Response to reviewers

Reviewer 1 :

This manuscript investigates the source-dependent optical, microphysical, and mineral signatures of four major dust outbreaks affecting the Mediterranean Basin during 2021–2022. The study combines a wide range of observational and modeling tools, including AERONET sun-photometer retrievals, MIDAS/MODIS dust optical depth, IASI dust products, HYSPLIT back-trajectories, lidar-based vertical information, ground-based in situ observations in Cyprus, UAV-based composition measurements, and METAL-WRF mineralogical simulations. The topic is scientifically relevant as mentioned in the manuscript that the Mediterranean is strongly affected by dust from both Saharan and Middle Eastern sources, and the optical properties of transported dust are essential for assessing radiative effects, air quality impacts, and model representation of dust aerosol. The manuscript is generally well organized and contains a valuable multi-platform analysis. A major issue is that some conclusions regarding the relative roles of mineralogy, mixing state, and anthropogenic influence are plausible but not yet fully demonstrated. Therefore, I would recommend publication if the following comments could be properly addressed after moderate revision.

Major Comments

#1. *One of the key conclusions of the manuscript is that the dominant mineral fractions simulated by METAL-WRF are broadly similar across events, and therefore the observed optical variability is mainly driven by dust-to-total aerosol ratio and mixing state rather than mineralogical differences. This conclusion is not fully demonstrated. The mineralogical analysis is available mainly for selected events and stations, whereas the optical analysis covers a broader set of AERONET sites and events. Moreover, METAL-WRF mineralogy is itself subject to uncertainties in source mineral maps, emission size distribution, transport, and deposition. The authors should more clearly distinguish between what is directly supported by the combined observations and what is inferred from the model. If possible, it would be helpful to provide a more quantitative comparison between mineral composition, DOD-to-AOD ratio, FMF, SSA, and ASY across the events. Or the conclusion should be phrased more cautiously, emphasizing that the current evidence suggests, rather than definitively proves, that aerosol mixing and dust fraction dominate the observed optical variability.*

We would like to thank the reviewer for this constructive comment. To facilitate a more quantitative intercomparison among the events, we have added a new Discussion section (5.1) that synthesizes the main findings from the observational and modelling datasets. We have also included a summary table presenting, for each event, the simulated mineral composition together with the DOD-to-AOD ratio, FMF, SSA, and ASY, as suggested by the reviewer. This comparison allows the optical and compositional characteristics of the four events to be assessed more directly and consistently.

We also agree that the available METAL-WRF simulations for Events C and D show broadly similar dominant mineral fractions, however the limited event coverage from simulations does not allow mineralogical variability to be evaluated across all four outbreaks or its optical influence to be quantitatively separated. This clarification has been added to the manuscript (Lines 465-466), and also the conclusions were adapted accordingly (see Lines: 605-610).

#2. *Another issue is that the manuscript states the Middle East event is characterized by finer and more absorbing particles, likely influenced by anthropogenic sources. This interpretation is reasonable and is supported by higher FMF, lower DOD-to-AOD ratios, lower ASY, and stronger absorption observed in Cyprus. Nevertheless, the evidence remains partly circumstantial. The manuscript would be strengthened if the authors provided additional support for the anthropogenic influence, such as co-variation with black carbon, organic aerosol, sulfate/nitrate, CO, or known emission regions along the transport pathways. It is also necessary to briefly discuss the source region and sector (e.g., oil industry) of anthropogenic pollution. It will be better if other possibilities, including source-specific mineral absorption, aging, coating by secondary aerosols, or mixed dust–pollution–marine aerosol states, could be discussed more systematically.*

We thank the reviewer for this helpful suggestion. . We have added time series of elemental carbon, estimated organic matter, sulfate, and nitrate concentrations to the Appendix, together with a map showing the main regional emission sources and the importance of fossil-fuel-related activities in the Middle East. In addition, we have revised the discussion in Lines 505-512 to explain how these complementary observations support the interpretation of anthropogenic influence during Event C.

#3. *The study focuses on four major dust outbreaks in 2021–2022, selected from widespread events affecting multiple AERONET stations. This is a reasonable design, but the conclusions are sometimes written in a way that may imply more general source-dependent behavior. Since only one Middle East event and a limited number of Saharan events are analyzed, it is important to clarify whether the findings are representative of broader source-region differences or mainly characteristic of these selected episodes. The authors should add a short discussion on the limitations of the case-study approach and specify which conclusions are robust across the selected events and which require confirmation with a larger event climatology.*

We thank the reviewer for the comment. We agree that the original wording might implied a source-region representativeness. The four outbreaks were selected because they were spatially extensive and different, affected multiple AERONET stations, and offered multi-platform observational and modelling coverage. However, they do not constitute a climatological sample of Saharan and Middle Eastern dust.

Based on this we have revised text throughout the manuscript (e.g. Lines 7, 12, 73, 81, 520-524) to distinguish clearly between event-specific findings and broader source-dependent interpretations. The conclusions are now framed around the selected episodes.

Specific Comments

#1. *The criterion for AERONET inversion quality is described as sky error < 6%, whereas the figure caption for Fig. 4 mentions sky error < 5%. Please check and make the threshold consistent throughout the text and figure captions.*

Thank you for pointing this out. We have now ensured consistency throughout the manuscript.

