# Responds to CC1

Dear authors,

While your study is of high interest, I have the feeling that you miss some important literature on the same subject and moreover, many of the aspects mentioned should be revised, focusing specifically on the following points that I see from a first reading:

**Reply:** We appreciate that you spent time reading our paper. An item-to-item reply to your comments is provided below.

Before addressing your comments/questions below, we would like to first provide a summary of the major revisions made to the manuscript:

- We added more detailed discussion regarding MODIS DAOD retrieval methodologies over ocean and land in section 2.2.
- We compared our MODIS- and CALIOP-based DAOD with values reported in previous studies based on MODIS and CALIOP, respectively. The comparison is added to the revised manuscript as section 3.1. For MODIS DAOD comparison, we compare our results with previous studies in both global and regional scales; For CALIOP, there isn't global CALIOP-based DAOD retrievals to compare our result with, therefore, the comparison is limited to regional scale. Overall, these comparisons suggest that our results are in reasonable agreement with previous studies, except for Voss and Evan 2020 over ocean (which can be explained by the use of different parameterization schemes).
- We evaluated our monthly mean MODIS- and CALIOP-based DAOD product by comparing with AERONET monthly mean coarse mode AOD (COD) from 2007 to 2019. We found that MODIS DAOD is statistically higher than AERONET COD by 26.7% over land and 18.5% over ocean, while CALIOP DAOD is lower than AERONET COD by 27.9% over land and 35% over ocean. This may suggest that the true DAOD probably fall between MODIS and CALIOP DAOD retrievals. Furthermore, by following the methodology proposed by Sayer et al. 2013, we estimated that the absolute expected error of MODIS DAOD is $0.65\times DAOD_M+0$ over land and $0.50\times DAOD_M+0$ over ocean, the absolute expected error of CALIOP DAOD is $0.52\times DAOD_C+0.02$ over land and $0.54\times DAOD_C+0.02$ over ocean. This analysis was added in section 3.2.

After these revisions, we think the paper is much improved and more focused, although the general conclusions still hold.

Q1. Differences between the CALIOP and MODIS global DODs are large. Is there any explanation about this discrepancy? Please note that the MODIS-derived global DOD is substantially higher than those reported in most of the recently published works (e.g., Ridley et al., 2016; Voss and Evan, 2020; Gkikas et al., 2021). A description is needed on how the global averages have been computed for both sensors. Do you acknowledge any weighting factors based on the grid cell surface area? According to Levy et al. (2009), the approach for the calculation of the global DOD is quite critical (see Fig. 5). Summarizing, I recommend including a table providing the corresponding global DODs given by relevant studies (relied either on observations or models) in order to check (and discuss) the consistency of your findings.

**Reply:** Thanks for the suggestion. We added a Table 2 in the revised manuscript (also shown below) to compare our DAOD retrievals with values reported in previous studies and discussed reasons for the differences.

Table 2. Compare global mean DAOD retrievals in this study with some relevant studies (Note the definition of global scope is different for different studies).

| Region | | DAOD@550nm | Reference |
|---|---|---|---|
| 90°S~90°N | Global | 0.03±0.005 | Ridley et al. 2016<br>Use multiple satellite platforms, in-situ AOD observations and four global models |
| 90°S~90°N | Global | 0.033 | Gkikas et al 2021<br>Use AOD from Aqua MODIS and DOD-to-AOD ratio from MERRA2 |
| 50°S~60°N | Over Ocean | 0.03±0.06 | Voss and Evan 2020<br>Over Ocean: use method in Kaufman et al 2005<br>Over Land: use method in Ginoux et al. 2012 |
| | Over Land | 0.1 | |
| 60°S~60°N | Over Ocean | 0.055, 0.020 | This Study<br>MODIS-based, CALIOP-based DAOD<br>(To calculate global mean DAOD for scope 90°S~90°N, we assume zero DAOD outside of region 60°S~60°N. We weight each grid-cell surface area into ocean, land and global DAOD average) |
| | Over Land | 0.103, 0.068 | |
| 90°S~90°N | Global | 0.057, 0.028 | |

For global scale comparison, the (new) Table 2 in the revised manuscript lists the global mean DAOD from previous studies and our study. Ridley et al. 2016 used multiple satellite platforms (MODIS and MISR), in-situ AOD observations and four global models to estimate global mean DAOD over 2004 ~ 2008. Gkikas et al. 2021 used AOD from Aqua MODIS and DOD-to-AOD ratio from MERRA2 to estimate global mean DAOD over 2003~2017. In contrast, as shown in Table 2 our MODIS-based global (90°S~90°N) DAOD is 0.057. However, difference in the global mean DAOD values from these studies should be expected as we use different methodology. In particular, both of aforementioned studies used model simulations to aid their global DAOD estimate, while our estimates are completely based on observations (More precisely, DAOD of the scope 60°S~60°N are completely based on observations, while outside of the scope, DAOD is assumed to be zero). In contrast, Voss and Evan 2020 (referred to VE20) used similar methods to our MODIS-based methodology and limited the global scope to 50°S~60°N, this is directly comparable to our global (60°S~60°N) mean MODIS DAOD values listed in Table 2. Below we focused on explaining the difference between our MODIS-based DAOD and values reported in Voss and Evan 2020.

