eastern Dust Aerosols and Their Associated Shortwave Direct Radiative Effects over Cyprus".

More emphasis should be put on the manuscript novelty within text originating from combination of measurement techniques, advanced validation of methods or data processing as they are main scopes of the AMT journal.

In general, this work contains robust datasets, however, multiple information on representativeness and statistics is missing. Moreover, the information on overall solar irradiance and other meteorological variables (wind speed, wind direction, temperature, etc.) is missing to properly support certain claims in the manuscript. The additional comments can be found in Specific comments section. I recommend cautious revision of the manuscript, as it contains inaccuracies, inconsistencies, formatting typos and false references within the text (See Technical comments section). Therefore, I suggest major manuscript revisions to be made before publication.

Specific comments:

Whole manuscript: Since the analysis is restricted to dust-event periods, the reported statistics represent a conditional distribution characterized by strong episodic variability.

In such cases, mean ± standard deviation may be sensitive to a small number of high intensity events and may not represent the typical optical state during dust outbreaks.

The authors are encouraged to assess the robustness of their results using additional statistical indicators (e.g., median and IQR).

We thank the reviewer for this valuable suggestion. Following this recommendation, we complemented all reported mean ± standard deviation statistics with the median and interquartile range (Q1–Q3). Specifically, Table 3 has been revised to include the median and Q1–Q3 of the daily mean AOD_{440}, SSA_{440}, $AE_{440-870}$, and ASY_{440} values for both Saharan and Middle Eastern dust events. In addition, Table S2 in the Supplement has been added to include the corresponding median and Q1–Q3 statistics for the AERONET-Dubovik aerosol classification (Marine, Biomass burning/Polluted, Dust, Mixed, and Continental), calculated from all individual AERONET observations.

1) L117-121: "During DJF, an increase of approximately 50% in PM2.5 has also been documented, rising from approximately 10 µg m^{-3} in DJF to about 15 µg m^{-3} in JJA, attributed to enhanced photochemical activity, reduced precipitation prolonging aerosol lifetime, and the transport of fine-mode pollutants from regional sources, including Turkey and, to a lesser extent, Europe (Pikridas et al., 2018)." It is not clear if the increase of PM2.5 occurred in DJF or in transition from DJF to JJA, please rewrite.

Thank you for pointing this out. We agree that the original wording was ambiguous. We have revised the sentence to clearly indicate that the reported increase in $PM_{2.5}$ occurs from winter (DJF) to summer (JJA), rather than during DJF itself. The revised text now more accurately reflects the findings of Pikridas et al. (2018) (lines 131 – 135).

L122: "To further support the analysis of aerosol conditions over Cyprus, observations from a second site located in Limassol CUT TEPAK station in Limassol which is operated at the Cyprus Atmospheric Remote Sensing Observatory National Facility (CARO NF) of the Eratosthenes Centre of Excellence at Limassol (34.677ºN, 33.0375ºE) (Ene et al., 2024)."

Please rewrite, the sentence is missing a verb. We thank the reviewer for noticing this. The suggested correction has been implemented.

L147: Do levels 1.0, 1.5 and 2.0 of data processing have the same time resolution? Level 1.5 was used for SSA and ASYM while Level 2.0 for AOD, AE, FMF and TCWV. How were uncertainties resulting from different data levels handled?

We thank the reviewer for highlighting this important point. The AERONET products used in this study do not have the same temporal resolution. AOD, AE, FMF, and TCWV are derived from direct-sun measurements, which are generally available every few minutes, whereas SSA and ASY are obtained from almucantar inversions and are therefore available less frequently during the day. To obtain SSA and ASY values at the times of the corresponding direct-sun observations, we applied temporal interpolation within each individual day. Specifically, the available Level 1.5 SSA and ASY retrievals were interpolated to the timestamps of the Level 2.0 direct-sun observations for dates on which valid measurements from both product types were available. Interpolation was performed independently for each day, thereby preventing interpolation across different days and limiting the influence of longer-term temporal variability.

What is the data availability after filtering out data for AOD (440nm) > 0.4?

We thank the reviewer for this comment. We have now quantified the reduction in data availability associated with the AOD_{440} > 0.4 requirement. For the Agia Marina Xyliatou AERONET dataset (2015–2022), there are 9,234 coincident Level 2.0 AOD_{440} retrievals. However, only 413 retrievals (4.5%) satisfy the AOD_{440} > 0.4 criterion required for Level 2.0 SSA and ASY retrievals. This substantial reduction in data availability motivated the use of Level 1.5 SSA and ASY retrievals, following the additional quality-control criteria proposed by Kazadzis et al. (2016)

Table 1: Were AOD and SSA measured at 675 nm used in the study? I can only identify results originating from 440 nm channel.

