Replies to Referee #1

We thank the Referee for his/her thorough review and encouraging assessment of our manuscript. We have carefully addressed each of the points raised, and we believe that the suggested revisions have helped to substantially improve the clarity and overall quality of the manuscript. Below, we provide a detailed, point-by-point response (in red) to the Referee's comments (in black).

General comments:

This manuscript presents an important contribution to the field of aerosol remote sensing by enhancing the estimation of dust lidar ratios (LRs) through a synergistic use of multiple satellite datasets (CALIOP, MODIS/MIDAS, and POLDER-3/GRASP). The research primarily addresses a critical limitation in the CALIPSO dust retrieval algorithm—the use of a fixed dust lidar ratio (LR) of 44 sr.

The effort to improve the accuracy of CALIOP-derived Dust Optical Depth (DOD) in North Africa and the Middle East is commendable and of clear relevance to both the scientific community and stakeholders.

A noteworthy contribution of the study is the clear demonstration that regional variability in dust properties necessitates the use of spatially and seasonally resolved LR values. The analysis reveals that higher LR values are required over North Africa (~53 sr), while lower values (~37 sr) are more appropriate for the Middle East. These adjustments lead to measurable improvements in DOD retrievals, particularly in regions like the Bodélé Depression and the western Sahara, which are known for intense dust activity.

The authors further validate their findings against AERONET sun-photometer measurements, reporting substantial reductions in both Mean Bias Error (MBE) and Root Mean Square Error (RMSE). Seasonal analysis also reveals strong correspondence between revised LR values and observed dust activity patterns, highlighting the method's robustness across varying climatic conditions.

We sincerely thank the Referee for the positive and encouraging feedback. We are pleased that the proposed methodology and its contributions to improving CALIOP-derived DODs were well received. We appreciate the recognition of the regional and seasonal variability in dust lidar ratios and the significance of addressing this limitation in the CALIPSO retrieval algorithm. We also thank the Referee for acknowledging the validation efforts and the robustness of the method across different regions and seasons. This valuable feedback is highly motivating and reinforces the relevance of our work for the aerosol remote sensing community.

While the methodology is generally robust and the findings are well-supported, I would like to offer several constructive observations that may help refine the study and guide future work as follows.

1. Although the improved dust LRs clearly lead to enhanced agreement with satellite and ground-based AOD measurements, the broader implications for climate modeling and radiative forcing are not fully explored. A quantitative analysis of the impact on surface energy budgets, direct radiative effects, or global dust forcing would elevate the study's significance, therefore I suggest to write a statement for future work related to this.

Thank you for this insightful comment. We agree that a quantitative assessment of the impact of revised dust LRs on surface energy budgets and radiative forcing would significantly enhance the broader relevance of our work. While such an analysis is beyond the scope of the current study, we have included a statement in the manuscript to highlight this as a direction for future research. Specifically, in the **Summary and conclusions** section (lines 667–671), we mention:
"In a follow-up study, we will investigate the dust-induced direct radiative effects based on radiative transfer model (RTM) simulations. This will involve the use of the updated CALIPSO dust profiles, the

intensive spectral optical properties (including single scattering albedo, asymmetry parameter, and refractive index) obtained by the GRASP/POLDER-3 retrieval algorithm for the identified dust cases, along with the spectral surface albedos sourced from the HAMSTER dataset (Roccetti et al., 2024)."
We hope this addresses the reviewer's concern and demonstrates our awareness of the broader implications of our findings.

2. The authors reference the relevance of their results for upcoming missions (e.g., EarthCARE) and future algorithm updates (CALIPSO v5). While promising, the manuscript does not provide a detailed roadmap for how the improved LRs will be operationally integrated. Outlining a pathway or collaboration with mission teams could enhance the practical value of the study.