As shown in (new) Table 2 of the revised manuscript, our DAOD based on MODIS over land (DAOD=0.103) is almost identical with that in VE20 (DAOD=0.1). Over ocean, our MODIS-based result (DAOD=0.055) is significantly larger than VE20 (DAOD=0.03). As we mentioned before, VE20 and our MODIS-based DAOD retrieval used the similar method. However, different parameters are used in the two MODIS over ocean retrieval methodologies, which is the main reason causing the non-negligible difference in our over-ocean mean DAOD. As shown in Eq (2) and Eq (3) in the revised manuscript, $f_c, f_{d,} f_m$ are required to estimate DAOD. We use MODIS over ocean retrievals to determine $f_c, f_{d,} f_m$, while Voss and Evan 2020 determine those parameters based on AERONET stations dominated by each aerosol type. We believe the use of different parameters in the estimation of DAOD over ocean is the main reason causing the difference between the two studies.
As we explained in the supplementary materials, after combining Eq (2) and Eq. (3) in the manuscript, we get the following equation for DAOD over ocean:

$$\tau_d = \frac{(\tau - \tau_m)f_c + \tau_m f_m - \tau f}{f_c - f_d} \ , \tag{1}$$

, where $f_c, f_{d,} f_m$ are the fine mode fraction of combustion, dust and marine aerosols, respectively. The values for these parameters used in our study and in VE20 are listed in the Table S4 of the supplementary material. It turns out that we used significantly larger $f_c$ and $f_m$, while a slightly smaller $f_d$, in comparison with VE20. Because the derived DAOD is positively proportional to these parameters, the use of larger $f_c$ and $f_m$, is probably the reason for a larger DAOD in our study.

Moreover, for regional scale comparison, we compared regional mean DAOD in Ridley et al. 2016 and Proestakis et al. 2018 with our MODIS and CALIOP results, respectively.
As we discussed before, the global mean DAOD in Ridley et al. 2016 may differ from our results due to the different retrieval methodology. To compare with Ridley et al. 2016, we selected the same 14 dust-laden regions provided in their paper (see their Figure 1) and plotted our DAOD results with the values reported in their Table 3. As aforementioned, in Ridley et al. 2016 the DAOD in these dust-laden regions is based on AERONET measurements and satellite retrievals, and therefore more comparable with our results. The comparison plots are provided in the Figure S2 and S3 of the supplementary material. Overall, our MODIS-based DAOD agrees very well with their results. Note that in their method, only in these dust laden regions the DAOD is constrained by observations (MODIS, MISR and AERONET) while the rest of the world is based on model simulation. Therefore, the comparison indicates that the two studies are in good agreement in terms of MODIS-based DAOD.

Table 1 in Proestakis et al., 2018 provides domain mean DAOD for six regions in Asia based on CALIOP observations. We selected the same 6 regions in East Asian and compared the regional mean DAOD between the two studies. As shown in Figure S4 and S5 of the supplementary material, Proestakis et al. 2018 are in excellent agreement with our CALIOP-based DAOD.

Overall, these comparisons suggest that our results are in reasonable agreement with previous studies, except for VE20 over ocean (which can be explained by the use of different parameterization schemes). On the other hand, the comparison results also reveal that MODIS-based is generally larger than CALIOP-based DAOD (See Figure S3 and S5 the supplementary materials). But the two methods were not systematically compared in previous studies, which is an important motivation of this study.

The description of the way we calculated global mean DAOD is added in caption of Table 4. Since Earth is a sphere, grid-cell surface area decreases toward the poles. We weight each grid-cell surface area into ocean, land and global DAOD average.

Q2. The manuscript could greatly benefit by previous studies that have performed similar analysis. For instance, the authors mention the climatological and conditional dust products, which have been introduced for the first time in Marinou et al., (2017) and then applied on Proestakis et al., (2018). No discussion or comparison is presented in the manuscript. Moreover, the separation methodology used in the manuscript has been extensively implemented in the framework of EARLINET (e.g. Tesche et al., 2009, 2011; Ansmann et al., Ansmann et al., 2011). Furthermore, Amiridis et al., (2013) introduced for the first time the depolarization-based separation methodology on CALIPSO. However, there is no reference or discussion on this study as well! Given that all the aforementioned studies are available in the literature, which are the innovative aspects of the present study?