Thank you for this comment. Although most of the results presented in the manuscript use AOD and SSA at 440 nm for consistency and because this wavelength is commonly used for aerosol characterization and classification, the 675 nm AOD and SSA values were used as input parameters in the libRadtran radiative transfer simulations. We have clarified this in the manuscript to avoid confusion (see Table 1 and Section 2.3.2).

The asymmetry parameter is described in the Method section but is not displayed or commented on throughout the manuscript. This variable could introduce additional value on the morphology of the measured particles and direction of scattered light.

In the revised manuscript, we have included the asymmetry parameter (ASY_{440}) in Table 3 together with the other aerosol optical properties and expanded the discussion accordingly. The long-term mean ASY_{440} is 0.75 ± 0.03 for Saharan dust and 0.73 ± 0.02 for Middle Eastern dust, indicating very similar forward-scattering characteristics for the two dust source regions. The close agreement between the ASY values suggests that differences in the direct radiative effects are primarily controlled by aerosol loading (AOD) and absorption properties (SSA), rather than by differences in the angular distribution of scattered radiation. This discussion has been added to Section 3.3.

L220: It would be valuable to comment on the validation procedure (e.g. graph in the SM, uncertainty estimation, etc.).

We thank the reviewer for this valuable suggestion. In the revised manuscript, the description of the validation procedure has been expanded in both the Methodology and Results sections. In the Methodology, we now provide a more detailed description of the validation approach, including the matching procedure between simulated and measured cloud-free irradiance, the SZA filtering criterion (SZA ≤ 65°), and the statistical metrics used to quantify model performance. In the Results section, we have expanded the discussion of the validation by reporting additional performance metrics, including the coefficient of determination (R^2), regression slope, mean bias error (MBE), root mean square error (RMSE), and their corresponding relative values for both Saharan and Middle Eastern dust cases. We have also added a discussion of the principal sources of uncertainty associated with the ground-based measurements, aerosol optical properties, temporal matching, and assumptions within the radiative transfer calculations. These additions provide a more comprehensive assessment of the reliability of the simulated surface irradiance prior to the calculation of the dust direct radiative effects.

L255-258: "For days when lidar measurements were unavailable or inconclusive, MODIS true-colour imagery from the instruments aboard NASA's Terra and Aqua satellites, accessed via the NASA GIBS/Worldview platform, was used to visually confirm the presence of dust and to assess its spatial extent and transport patterns (section 2.2.2)." The authors declare that LIDAR measurements were incorporated in 2017. However, the analysis was performed on datasets from 2015, so I assume 2 years of data were treated based on satellite measurements. Were LIDAR measurements compared against satellite retrievals to assess the comparability of used methods?

Thank you for this important comment. We would like to clarify that MODIS imagery was not used as a replacement for the lidar observations. Throughout the entire study period (2015–2022), dust source attribution was based primarily on AERONET observations combined with HYSPLIT backward trajectories. When lidar observations were available (from 2017 onwards), the trajectory starting altitudes were initialized using the observed dust layer heights. For the earlier period (2015–2016), when lidar measurements were not available, HYSPLIT trajectories were instead initialized at fixed altitudes of 1000, 2000, 3000, and 4000 m above ground level to capture the potential transport pathways at different atmospheric layers. MODIS true-colour imagery was used only as an auxiliary tool to visually confirm the presence and spatial extent of the transported dust plume. Consequently, no direct comparison between lidar and MODIS was performed, as the two datasets served different purposes within the methodology. We have revised the manuscript to clarify this point.

L268: The authors chose FMF < 0.4 for the threshold of coarse-mode dominance. Please comment on this choice.

Thank you for this comment. We have clarified the rationale for selecting the FMF threshold of 0.4. The chosen threshold is consistent with previous studies (Gobbi et al., 2007; Logothetis et al., 2020; Rogozovsky et al., 2024) and is also supported by the bimodal FMF distribution observed in our dataset, where FMF ≈ 0.4 corresponds to the transition between coarse-mode-dominated mineral dust and mixed aerosol populations. This explanation has been added to Section 2.4.2.