#2. *The station ordering by distance from source is useful, but for event D the manuscript acknowledges that the sequence is not straightforward because multiple sub-events occurred. In this case, the interpretation of evolution with distance should be treated cautiously.*

We thank the reviewer for this comment. The original manuscript already noted 'For specific events (like event D), the sequence was not clear due to the multiple occurring events, and the numbering may not accurately reflect the actual station's distance from the source.' (Line 271-273). To make the interpretation of sequence more clear we also added a clarification for event D in line 273.

#3. *In Fig. 3, the manuscript should briefly discuss the uncertainty of assigning aerosol types based only on AOD–AE space, particularly in mixed dust–pollution and dust–marine aerosol conditions.*

We thank the reviewer for giving us the opportunity to discuss the limitations of this classification. We agree that aerosol types cannot be assigned solely from the AOD and Ångström exponent space, particularly under mixed conditions. Dust-pollution and dust-marine mixtures may occupy overlapping regions because both fine anthropogenic particles and coarse marine aerosol can shift AOD and AE.

We have therefore revised the manuscript to clarify that the classification shown in Fig. 3 should be regarded as an indicative framework rather than a quantitative aerosol typing (Lines 289-292). In this study, the AOD–AE relationship is used to complement the broader interpretation which is based on additional parameters, including the dust-to-total AOD ratio, fine-mode fraction, single-scattering albedo, asymmetry parameter, trajectories, and the other observational and modelling products presented in the manuscript.

#4. *The Cyprus case study is one of the strongest parts of the manuscript. It would be helpful to make the comparison between events A, C, and D more explicit in terms of dust mass, absorption coefficient, and elemental abundance. A compact summary table may improve clarity.*

As per comment 1 of the reviewer a summary table has been added to the manuscript in Section 5.1.

#5. *In Fig. 11, the text states that event C exhibits the highest absorption "~50% across the entire spectral range," but the unit and meaning of this percentage are not clear. Please revise this sentence and specify whether this refers to a relative increase compared with Saharan events.*

Thank you for this comment. We revised the sentence to clarify that the reported value refers to a relative increase compared to other events in the absorption coefficient. The text now states that Event C exhibits absorption coefficients approximately 50% higher than those observed during Events A and D across the measured spectral range (Lines 437).

#6. *The METAL-WRF analysis indicates broadly similar mineral fractions among events, but the comparison with UAV-based observations shows discrepancies in Al and Mg. These discrepancies should be discussed in more detail, because they may affect the conclusion about mineralogical similarity.*

Thank you for the comment. Maybe the original manuscript did not sufficiently distinguish between two separate aspects of the analysis: (i) the inter-event comparison of the mineral fractions simulated by METAL-WRF and (ii) the evaluation of the simulated composition against UAV-based measurements for the cases in which such observations were available.

The statement regarding broadly similar mineral fractions among the events refers specifically to the METAL-WRF simulations. The discrepancies in selected elements therefore do not contradict the limited inter-event variability simulated by METAL-WRF. On this we have added a clarifying sentence near the discussion of Fig.~16 to make this distinction explicit (Line 471-472).

We also refined the comparison presented in Fig.~16 by expressing both the simulated and UAV-based results as elemental mass fractions. This reduces the influence of differences in the estimated total dust loading and enables a more direct comparison of the relative elemental composition derived by the two approaches. The revised analysis shows a good agreement between all elements, with larger discrepancies for Mg and Ca. These discrepancies might be associated with the representation of Ca- and Mg-bearing minerals as well size-dependent transport and removal processes in the model. This discussion has been added in Lines 489-492 and in the Discussion section 5.2.

***#7.** The manuscript should more clearly explain how the dust-layer altitude used for METAL-WRF mineralogical averaging was selected and how sensitive the mineral fractions are to this vertical selection.*

We thank the reviewer for the comment. We believe that the reviewer focuses on the averaging used for the illustrations in Fig 15 and 16. For Fig. 15 as stated in the manuscript (Line 447), the altitude of dust is derived be applying concentration threshold for aluminum being ≥ 0.5 μgr/m3. In contrast, in our analysis for Fig.16, the simulated concentrations were extracted at the altitudes samples by the filters on UAVs to enable direct comparison with UAV-based observations. We have now added in the manuscript this clarification in Lines 476-477

To assess the sensitivity as suggested by the reviewer, we repeated the calculation using altitude intervals of ±100, ±250, and ±500 m around the selected altitude ranges. Relative to the originally used range, extending the range to ±250 m resulted in mean absolute differences of ~3% for Si, Fe, Al, Mg, and Ca, and maximum differences below 10%. Extending the interval to ±500 m resulted in larger differences of approximately 9–11% on average and up to about 17–18% on individual days. These results are summarized in the Table here:

Element	**Mean abs. change, ±250 m**	**Maximum change, ±250 m**	**Mean abs. change, ±500 m**	**Maximum change, ±500 m**
Si	2.8%	5.9%	9.5%	16.8%
Fe	2.9%	8.7%	10.1%	18.2%
Al	2.9%	6.8%	9.4%	17.3%
Mg	3.0%	8.8%	9.4%	17.2%
Ca	3.1%	10.3%	11.1%	18.2%

Based on these results we conclude that the composition is only moderately affected when the averaging range is extended to ±500 m and therefore we can stick to the original averaging intervals. A discussion was added in the manuscript for the averaging interval selection in Lines .550-551.

#8. *Line#217 "at a vertical spacing of ±", seems missing a number here.*

Thank you for spotting this error. Now we fixed the text.