**Reply:** Thanks for the suggestions and references. In the revised paper, we made the following modifications

First, we cited Marinou et al. 2017 and Proestakis et al. 2018 when introducing our conditional DAOD product in section 4. As discussed in Q1, the comparison with previous studies such as Ridley et al. 2016 and Proestakis et al. 2018 of regional mean DAOD were added in Section 3.1.

Second, we add a few sentences in section 2.1 about the depolarization-based dust separation algorithm that include the mentioned references: ‘The depolarization-based dust separation algorithm is based on the method developed by Shimizu et al. (2004), Hayasaka et al. (2007) and Tesche et al. 2009. The algorithm has been implemented in the framework of surface lidar network such as European Aerosol Research Lidar Network (EARLINET) (Ansmann et al. 2011) and also applied to CALIOP observations (Yu et al., 2012; Amiridis et al. 2013; Yu et al., 2015a).’. Third, we would like to clarify that the innovative aspects of this study include:

(a)The previous depolarization-based dust separation based on CALIOP observations are mostly regional studies. While our study extends to a global scale.

(b)We systematically compare depolarization-based (shape-based) DAOD from CALIOP with size-based DAOD from MODIS and discuss their differences.

(c)We further investigate DAOD interannual variability and trends in major dust source and outflow regions based on two DAOD retrievals.

Q3. Lines 105-109: Please update the information based on the final paper version of Gkikas et al. (2021) in which the MODIS-Aqua Collection 6.1 data, over the period 2003-2017, have been used.

**Reply:** Thanks. The information was updated in the revised manuscript as ‘Gkikas et al. 2021 developed a global fine resolution (0.1° x 0.1°) DAOD dataset for the period 2006-2017 by scaling MODIS retrieved Collection 6.1 Aerosol Optical Depth (AOD) with the DAOD-to-AOD ratios provided by MERRA-2 (Modern-Era Retrospective analysis for Research and Applications, Version 2) reanalysis (Gelaro et al., 2017).’

Q4. Lines 251-264: A short description of the applied techniques for the derivation of DOD is needed, based on MODIS, over continental and marine regions. How much feasible is to discriminate mineral particles from sea-salt over oceans relying only on size parameters? It is not clear to me how you can separate dust from sea-salt over land using a very high single scattering albedo (almost equal to 1; similar to those recorded for sea-salt particles) and ignoring its spectral variation. Moreover, how much reliable the Ångström exponent is above land (see Section 4.4.5 in Levy et al. (2013))? Are you using only Deep Blue retrievals over land? In this case, how do you discriminate dust aerosols from other types when the Dark Target algorithm it is applied?

**Reply:** To answer this question, we provide a more detailed description for our MODIS-based dust retrieval in the revised manuscript (i.e., Section 2.2).

For MOIDS over-ocean DAOD retrieval, an approach was developed in previous studies to separate DAOD from other types of aerosol by using aerosol optical depth (τ) and fine mode fraction (f) retrieved from MODIS Dark Target retrieval over ocean. Both $\tau$ and $f$ refer to properties at 550 nm. In this approach, both $\tau$ and fine-mode AOD ($f\tau$) are assumed to be composed of marine aerosol, dust and combustion aerosols, i.e.,

$$\tau = \tau_m + \tau_d + \tau_c \ , \tag{2}$$

$$f\tau = f_m\tau_m + f_d\tau_d + f_c\tau_c \ , \tag{3}$$

Where the subscripts m, d, and c represent marine aerosol, dust and combustion aerosol, respectively. Note that marine aerosol refers to all aerosols originated from ocean, including not only sea salt but also DMS-produced sulfate and organic aerosol Based on Eq. (2) and (3), $\tau_d$ can be calculated from MODIS-retrieved $\tau$ and $f$, with appropriate parameterizations for $f_m, f_d, f_c$ and $\tau_m$. More specifically, $f_m, f_d, f_c$ were determined from retrieved $f$ in selected regions and seasons for which a specific aerosol type dominates, $\tau_m$ was parameterized as a function of wind speed (details can be found in Kaufman et al., 2005; Yu et al., 2009, 2020). We don't use size parameters to discriminate dust from sea-salt.