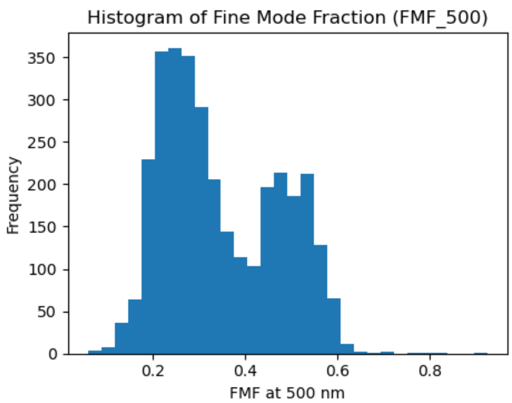


Figure R2.1: Histogram of the fine-mode fraction at 500 nm (FMF_{500}) for all aerosol observations used in this study. The bimodal distribution indicates two distinct aerosol populations, with a transition around FMF ≈ 0.4, supporting the use of FMF < 0.4 as the threshold for identifying coarse-mode-dominated mineral dust events.

L274-278: I suggest shortening the introductory part of 2.4.3 Estimation of dust direct radiative effects as it was explained in the 1. Introduction. We agree with the reviewer's suggestion and have revised the manuscript accordingly.

Figure 2: The percentages in Pie charts overlap and are not truly visible (b.iii, b.iv). What is the time resolution of data points and what is the data availability after data processing in Figure 2a? Where do median/mean with IQR/std lay within classified aerosol types?

We thank the reviewer for this helpful suggestion. Figure 2d has been revised to include the number of observations, mean ± standard deviation, and median with interquartile range for both AOD_{440} and $AE_{440–870}$ within each aerosol class. These statistics provide a quantitative description of the position and spread of the classified aerosol populations and confirm that their central tendencies are consistent with the adopted classification thresholds. The corresponding discussion has been added to the revised manuscript and the table to the supplement.

Table R2.1: Summary statistics of aerosol optical depth at 440 nm (AOD_{440}) and Ångström exponent ($AE_{440–870}$) for the aerosol classes identified using the AERONET-Dubovik climatology classification at the Agia Marina Xyliatou (AMX) station during the study period (2015–2022). The table reports the number of observations (N), mean ± standard deviation (SD), and median with interquartile range (IQR) for each aerosol type.

Aerosol Type	**N**	**AOD_{440} (Mean ± SD)**	**AOD_{440} Median [IQR]**	**$AE_{440–870}$ (Mean ± SD)**	**$AE_{440–870}$ Median [IQR]**
Marine	10,632	0.109 ± 0.047	0.107 [0.069–0.148]	0.868 ± 0.268	0.943 [0.687–1.094]
Biomass burning / polluted	1,803	0.276 ± 0.083	0.247 [0.221–0.291]	1.710 ± 0.079	1.697 [1.650–1.754]
Dust	3,499	0.301 ± 0.108	0.269 [0.229–0.334]	0.477 ± 0.270	0.421 [0.256–0.709]
Mixed	3,591	0.283 ± 0.079	0.260 [0.225–0.314]	1.368 ± 0.168	1.408 [1.238–1.512]

Continental	15,721	0.112 ± 0.044	0.110 [0.077–0.145]	1.502 ± 0.198	1.476 [1.348–1.632]