Thank you for your constructive comment. We assume that the Referee is referring to the part of the manuscript where we discuss the relevance of our results considering upcoming satellite missions and algorithm updates (see Section 5, lines 676–681). Specifically, we would like to clarify that our intention is not to suggest an operational integration of the derived dust lidar ratios from our study into the EarthCARE or CALIPSO v5 algorithms. Rather, our aim is to highlight the value of our findings as a benchmark for future intercomparisons.
For instance, the EarthCARE mission will provide vertically resolved lidar ratio profiles through the ATLID instrument, and these observations will offer a valuable opportunity to compare against our regionally and seasonally adjusted lidar ratios. Likewise, the upcoming CALIPSO Version 5 algorithm will include updated aerosol models with new lidar ratio values. In this context, our work underscores the importance of using regionally refined lidar ratios and can contribute to the broader discussion on algorithm improvement, rather than being directly integrated into these systems.
We have revised the manuscript accordingly to clarify this point and avoid potential misunderstandings. The modified part now states:

"*A better assessment and validation of our findings will be possible through comparison with the vertically resolved lidar ratio observations to be provided by the ATLID lidar onboard the EarthCARE satellite (Illingworth et al., 2015; Wehr et al., 2023). Finally, one of the key updates in the forthcoming CALIPSO Version 5 retrieval algorithm involves the adoption of new aerosol models for lidar ratio estimation, further highlighting the need for an improved and regionally representative characterization of this critical parameter.*"

In conclusion this work represents a valuable contribution to aerosol remote sensing, offering practical improvements to satellite dust retrievals in one of the most important source regions globally. Addressing the aforementioned limitations in future research would not only strengthen the current findings but also broaden the applicability of the proposed methodology across other regions and satellite missions.

Specific comments:

Page 7 in paragraph 220-please provide a reference for the interpolation procedure to derive AOD at 532nm.

Thank you very much for your comment. The original statement on interpolation was brief, but we have now provided a more detailed explanation of the equations applied for the interpolation within the POLDER-3/GRASP section. The common part of the AERONET section has been transferred to the POLDER-3/GRASP section and modified accordingly. We hope these changes make everything clearer.

Based on the applied modifications, the differences between the interpolation procedures for the two sections (POLDER-3/GRASP Components and AERONET) are as follows:

1. In the case of POLDER-3/GRASP Components, the Ångström exponent is estimated from the provided AODs (Equation 1), and then the AOD at 532 nm is estimated (Equation 2).

2. In the case of AERONET, the Ångström exponent is already provided, and only Equation 2 is applied.
3. For POLDER-3/GRASP, the Ångström exponent is estimated for the 440–670 nm wavelength range, whereas for AERONET, the Ångström exponent is provided for the 440–675 nm wavelength range.

Figure 3-page 11- the shades of red/purple are very close and not easily distinguishable-please choose contrasting colors.

We sincerely apologize for the color choices in Figure 3. We have updated the colors to make them more easily distinguishable, and we have also increased the font size of the legend. You can now compare the previous version of Figure 3 with the updated one. We hope this clarifies the issue.

Figure 3 before modification:

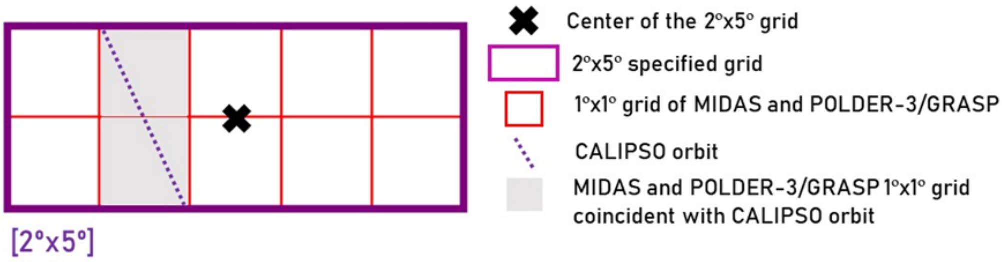


Figure 3 after modification:

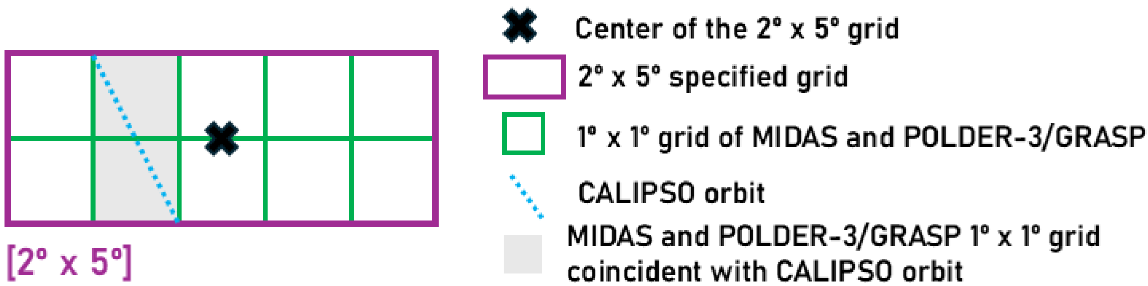


Figure 4 page 14 – in caption for the correlation factor, better use “R”.

Thank you very much for noticing. In the figure, we use the letter "R" to represent the correlation coefficient, but in the legend, we mistakenly used "r"

Page 15 line 398 -I think could be useful to write in here when you refer to Figure S1 and S2 to specify that they could be found in the supplement material.

We apologize for overlooking the reference to the Supplement. We have modified the specified part as follows:
“Additionally, as shown in Figs. S1 and S2 (provided in the Supplement), most of...”

Figure 8 page 21- Very difficult to follow all information in panels a and b; too much information; For me it could be much better if you put on separate panels the graphs related to annual/seasonal.The shades of red and brown for me are very confusing- difficult to distinguish; I would change brown with a different color-maybe black or grey.

Thank you for your valuable comment, and we apologize for any inconvenience caused. In response, we have modified the red and brown colors to orange and cyan, respectively, to improve visual clarity and resolve the difficulty in distinguishing between the curves. All figures in the manuscript have been adjusted using the **Copernicus color blindness simulator** to ensure accessibility for readers with color vision deficiencies.

While we appreciate your suggestion to separate the annual and seasonal analyses into different panels, we have chosen to present all relevant information in a single plot to facilitate direct comparison. Displaying the data side by side allows the reader to better evaluate the impact of using upgraded seasonal LR values (cyan bars) in contrast with both the annual LR values (green and blue bars) and the default CALIPSO V4 LR value of 44 sr (orange bars).

Figure 8 before modification:

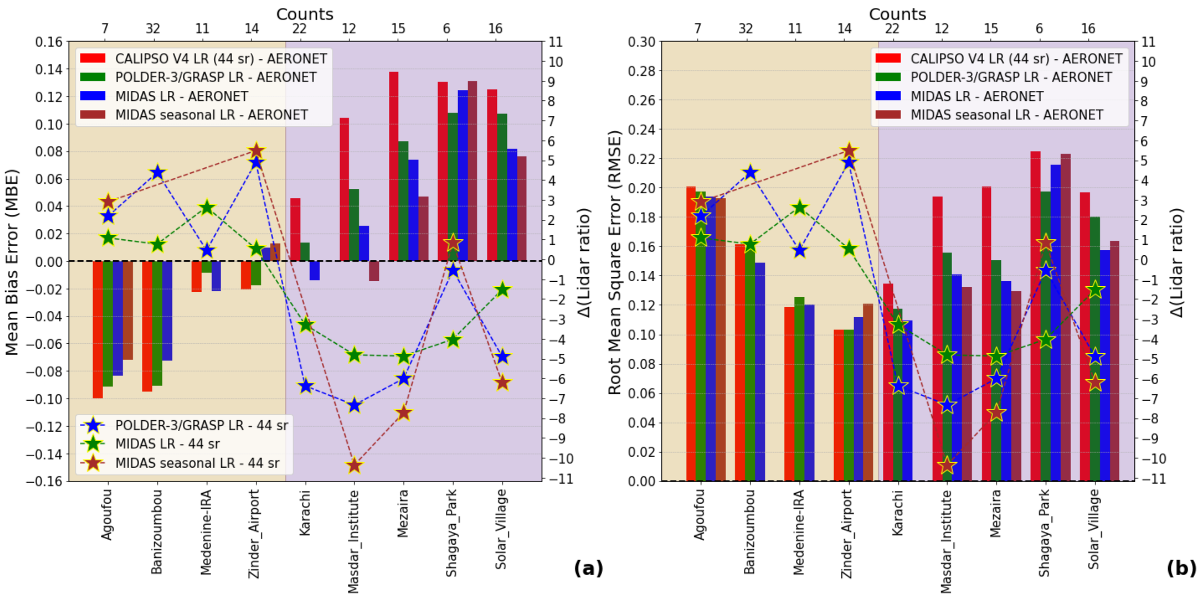
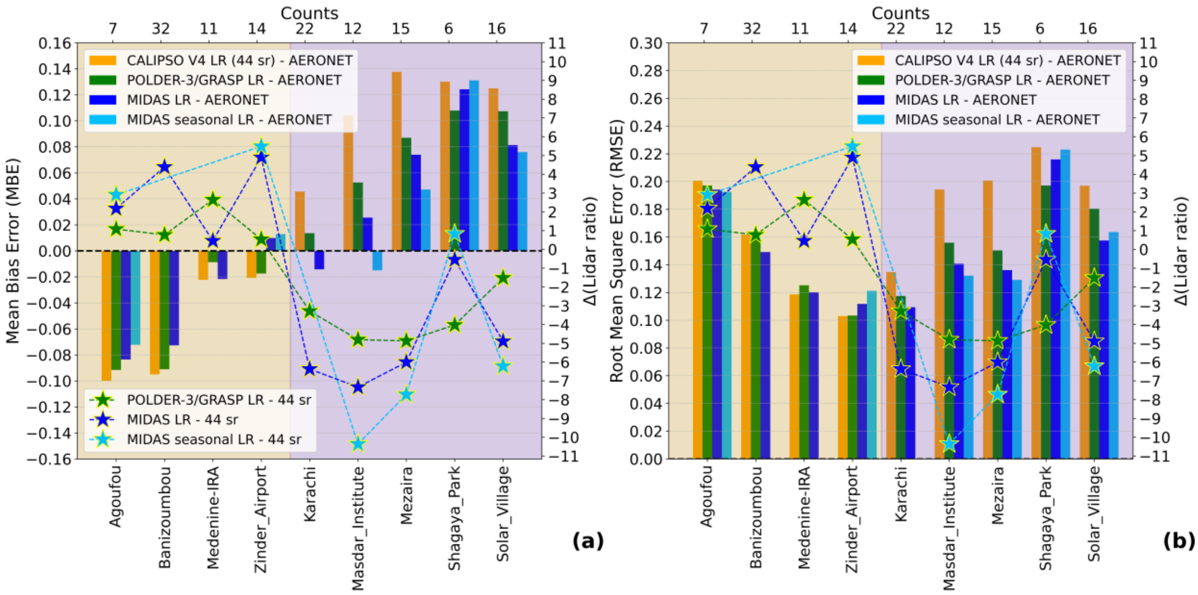


Figure 8 after modification:



Line 500- when you refer to depolarisation thresholds are you referring that the value is set for 0.28 for dust? In general when reading the word "thresholds" I would look for an interval between max and min values. Please clarify.

Thank you for your comment. We have replaced the term "threshold" with the term "value" and revised the section of the manuscript describing the separation of the dust mixtures to improve clarity and comprehension.

Line 510 Add respectively after "derived from the CALIOP-POLDER-3/GRASP and CALIOP-MIDAS synergies".

Thank you for the addition. We have modified the sentence as follows: "Concurrently, we have reproduced the temporally averaged maps utilizing the revised dust LRs (a-ii to a-iv), derived from the CALIOP-POLDER-3/GRASP and CALIOP-MIDAS synergies, respectively."

Line 514- I have noticed you have used the word "departure" several times when you refer to the difference between two values- not sure if it is correctly used- please check with an English speaker.

Thank you for your comment. We have replaced the word "departure" throughout the manuscript and made the necessary adjustments. For instance, in some cases, we opted for the word "differences" which is more commonly used in remote sensing literature.