Over land, MODIS aerosol properties including AOD, Ångström exponent, SSA are retrieved from the Deep Blue (DB) algorithm. Dark target aerosol products over land are not used in this study DAOD over land is derived from the AOD using one criterion based on size distribution (to distinguish fine and coarse modes) and the other criterion based on absorption (to distinguish between scattering sea salt and absorbing dust). To apply first criterion, we use the following formula established by Anderson et al. 2005 using in-situ data:

$$COD_M = AOD \times (0.98 - 0.5089\alpha + 0.051\alpha^2) \ , \tag{1}$$

Where $\alpha$ is the Ångström exponent (a measure of the wavelength dependence of optical depth) which has been shown to be highly sensitive to particle size (Eck et al. 1999),

$COD_M$ is the coarse mode fraction (aerodynamic diameters larger than $1\mu m$) of AOD retrieved from MODIS, with a contribution from absorbing (DAOD) and scattering aerosols (sea salt aerosol optical depth). This relationship is derived from the formula of Anderson et al. 2005 derived from in-situ data. The second criterion requires the single-scattering albedo at 470 nm to be less than 0.99 for the retrieval of DAOD (more details can be found in Pu and Ginoux, 2018). Nevertheless, marine aerosol would be negligible in broad continental regions except in coastal areas.

Q5. Section 3.1: Since you are using CALIPSO and Aqua retrievals, you can collocate them in order to eliminate the impact of the different sampling between the two satellite sensors which are flying in the A-Train constellation. Taking advantage of the almost coincident observations you can assess the assumptions made in Lines 394 – 407.
**Reply:** Thanks for the suggestion. However, this work focuses on a climatological monthly mean DAOD product on a global scale derived from CALIOP observations and its comparison with MODIS-based DAOD retrievals. Because we are using CALIOP nighttime data with high quality, it is challenging to collocate CALIOP with MODIS/Aqua.

Q6. Trend analysis: I cannot understand why you put so much focus in EAS and NWP without discussing other regions of the planet (e.g. Middle East).
**Reply:** We examined possible trends of dust optical depth on a global scale, in the dust belt and the major dust outflow regions. What we found was that in EAS and NWP, both MODIS and CALIOP showed statistically significant trends (see Table 5 in the revised manuscript). For other regions, either there is no statistically significant trend from two sensors or only one sensor shows a statistically meaningful trend. Therefore, we focused on understanding factors contributing to the dust trends in EAS and NWOP.

Q7. Uncertainty analysis: It would be important to present global maps of the DOD uncertainty both for CALIOP and MODIS in order for the reader to better understand how uncertain the obtained DOD averages are.
**Reply:** Thanks for the suggestion. This is an important question. However, we don’t have all the information needed to quantify all the DAOD uncertainties as discussed in our manuscript, the choice of depolarization ratio (DPR) for dust aerosols and non-dust aerosols also introduces uncertainty in DAOD. The uncertainty induced by DPR is region dependent. We added a map plot Figure S6 in the supplementary material to show the uncertainty induced from the DPR assumption. However, the uncertainty source of MODIS- and CALIOP-based DAOD are from many sources, it’s impossible for us to quantify all of them within one study. In this revised manuscript, we have assessed DAOD uncertainty through comparing satellite derived DAOD with AERONET observed coarse mode AOD

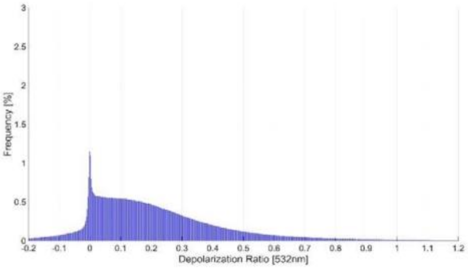
Q8. Lines 619-627: I don’t agree with this statement. It is true that it is not easy to evaluate DOD retrievals against AERONET because the sun-photometric measurements are representative for the entire atmospheric column. Nevertheless, you can select either sites (even though are few of them) in desert areas (the contribution of other aerosol species is minor or negligible), or to set appropriate coincident thresholds on AOD and Ångström exponents (see for example Basart et al. (2009)) or to rely on almucantar retrievals (Gkikas et al., 2021) or to follow the approach that you are mentioning in your manuscript (Pu and Ginoux, 2018). In any case, an evaluation analysis it is needed in order to support the reliability of the satellite DODs (see also Schuster et al., 2012; Amiridis et al. 2013).
**Reply:** Thanks for the suggestion. We have evaluated our MODIS- and CALIOP-based monthly mean DAOD by comparing with AERONET monthly mean coarse mode optical depth (COD) from 2007 to 2019 and put our analysis in the revised manuscript (i.e., section 3.2). We found that MODIS DAOD is statistically higher than AERONET COD by 26.7% over land and 18.5% over ocean, while CALIOP DAOD is lower than AERONET COD by 27.9% over land and 35% over ocean. We suggest that the true DAOD may fall between MODIS and CALIOP DAOD retrievals.