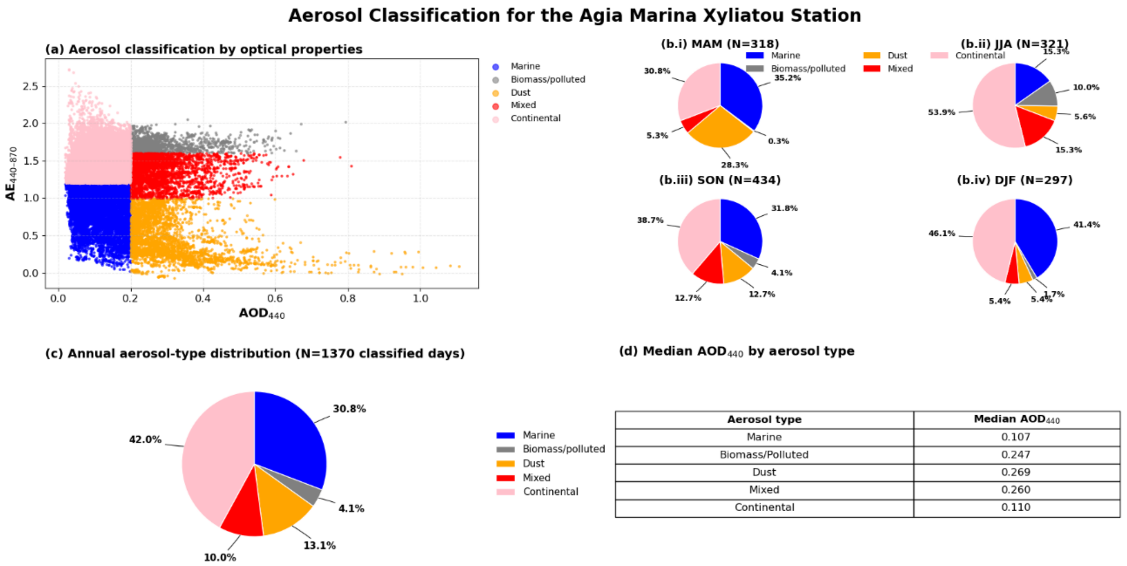


Figure R2.2: (a) Aerosol classification by AERONET-Dubovik's climatology (Marine particles, Biomass Burning-Polluted particles, Dust, Mixed and Continental particles) of AMX station [blue: marine, gray: biomass/burning-polluted, orange: dust, red: mixed, pink: continental]. (b) Pie chart of the seasonal classification of Aerosols in "MAM": March-April-May, "JJA": June-July-August, "SON": September-October-November, "DJF": December-January-February. (c) Annual aerosol type distribution. (d) Summary table of the median AOD 440nm by aerosol type.

It may be valuable to calculate wind roses for different seasons (Figure 2b) to see the predominant wind direction.

We thank the reviewer for this valuable suggestion. To provide additional information on the local meteorological conditions at the Agia Marina Xyliatou (AMX) station, we calculated seasonal statistics of the surface meteorological observations, including the prevailing wind sector and its frequency. These results have been included in the Supplementary Material (Table S1). The analysis shows that southerly winds dominate during winter, spring, and autumn, whereas north-northwesterly winds prevail during summer.

However, we respectfully note that seasonal surface winds alone cannot be used to attribute the aerosol classes presented in Figure 2 to their geographical source regions. AERONET measures aerosol optical properties integrated over the entire atmospheric column, whereas surface winds describe only the local near-surface flow. Aerosol layers reaching AMX are frequently associated with regional and long-range transport at elevated altitudes that are not necessarily represented by the local surface wind direction.

This distinction has been demonstrated in previous studies at AMX. Pikridas et al. (2018) identified the station as a regional-background site whose aerosol variability is strongly influenced by transported Saharan and Middle Eastern dust, continental polluted air masses, and marine sectors. More recently, Bimenyimana et al. (2026) combined chemical source apportionment with air-mass cluster analysis and showed that AMX is affected by transported air masses originating from North Africa, the Middle East, Turkey, Europe, and marine sectors, while local anthropogenic influence remains limited.

Consequently, a comprehensive source attribution of all aerosol classes presented in Fig. 2 would require dedicated trajectory-cluster and source-apportionment analyses rather than seasonal surface winds alone. Such an analysis is beyond the scope of the present study, which focuses specifically on mineral dust. For the dust cases analysed here, the geographical origin was determined using height-dependent HYSPLIT backward trajectories, supported by lidar observations and MODIS imagery. We have therefore added the seasonal meteorological statistics (Table

S1) together with a brief discussion clarifying the regional representativeness of AMX and the limitations of using local surface winds for column-integrated aerosol source attribution.

References:

Pikridas et al (2018) https://www.sciencedirect.com/science/article/pii/S1352231018305016

Bimenyimana et al. (2026) https://acp.copernicus.org/articles/26/1605/2026/

L325-330: How did the frequency and intensity of dust events evolve over the years for SA and ME?

We thank the reviewer for this valuable suggestion. We investigated the interannual evolution of dust frequency, aerosol loading, and surface radiative attenuation for both Saharan and Middle Eastern dust. To keep the main manuscript focused, the analysis has been included as Figure S7 in the Supplementary Material. The figure shows the annual dust-day frequency together with the annual mean daily AOD_{440}, surface attenuation, and relative attenuation, allowing the interannual variability of both dust source regions to be assessed.