Lines 528-529- "Within the zone of high DODs, the two peaks are more distinguishable when the new LRs have been calculated from the collocated CALIOP-MIDAS sample on a seasonal basis." I do not agree with this statement. That area looks very similar in the 2 cases. At least is not \'more distinguishable\' for me.

We apologize for the confusion. You are correct. Based on Figure 9a-iv, the peaks **are not more distinguishable** when the seasonal LR maps are applied to CALIOP's backscatter retrievals for estimating the annual DOD. This sentence was likely carried over from a previous version and was used to describe the increment of DOD hotspots in Figure 10 over North Africa when the CALIOP-MIDAS seasonal LR maps are implemented. We removed the sentence.

Figure 11- Again, I have difficulties to distinguish red and brown curves.

Thank you for your comment. In response to your feedback, we have changed the red and brown curves to orange and cyan, respectively, to improve their visibility and make them more easily distinguishable. To ensure accessibility, we verified the updated colors using the Copernicus color blindness simulator.

Figure 11 before modification:

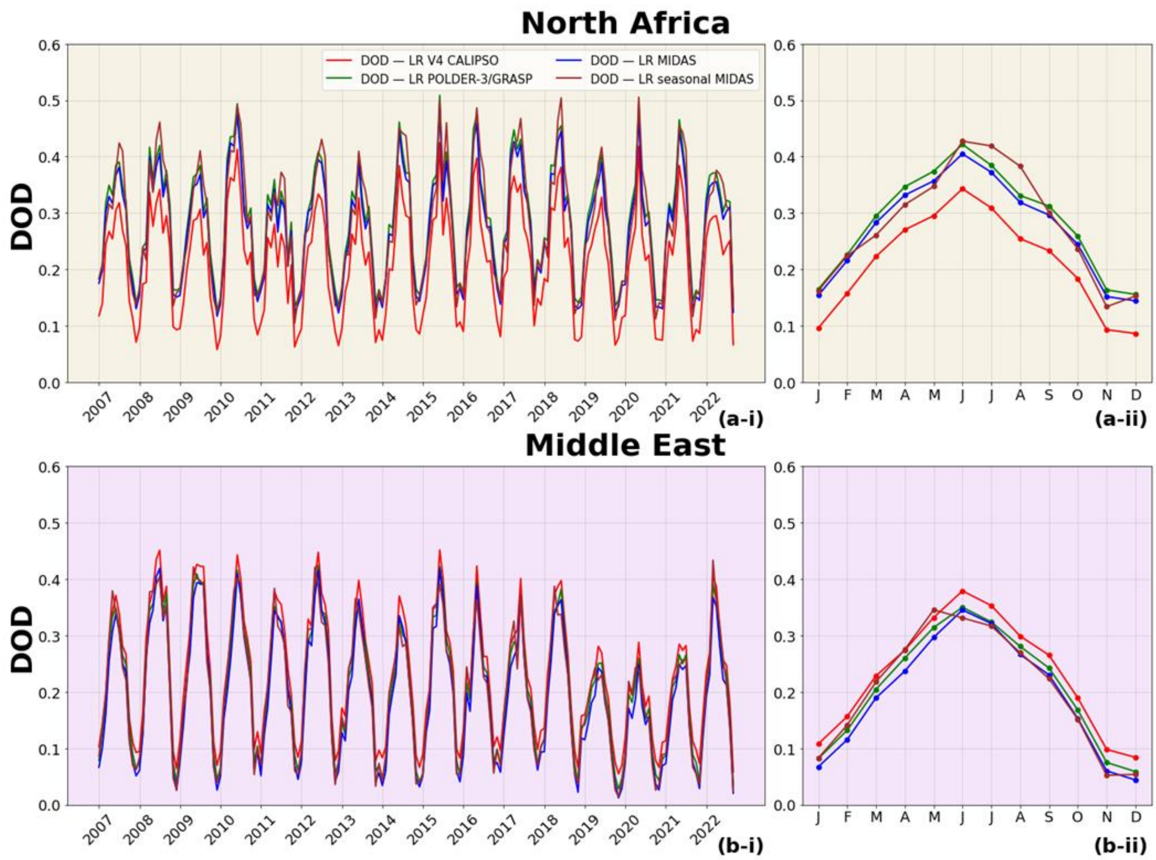
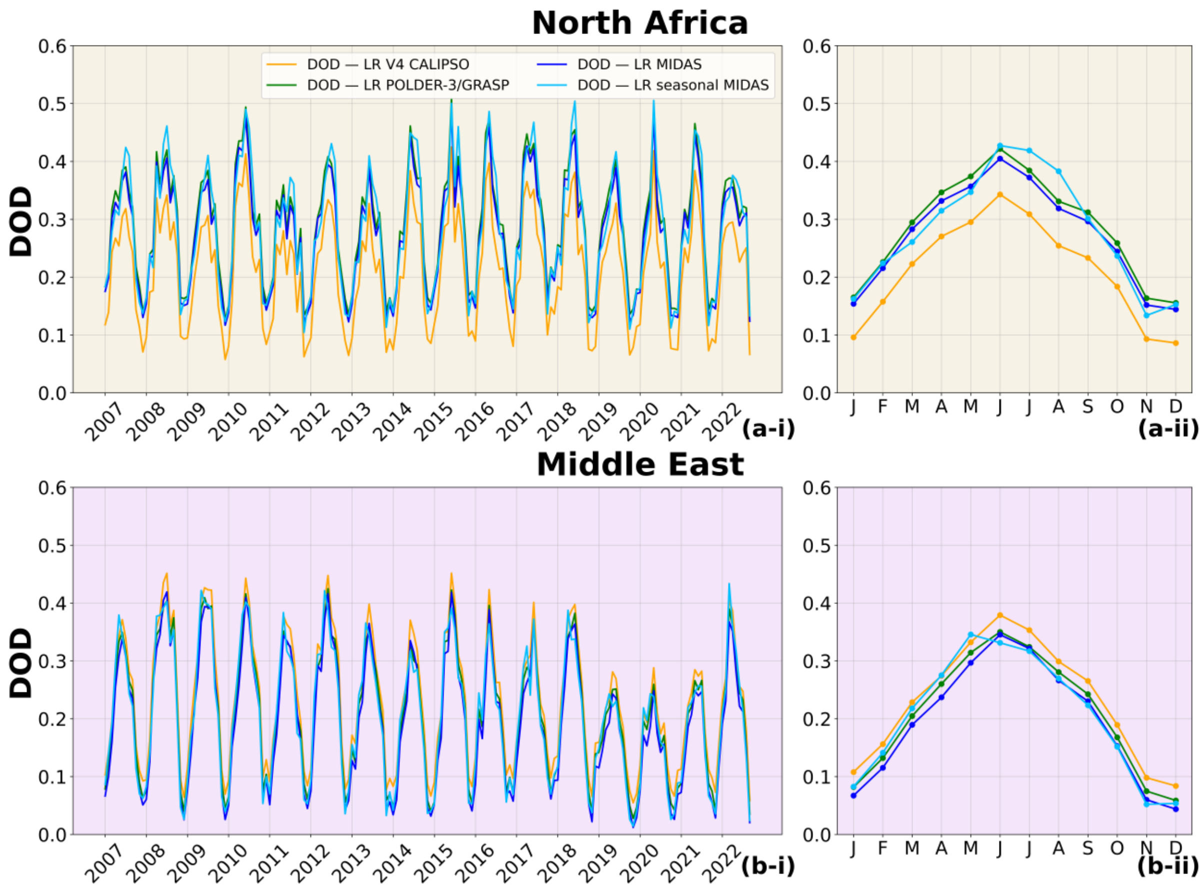


Figure 11 after modification:


North Africa
DOD — LR V4 CALIPSO
DOD — LR POLDER-3/GRASP
DOD — LR MIDAS
DOD — LR seasonal MIDAS
DOD
(a-i)
(a-ii)
Middle East
DOD
(b-i)
(b-ii)