Furthermore, referring to the methodology proposed by Sayer et al. 2013, we estimated that the absolute expected error of MODIS DAOD is $0.65\times \mathrm{DAOD_M}+0$ over land and $0.50\times \mathrm{DAOD_M}+0$ over ocean, the absolute expected error of CALIOP DAOD is $0.52\times \mathrm{DAOD_C}+0.02$ over land and $0.54\times \mathrm{DAOD_C}+0.02$ over ocean.

Q9. Table 1: Are you using the spectral SSAs or only the values at 470 nm?

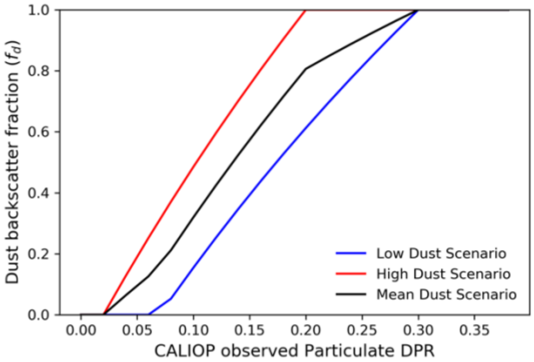
**Reply:** Thanks for pointing out this inconsistency. In over-land MODIS DAOD retrieval, we require SSA at 470 nm to be less than 0.99 to separate dust from sea salt. The information in Table 1 was corrected.

Q10. In the manuscript, dust is distinguished from non-dust aerosols based on particle shape information (i.e., the use of particulate depolarization ratio) for CALIOP. However, the particulate depolarization ratio in L2 is too noisy, showing values for dust, dusty marine, polluted dust aerosol subtypes from negative up to 1.0 and above (see figure below).



Moreover, approximately 11% of all dust, dusty marine, polluted dust aerosol subtypes have particulate depolarization ratios < 0.05. Since in the methodology the dust, dusty marine, polluted dust aerosol subtypes are assumed mixtures of dust and non-dust components, how do the authors treat the negative and larger-than-one particulate depolarization cases in their Quality Assurance procedure? Do the authors consider the dusty aerosol mixtures of particulate depolarization ratio lower than 0.05 as non-dust mixtures? Which are the uncertainties introduced in the final dust product by these values? Please quantify.

**Reply:** We understand that CALIOP observations of depolarization ratio are quite noisy at their native resolutions. In our study, if CALIOP observed particulate depolarization ratio (DPR) <0, then we make it to be 0, if it is >1, then we make it to be 1. In our approach, we don't use CALIOP aerosol type information. We check all the detected aerosol features and use the observed depolarization ratio to separate dust from non-dust aerosol. The figure on the right shows the relationship between dust fraction ( $f_d$ ) and CALIOP observed DPR. The red curve is for high dust scenario, which is the results of combination of $\delta_d = 0.2$ and $\delta_{nd} = 0.02$. The blue curve is for low dust scenario, which is the results of combination of $\delta_d = 0.3$ and $\delta_{nd} = 0.07$. The black line is the mean of high and low dust scenarios. The DAOD derived for different dust scenarios (high, low and mean) are all included in our product.



To quantify the uncertainty caused by DPR selection, we also calculated DAOD in the lowest ($\delta_d = 0.30$ and $\delta_{nd} = 0.07$) and the highest ($\delta_d = 0.20$ and $\delta_{nd} = 0.02$) dust fraction scenarios. The uncertainty induced by DPR is region dependent (see Figure S6 in the supplementary material). The uncertainty is much lower in dust dominant regions than other regions. The averaged uncertainty for regions with DAOD>0.05 is 20%, while the averaged uncertainty for other regions is 38%.

Q11. The authors provide a CALIPSO-based dust product, based on the particulate depolarization ratio, applied to L2 backscatter coefficient profiles. Based on the manuscript it is not clear whether the methodology is applied only on the dust, dusty marine, and polluted dust aerosol subtypes, and not at the other types (e.g. elevated smoke, marine, ...) at the 60m aerosol layer. Or whether an average over consecutive 60m layers is computed to remove noise. Please provide more in-depth description of the selected methodology. Moreover, which is the effect of the identified aerosol subtype misclassification on the dust product? Many important studies are mentioned by the authors (e.g. Burton et al., 2013), however the effect of the misclassification on the dust product needs discussion and quantification.

**Reply:** In our CALIOP-based DAOD retrieval, the methodology was applied to all CALIOP detected cloud-free aerosol layers. Therefore, this DAOD retrieval does not depend on CALIOP standard aerosol subtype classification.