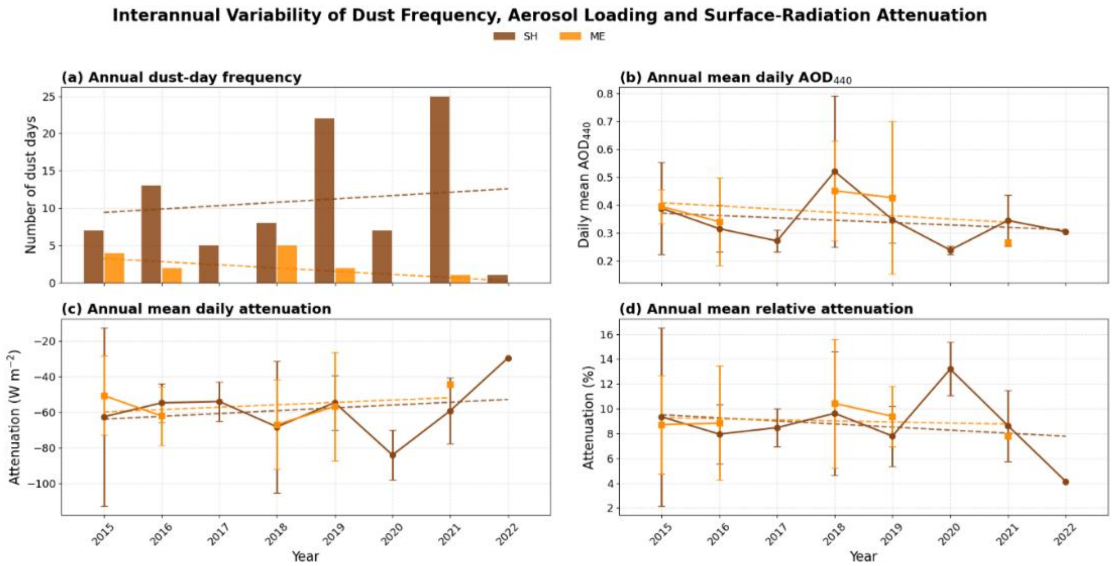


Figure R2.3: Interannual variability of (a) annual dust-day frequency, (b) annual mean daily AOD_{440}, (c) annual mean daily surface attenuation (DRE), and (d) annual mean relative attenuation (%) for Saharan (SH) and Middle Eastern (ME) dust over the study period (2015–2022). Error bars represent ±1 standard deviation. Dashed lines indicate linear trends.

L339: "Figure 2(iv) table of this classification by showing the median AOD_{440} for each aerosol type." Please double check the sentence. This has been corrected in the revised manuscript.

L342: Although marine and continental aerosols exhibit lower median AOD compared with dust and mixed aerosols, AOD alone does not fully characterize their radiative effects. Intensive optical properties (e.g., SSA, Ångström exponent, backscattering ratio or asymmetry parameter), which are independent of aerosol loading, determine aerosol scattering and absorption efficiency and may substantially influence radiative impacts even under lower AOD conditions. Thank you for this comment.

L355: The authors are using 72-hour backward air mass trajectories computed with the HYSPLIT model to verify dust classification by AERONET-Dubovik method. However, later in text (L386), 96-hour backward air mass trajectories were used for LIDAR Depolarization-based method. Please comment on choice of the backward tracking periods.

Thank you for identifying this inconsistency. All HYSPLIT backward trajectories used in this study were calculated for 72 hours. The reference to four-day trajectories in Line 386 was a typographical error and has been corrected to three-day in the revised manuscript.

Figure S1: This Figure in SM is valuable in terms of AMT scope as it clearly compares methods of dust origin identification. The authors may consider moving it into the main text. At the same time, I would suggest moving multiple plots into SM and keep max 10-11 Figures in the main text. Thank you for this, we tried to minimize to main Figures and move some of them in the supplement.

The method comparison from Figure S1 never agreed on the identification of ME, while it was very successful for SA. Please comment.

It should be noted that the agreement between the two approaches is considerably stronger for Saharan dust than for Middle Eastern dust (Figure 4b now). While Saharan dust cases are consistently classified by both methods, several cases attributed to Middle Eastern dust by the AD classification are identified by the LD classification as Dust mixtures or Other aerosols. This behaviour reflects the different objectives of the two methodologies: the AD classification identifies the geographical source region of the transported dust, whereas the LD classification characterizes the optical properties and mixing state of the aerosol at the measurement site. Consequently, aerosol mixing during transport from the Middle East can modify the optical characteristics sufficiently for the arriving aerosol to be classified as Dust mixtures or Other, despite retaining a Middle Eastern dust origin.

L415: SA is transported over the sea, thus can be mixed with sea salt as well. Thank you for this comment.

L515: "For a more compact and quantitative comparison of particle size between the two origins, because it summarizes the combined influence of the peak position and the coarse/fine partitioning." Please rephrase. Thank you for pointing this out. The manuscript has been revised accordingly.

L570: The authors are often claiming that SA episodes are more frequent, but ME can have comparable impact based on individual high-loading episodes. How is the intensity of dust event evaluated/described in this study? Can authors estimate the averaged episodical intensity of SA compared to ME?