Q12. Based on the methodology, the dust, dusty marine, and polluted dust aerosol mixtures are distinguished into a dust and a non-dust component. Thus, at the end, there are three types of backscatter coefficient: (1) the initial backscatter coefficient of non-dust mixtures (e.g. elevated smoke, ...), (2) the dust backscatter coefficient of the separated dust component, and (3) the remaining backscatter coefficient of the separation, the non-dust component. According to my understanding the extinction coefficient of (1) does not change since the methodology is not applied to non-dust mixtures. Regarding the case (2), a uniform global Lidar Ratio (LR) is implemented to calculate the dust extinction coefficient. However, the authors do not discuss the case three (3), regarding the remaining backscatter coefficient of the non-dust component. For the calculation of the non-dust extinction coefficient component, the authors should identify the non-dust aerosol subtype in the dusty aerosol mixture, in order to assign a proper LR. The authors have not provided a detailed explanation. Since the AOD is then computed by the integration of the extinction coefficient profile, the authors should either provide a solid justification of the non-dust aerosol- subtype assignment including quantification the corresponding uncertainties, or to avoid using the new AOD and the corresponding Sections, after the intermediate dust separation.

**Reply:** Thanks for the comment.

In our CALIOP-based DAOD retrieval, our methodology was applied to all types of aerosol layers. Therefore, there are two types of backscatter coefficient: (1) the backscatter coefficient for dust component (2) the backscatter coefficient for non-dust component. Meanwhile, in addition to backscatter coefficient profile, we also have extinction coefficient profile for total aerosol from CALIOP level 2 product. The extinction coefficient profile here is used to calculate total AOD.

In this study, we focus on dust aerosol, therefore, we assign a global uniform LR (44sr, which is consistent with LR used in CALIOP standard product) for dust component to calculate dust extinction coefficient vertical profile. Then DAOD could be calculated by integrating dust extinction coefficient profile for each column.

For non-dust component, it is not our focus in this study. We did not assign any LR for non-dust components, which is impossible (marine aerosol and smoke pollution can differ in LR by about a factor of 3). The total AOD shown in this study is calculated by integrating the total extinction profile from CALIOP L2 product.

Q13. It is not properly discussed, how the averaging extinction coefficient procedure is computed, prior to integration for the DAOD. According to Amiridis et al. (2013) and Tackett et al. (2018), the methodology should follow first a "per-overpass" averaging within a specific grid, and accordingly integration of the mean profile, calculated by all overpasses in the grid. However, the methodology followed by the authors is not clear in this point. Please discuss, and in case a different methodology is provided justify the selected approach or revise accordingly.

**Reply:** Thanks for the suggestion. We added more discussion on how we average extinction coefficient in Section 2. Below is our updated description.

In each 2º (latitude) ×5º (longitude) grid, at each altitude, dust backscatter coefficient is derived by multiplying CALIOP total backscatter coefficient with the calculated $f_d$. Then we apply LR to the dust backscatter coefficient to get the dust extinction coefficient for each overpass. The monthly mean dust extinction coefficient is calculated at each altitude for grids with larger than 5 samples within the month. Then DAOD is calculated by integrating the monthly mean dust extinction coefficient profile for each grid.

Q14. The manuscript would greatly benefit by introducing tables of the Quality Assurance procedures, applied to both CALIPSO and MODIS, including the corresponding literature related to each filter.

**Reply**: Thanks for the suggestion. The table containing the Quality Assurance procedures are added in the supplementary material as Table S1.

Table S1. Summary of Quality Assurance procedures in CALIOP- and MODIS-based DAOD retrievals.

| | Quality Assurance (references) |
|---|---|
| CALIOP | (a) Select cloud-free columns or columns with high-level optically thin clouds using CALIOP L2 cloud layer product. (Yu et al. 2015a)<br>(b) Use CAD score between –90 and –100 (Yu et al. 2019)<br>(c) Use EXT_QC values of 0, 1, 18, and 16 (Winker et al. 2013) |
| MODIS (Ocean) | QAC>=0 (Levy et al. 2013), AOD <0 was excluded |
| MODIS (Land) | Retrieved aerosol properties with a standard deviation less than 0.15 among 10x10 pixels are assumed cloud free and are flagged with the highest quality flag (QA=3). Here we use products of QA=3 following the recommendation of Hsu et al. (2013) |

Q15. What I am missing in the study is a validation intercomparison against ground reference lidar instruments to validate the profiles acquired (e.g. EARLINET/ACTRIS), or even an intercomparison against dust models.

**Reply:** Thanks for the suggestion. We added a section for comparison with AERONET retrievals. Although a comparison with EARLINET/ACTRIS or against dust models would be nice, it is beyond the scope of this study and may be pursued in future research. The focus of this paper is to assess consistency and inconsistency between CALIOP shape-based DAOD and MODIS size-based DAOD.

Q16. The uncertainty analysis is not performed in-depth. Many aspects, such as the effect of non-uniform global Lidar Ratio, the presence of highly polarizing pollen, the presence of volcanic particles or the effect of depolarizing marine particles (in Low RH), the effect of topography and orography (e.g. weighting effects on the mean profiles due to mountains), negative or high positive backscatter values and how they are treated (including references) are not discussed and quantified through a proper error-propagation analysis and an estimation of the uncertainties.

**Reply:** Thanks for the comment. There are multiple uncertainty sources, we do not think it is possible to quantify each of them in this study. We agree that the presence of pollen, volcanic ash, and cube-like sea salt particles, all with elevated DPR, would have led to an overestimate of CALIOP DAOD. This is now discussed in the paper. However, it is impossible to quantify the overestimate.

For the uncertainty analysis, in the revised manuscript, we discuss the uncertainty induced from LR assumption and DPR in Section 3.2.

This study assumes dust lidar ratio to be 44 ± 9 $sr$ at 532 nm, which is the value used in the CALIOP V4 product (Kim et al. 2018) and is comparable to previous studies and basically covers the range of typical dust lidar ratios. The ±9 $sr$ induces ±20% DAOD uncertainties as shown in the shaded area in Figure 9.

To quantify the uncertainty caused by DPR selection, we also calculated DAOD in the lowest ($\delta_d$=0.30 and $\delta_{nd}$=0.07) and the highest ($\delta_d$ =0.20 and $\delta_{nd}$=0.02) dust fraction scenarios. The uncertainty induced by DPR is region dependent (Figure S6). The uncertainty is much lower in dust dominant regions than other regions. The averaged uncertainty for regions with DAOD>0.05 is 20%, while the averaged uncertainty for other regions is 38%.

Moreover, as shown in the answer of Q8, we estimated the absolute expected error of our DAOD products by comparing with AERONET COD.

References:

Anderson, T. L., Wu, Y., Chu, D. A., Schmid, B., Redemann, J., & Dubovik, O. (2005). Testing the MODIS satellite retrieval of aerosol fine-mode fraction. *Journal of Geophysical Research D: Atmospheres*, *110*(18), 1–16. https://doi.org/10.1029/2005JD005978

Eck, T. F., Holben, B. N., Reid, J. S., Dubovik, O., Smirnov, A., O'Neill, N. T., … Kinne, S. (1999). Wavelength dependence of the optical depth of biomass burning, urban, and desert dust aerosols. *Journal of Geophysical Research Atmospheres*, *104*(D24), 31333–31349. https://doi.org/10.1029/1999JD900923

Gasteiger, J., Wiegner, M., Groß, S., Freudenthaler, V., Toledano, C., Tesche, M., & Kandler, K. (2011). Modelling lidar-relevant optical properties of complex mineral dust aerosols. *Tellus, Series B: Chemical and Physical Meteorology*, *63*(4), 725–741. https://doi.org/10.1111/j.1600-0889.2011.00559.x

Gelaro, R., McCarty, W., Suárez, M. J., Todling, R., Molod, A., Takacs, L., … Zhao, B. (2017). The modern-era retrospective analysis for research and applications, version 2 (MERRA-2). *Journal of Climate*, *30*(14), 5419–5454. https://doi.org/10.1175/JCLI-D-16-0758.1

Gkikas, A., Proestakis, E., Amiridis, V., Kazadzis, S., Di Tomaso, E., Tsekeri, A., … Pérez Garciá-Pando, C. (2021). ModIs Dust AeroSol (MIDAS): A global fine-resolution dust optical depth data set. *Atmospheric Measurement Techniques*, *14*(1), 309–334. https://doi.org/10.5194/amt-14-309-2021

Hsu, N. C., M. J. Jeong, C. Bettenhausen, A. M. Sayer, R. Hansell, C. S. Seftor, J. Huang, and S. C. Tsay. 2013. "Enhanced Deep Blue Aerosol Retrieval Algorithm: The Second Generation." *Journal of Geophysical Research: Atmospheres* 118(16):9296–9315

Järvinen, E., Kemppinen, O., Nousiainen, T., Kociok, T., Möhler, O., Leisner, T., & Schnaiter, M. (2016). Laboratory investigations of mineral dust near-backscattering depolarization ratios. *Journal of Quantitative Spectroscopy and Radiative Transfer*, *178*, 192–208. https://doi.org/10.1016/j.jqsrt.2016.02.003

Kaufman, Y. J., Koren, I., Remer, L. A., Tanré, D., Ginoux, P., & Fan, S. (2005). Dust transport and deposition observed from the Terra-Moderate Resolution Imaging Spectroradiometer (MODIS) spacecraft over the Atlantic Ocean. *Journal of Geophysical Research D: Atmospheres*, *110*(10), 1–16. https://doi.org/10.1029/2003JD004436