We thank the reviewer for this important comment. We agree that the intensity of the dust events should be quantitatively defined. In the revised analysis, a dust event is represented by a dust day, and its intensity is characterized primarily by the daily mean aerosol optical depth at 440 nm (AOD_{440}), calculated from all valid observations available during that day. Daily mean surface DRE was additionally examined as a measure of the corresponding radiative impact. The analysis included 152 Saharan and 19 Middle Eastern dust days. The mean daily AOD_{440} was 0.344 ± 0.129 for Saharan dust and 0.396 ± 0.133 for Middle Eastern dust. A Mann–Whitney U test indicated that the distributions differed significantly at the 5% level ($p = 0.0285$). The corresponding mean daily surface DRE was −57.5 ± 24.6 W m^{-2} for Saharan dust and −66.2 ± 24.1 W m^{-2} for Middle Eastern dust, with a significant difference between the distributions ($p = 0.0468$). These results indicate that Saharan dust events were substantially more frequent and included the strongest individual daily events, whereas the less frequent Middle Eastern dust events exhibited a slightly higher average daily aerosol loading and stronger average surface cooling within the available sample. We have revised the manuscript to define event intensity explicitly and to include this quantitative comparison.

Table R2.2: Comparison of the intensity of Saharan and Middle Eastern dust events during the study period (2015–2022). Event intensity is characterized using the daily mean aerosol optical depth at 440 nm (AOD_{440}) and the corresponding daily mean surface shortwave direct radiative effect (DRE). The table presents the number of dust days, mean ± standard deviation (SD), median, and maximum daily AOD_{440}, together with the mean daily surface DRE ± SD for each dust source region.

Source	**Dust days**	**Mean daily AOD_{440}**	**Median AOD_{440}**	**Maximum AOD_{440}**	**Mean surface DRE**
Saharan	152	0.34 ± 0.13	0.31	0.95	−57.5 ± 24.6 W m^{-2}
Middle Eastern	19	0.40 ± 0.13	0.39	0.79	−66.2 ± 24.1 W m^{-2}

L577: The analysis of meteorological conditions including temperature or solar irradiance is missing to see the magnitude of variability in incoming solar radiation.

We thank the reviewer for this valuable suggestion. To provide additional meteorological context for the study period, we have added Table S1 to the Supplement, which summarizes the seasonal meteorological conditions at the Xyliatos Dam station during 2015–2022. The table includes the seasonal mean air temperature, relative humidity, wind speed, and prevailing wind sector. These parameters characterize the seasonal environmental conditions under which the aerosol observations were acquired

L581: Do authors want to refer to Figure 8 instead of Figure 5? Yes thank you.

L575-589: Repetitive phrasing of the outcomes, please consider rewriting. This has been corrected in the revised manuscript.

Figure 5: Despite almost identical AOD440nm of SA and ME in MAM, SSA440nm differs (irregular pattern for ME). Please elaborate on potential reason.

Thank you for this observation. We have expanded the discussion of Figure 5 to explain the differing SSA behaviour during MAM. Although Saharan and Middle Eastern dust show similar AOD_{440} values, the Middle Eastern SSA_{440} climatology is based on substantially fewer cases and is therefore more sensitive to individual events. We also clarify that similar AOD does not necessarily imply similar SSA, because SSA depends on aerosol composition, particle size, ageing, and mixing state. The irregular Middle Eastern pattern may thus result from both the limited sample size and the greater heterogeneity of these dust events.

L633-634: "For AOD at 440nm the surface cooling, reach values up to -204W/m2 and -47 W/m2 at the TOA and for the atmosphere reaching the 182 W/m2 for Sahara dust." Please rephrase. Thank you

Figure 9: I suggest splitting SA and ME into separate plots (e.g. matrix 2x3) for better visibility of datapoints as well as the position of low SSA values. The authors used Pearson correlation coefficient to evaluate correlation between DREs and AOD for each dust source and layer of the atmosphere. Were data tested for normal distribution? If data are not normally distributed, I would recommend using different nonparametric statistical indicators.

Figure 9 has been completely revised and is now presented as a 2 × 3 panel, with Saharan and Middle Eastern dust shown separately and the surface, atmosphere, and TOA DRE relationships displayed in individual panels. This considerably improves the visibility of the observations, regression lines, and the distribution of SSA values.

Following the reviewer's recommendation, we also assessed the normality of the variables using the Shapiro–Wilk test. Since several variables deviated from a normal distribution, we complemented the Pearson correlation coefficient with Spearman's rank correlation coefficient (ρ), which is more appropriate for non-parametric data. Both coefficients are now reported in Figure 9. The Spearman coefficients confirm the strong monotonic relationships observed for the surface and atmospheric DREs, while also indicating the weaker monotonic relationship between AOD and TOA DRE, particularly for Saharan dust. The revised figure and accompanying text have been updated accordingly.

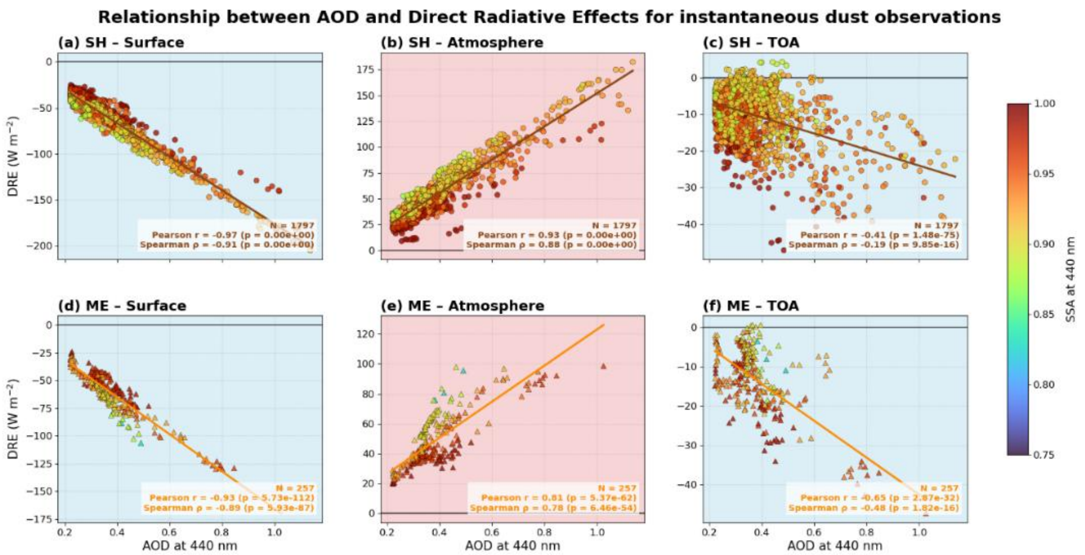


Figure R2.4: Relationship between aerosol optical depth at 440 nm (AOD440) and instantaneous shortwave direct radiative effects (DRE) at the surface, atmosphere, and top of the atmosphere (TOA) for Saharan (SH; a–c) and Middle

Eastern (ME; d–f) dust observations. Symbols are coloured according to the single-scattering albedo (SSA) at 440 nm. Solid lines represent linear regression fits. Pearson and Spearman correlation coefficients (ρ), associated p-values, and the number of observations (N) are reported in each panel.

L708: Do authors want to refer to Figure 12 instead of Figure 11? Thank you.

Figure 14b: The color-coding of datapoints with SSA values could provide information on aerosol absorption/scattering ability.

We thank the reviewer for this helpful suggestion. We examined an alternative version of Figure 14b in which the data points were colour-coded according to SSA at 440 nm. However, the colour coding did not reveal a clear or systematic relationship between SSA and either AOD or the Ångström exponent. The points remained primarily separated according to dust event and source region, while the additional colour scale reduced the visual clarity of the figure without providing substantial new information. We therefore retained the original version of Figure 14b in the revised manuscript. The SSA values and their relevance to the scattering and absorption characteristics of the selected events are already reported and discussed in the accompanying text.

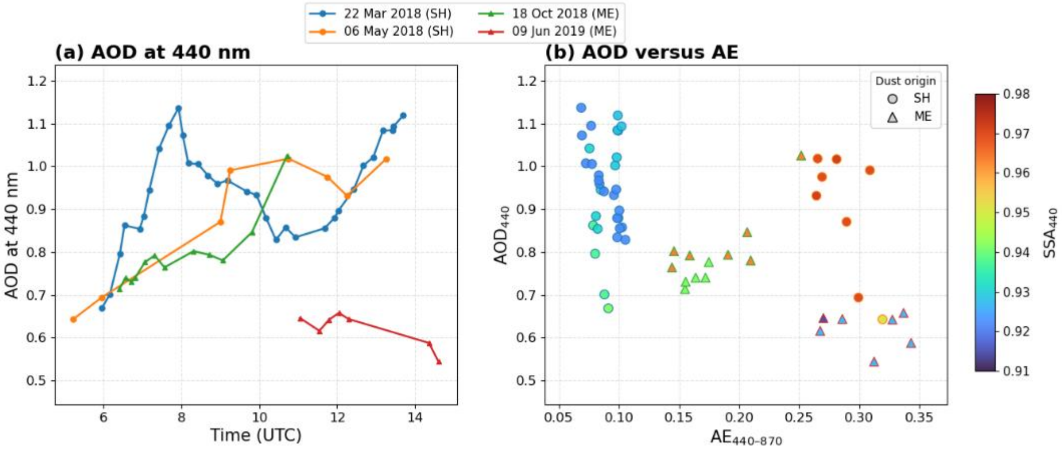


Figure R2.5: Optical characteristics of the four selected high-AOD dust events. (a) Temporal evolution of aerosol optical depth at 440 nm (AOD_{440}) during the two Saharan (SH; 22 March and 06 May 2018) and two Middle Eastern (ME; 18 October 2018 and 09 June 2019) dust events. (b) Relationship between AOD_{440} and the Ångström exponent ($AE_{440–870}$) for the same events. Symbols denote the dust source region (circles: Saharan; triangles: Middle Eastern), while colours indicate the single-scattering albedo at 440 nm (SSA_{440}). The figure illustrates the differences in aerosol loading, particle size, and scattering properties among the selected dust events.