Kok, J. F., Ridley, D. A., Zhou, Q., Miller, R. L., Zhao, C., Heald, C. L., … Haustein, K. (2017). Smaller desert dust cooling effect estimated from analysis of dust size and abundance. *Nature Geoscience*, *10*(4), 274–278. https://doi.org/10.1038/ngeo2912

Kurosaki, Y., & Mikami, M. (2003). Recent frequent dust events and their relation to surface wind in East Asia. *Geophysical Research Letters*, *30*(14). https://doi.org/10.1029/2003GL017261

Lee, E. H., & Sohn, B. J. (2011). Recent increasing trend in dust frequency over Mongolia and Inner Mongolia regions and its association with climate and surface condition change. *Atmospheric Environment*, *45*(27), 4611–4616. https://doi.org/10.1016/j.atmosenv.2011.05.065

Levy, R. C., Mattoo, S., Munchak, L. A., Remer, L. A., Sayer, A. M., Patadia, F., and Hsu, N. C.: The Collection 6 MODIS aerosol products over land and ocean, Atmos. Meas. Tech., 6, 2989–3034, https://doi.org/10.5194/amt-6-2989-2013, 2013.

Mielonen, T., Arola, A., Komppula, M., Kukkonen, J., Koskinen, J., De Leeuw, G., & Lehtinen, K. E. J. (2009). Comparison of CALIOP level 2 aerosol subtypes to aerosol types derived from AERONET inversion data. *Geophysical Research Letters*, *36*(18).

https://doi.org/10.1029/2009GL039609

O’Neill, N. T., Eck, T. F., Smirnov, A., Holben, B. N., & Thulasiraman, S. (2003). Spectral discrimination of coarse and fine mode optical depth. *Journal of Geophysical Research: Atmospheres*, *108*(17). https://doi.org/10.1029/2002jd002975

Proestakis, E., Amiridis, V., Marinou, E., Georgoulias, A. K., Solomos, S., Kazadzis, S., … Van Der A, R. J. (2018). Nine-year spatial and temporal evolution of desert dust aerosols over South and East Asia as revealed by CALIOP. *Atmospheric Chemistry and Physics*, *18*(2), 1337–1362. https://doi.org/10.5194/acp-18-1337-2018

Pu, B., & Ginoux, P. (2018). How reliable are CMIP5 models in simulating dust optical depth? *Atmospheric Chemistry and Physics*, *18*(16), 12491–12510. https://doi.org/10.5194/acp-18-12491-2018

Qian, W., Quan, L., & Shi, S. (2002). Variations of the dust storm in China and its climatic control. *Journal of Climate*, *15*(10), 1216–1229. https://doi.org/10.1175/1520-0442(2002)015<1216:VOTDSI>2.0.CO;2

Ridley, A. D., Heald, L. C., Kok, F. J., & Zhao, C. (2016). An observationally constrained estimate of global dust aerosol optical depth. *Atmospheric Chemistry and Physics*, *16*(23), 15097–15117. https://doi.org/10.5194/acp-16-15097-2016

Sayer, A. M., Hsu, N. C., Bettenhausen, C., & Jeong, M. J. (2013). Validation and uncertainty estimates for MODIS Collection 6 “deep Blue” aerosol data. *Journal of Geophysical Research Atmospheres*, *118*(14), 7864–7872. https://doi.org/10.1002/jgrd.50600

Yu, H. B., Chin, M., Bian, H. S., Yuan, T. L., Prospero, J. M., Omar, A. H., … Zhang, Z. B. (2015). Quantification of trans-Atlantic dust transport from seven-year (2007-2013) record of CALIPSO lidar measurements. *Remote Sensing of Environment*, *159*, 232–249. https://doi.org/10.1016/j.rse.2014.12.010

Yu, H., Chin, M., Remer, L. A., Kleidman, R. G., Bellouin, N., Bian, H., & Diehl, T. (2009). Variability of marine aerosol fine-mode fraction and estimates of anthropogenic aerosol component over cloud-free oceans from the Moderate Resolution Imaging Spectroradiometer (MODIS). *Journal of Geophysical Research Atmospheres*, *114*(10). https://doi.org/10.1029/2008JD010648

Yu, H., Yang, Y., Wang, H., Tan, Q., Chin, M., Levy, R., … Shi, Y. (2020). Interannual Variability and Trends of Combustion Aerosol and Dust in Major Continental Outflows Revealed by MODIS Retrievals and CAM5 Simulations During 2003–2017. *Atmospheric Chemistry and Physics Discussions*, 1–38. https://doi.org/10.5194/acp-2019-621