L760: Figure 15a instead of Figure 14a? Thank you very much for noticing. We changed it.

L777-778: "January February and June July show weaker relative attenuation (typically below 10%), reflecting both reduced dust activity, and lower incoming solar radiation." Please provide evidence of decreased June July lower incoming solar radiation.

Thank you for pointing this out. We agree that the explanation regarding lower incoming solar radiation does not apply to June and July. We have revised the text to distinguish between the winter months, where reduced solar irradiance contributes to the weaker attenuation, and the summer months, where the weaker attenuation is primarily explained by the lower occurrence and intensity of dust events.

Figure 15: It may be interesting to see how the attenuation of radiation changes over years. Could authors investigate the influence of climate change on the frequency and intensity of dust events in this region?

We explored the interannual variability of dust frequency, aerosol loading and radiative attenuation over the study period (2015–2022). Although year-to-year variability is evident, the observational record spans only eight years, which is insufficient for a robust assessment of long-term climatic trends or climate-change impacts on dust activity. Because such an analysis would extend beyond the scope of the present work and could lead to overinterpretation of a relatively short time series, we decided not to include it in the revised manuscript. We have added a short statement in the Discussion acknowledging that longer observational records are required to investigate possible climate-related changes in dust frequency and intensity. (Figure R2.3)

L809: Figure 15 instead of Figure 14? Thank you very much for noticing. We changed Figure it.

Technical comments:

Whole manuscript: Please pay attention to the consistency throughout the whole manuscript, namely: consistent spacing of wavelength and unit (e.g. 440 nm) and format of unit (W/m2 vs W m-2); space between the end and beginning of the new sentence; consistent usage of abbreviations (e.g. Ångström exponent (440–870 nm) vs AE vs 440-870 _AE); references to Figures (Fig. 2 vs Figure 2 or Figure 2b-i in text but Figure 2b.i in the plot); consistent decimal places; formatting of figure/table titles (bold vs regular or Figure 3. vs Figure 3:); please keep consistent line spacing. Thank you for this very important comment ! We revised the manuscript.

L61: Excess dot before citation brackets. Thank you.

L63: Previous studies (Dayan et al., 1991; Gkikas et al., 2018; Logothetis et al., 2021; Moustaka et al., 2024) revealed…. This has been corrected in the revised manuscript.

L64: Dayan et al., (1991), please remove comma. Thank you for noticing.

L75: Regarding the surface DREs, Di Biagio et al. (2010) reported an instantaneous daily maximum… thank you

L78: Additionally, dust aerosols can greatly affect energy production (Hansen et al., 1997; Kosmopoulos et al.,2017, 2018), … thank you

L97: SSR is not defined in text. Yes thank you for pointing this out we change it into GHI.

L105: Please pay attention to spaces and brackets and keep the formatting consistent: (35.04º N; 33.06º E; 535 m a.s.l.)… Thank you for this one.

L199: …are used… This has been corrected in the revised manuscript.

L285: …Moustaka et al. (2023), … Thank you.

L364: …Figure 3… Thank you for pointing this out. The manuscript has been revised accordingly.

L524: Undefined RTM, also, please keep the consistency of either RTM or RT models. Thank you, this comment have been implement throughout the manuscript.

L638: "This relationship is quantified further in Section 3.6 (Fig. 11)." Thank you

L710: Please correct sentence from : "At the surface, the selected Saharan dust events produce the strongest cooling, with DRE at surface values ranging from −168 to −126 W m^{-2}, compared to −126 to −96 W m^{-2} for the selected ME cases." to "At the surface, the selected Saharan dust events produce the strongest cooling, with DRE at surface values ranging from −167 to −126 W m^{-2}, compared to −127 to −96 W m^{-2} for the selected ME cases." The suggested correction has been implemented.

We thank the reviewer for these helpful technical comments. All of the suggested corrections have been implemented, including the individual edits listed below. In addition, we performed a comprehensive final check of the entire manuscript to ensure consistency in formatting and notation throughout, including wavelengths, units, abbreviations, decimal places, figure and table references, titles, spacing, punctuation, and line spacing.