Responses to the RC1

This article reports an analysis of both CALIOP and MODIS retrievals spanning over a decade in order to compile climatological records of the spatial variability of dust aerosol optical depth and its interannual (and inter-decadal) variability. For the CALIOP record, the authors also obtained vertical profiles of extinction efficiency using the methodology previously developed in Yu et al. (2015). Overall, this is insightful work that could be an important contribution to the field and the paper was a pleasure to read. I do have a few major comments relating to the methodology and the interpretation of the results. The article thus requires major revisions.

Reply: We would like to thank the reviewer for constructive comments. We have taken these comments seriously and revised the manuscript accordingly. An item-to-item reply to the reviewer's comments is provided in this response.

Before addressing the comments/questions in detail, 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. 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.

Main Comments:

Q1. There is a very large difference in the DAOD obtained from the CALIOP (0.029 on a global basis) and the MODIS record (0.063 on a global basis). The MODIS result of a global DAOD of 0.063 is about one-and-a-half to two times other estimates in recent papers (Ridley et al., 2016; Voss and Evan, 2020; Gkikas et al., 2021), and much larger than simulated by any global aerosol model (see Figure 3 in Gliss et al., 2021). Therefore, I think the authors should include more discussion of what is causing their MODIS climatology to yield a much larger DAOD than other literature estimates. That should include a more detailed error analysis, and particularly an analysis of errors affecting the MODIS estimate such as errors in the DAOD/AOD ratio (see further comments below).

Reply: These are great questions and suggestions and also thanks for the references. Following your suggestions, we added a new section (i.e., section 3.1) in the revised manuscript to compare our study with previous ones and discuss the causes for differences. We also included several new tables (Table 2 and Table S2, S3) and figures (Figure S2, S3, S4 and S5) in both manuscript and supplementary material to support the discussion.

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, it is important to note that the global mean DAOD values from these studies are not directly comparable to our global mean results because of the methodology differences. 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 $f_c, f_{d,} f_m$ and hence derive DAOD in self-consistent manner, while Voss and Evan (2020) determine these parameters based on observations in AERONET stations dominated by each aerosol type. The use of different characteristic parameters in the estimation of DAOD over ocean is the main reason for 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:

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

, 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 results. As we discussed before, the global mean DAOD in Ridley et al. 2016 is not directly comparable to 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 constrained by 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 Ridley et al. (2016), DAOD outside of the dust-laden regions came largely from model simulations and imperfect parameterizations of dust transport and removal processes in the model may have led to significant difference from our 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, values from Proestakis et al. (2018) are in excellent agreement with our CALIOP-based DAOD.

Overall, these regional and global 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 DAOD 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 has motivated us to carry out this study.

Q2. A key part of the methodology that is novel is obtaining the ratio of DAOD to AOD from MODIS data, which allows the authors to obtain a climatology of DAOD from well-established MODIS Aqua retrievals of AOD. However, more details should be provided of the procedure for obtaining DAOD/AOD, especially as errors in this procedure seem to be a likely culprit of the large differences between the CALIOP-based and the MODIS-based climatology (e.g., lines 427-9).

- It seems that the DAOD/AOD ratio over land was calculated using the previous analysis in Pu and Ginoux (2018). Considering how important this is for the final results, this method should be summarized and explained here, and its strengths and limitations discussed.
- It's briefly mentioned that the methodology of Yu et al. (2020) was used to obtain the DAOD/AOD ratio over ocean (line 280). Please similarly explain this method in sufficient detail for the reader to understand this.

Reply: Thanks for the suggestion. we have explained the methods in the manuscript to help readers understand the methodology and facilitate discussion of strengths and weaknesses of the methods.

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 τ and f refer to properties at 550 nm hereafter, unless specified otherwise. In this approach, both τ 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. Based on Eq. (2) and (3), τ_d can be calculated from MODIS-retrieved τ and f, with appropriate parameterizations for f_m, f_d, f_c and τ_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, τ_m was parameterized as a function of wind speed (details can be found in Kaufman et al., 2005; Yu et al., 2009, 2020).

Over land, MODIS aerosol properties including AOD, Ångström exponent, SSA are retrieved from the Deep Blue (DB) algorithm. 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 depending quadratically on the Ångström exponent (α), a measure of the wavelength dependence of optical depth or extinction (Eck et al., 1999):

$$COD_M = AOD \times (0.98 - 0.5089\alpha + 0.051\alpha^2) \ , \tag{4}$$

Where 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). This description was added in the revised manuscript (section 2.2).

Q3. Related to the previous comments is that the authors should expand the discussion in Section 4 to propagate their uncertainties into their final results, obtaining error bars on the DAOD climatology from both MODIS and CALIPSO. For CALIPSO, paragraph 1 includes an error estimate due to assumptions about the dust depolarization ratio; it seems straightforward to propagate the error of the lidar ratio into this estimate and perhaps from CALIPSO's low sensitivity (an error estimate for that is also discussed earlier in the paragraph). For MODIS, there is some quantitative analysis of errors mentioned near the end of section 4 but more detail should be added. This would be a combination of the well-characterized errors in the AOD retrieval and errors in the DAOD/AOD ratio.

Reply: Good point. It is important to quantify uncertainties associated with our MODIS- and CALIOP-based DAOD.

In CALIOP-based DAOD retrieval, we assume dust lidar ratio (LR) to be $44 \pm 9\ sr$ at 532nm. This range of LR is comparable to previous studies and basically covers the range of typical dust LR. The $\pm 9\ sr$ LR uncertainties induces around $\pm$ 20% uncertainties in DAOD (the shaded area in Figure 9 in the revised manuscript).

For DAOD uncertainty from depolarization ratio (DPR), we added Figure S6 in the supplementary material to show the global distribution of DPR induced DAOD uncertainties. We found that 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%.

It is difficult to quantify DAOD uncertainty induced by each source in one study. Instead, we estimate absolute expected error of MODIS- and CALIOP-based DAOD by comparing with AERONET in-situ measurements of monthly mean coarse mode optical depth (COD). In this process, we consider AERONET COD as a proxy of DAOD since so far there is not a valid method to derive DAOD from AERONET AOD.

For over-land dust retrievals between 2007 and 2019, there were 16653 MODIS, CALIOP monthly mean DAOD retrievals collocated with observations from 761 AERONET sites located within a 1-degree MODIS and CALIOP grid cell (Figure 1 in the revised manuscript). Overall, MODIS DAOD is biased high compared with AERONET COD, with absolute bias $of\ B_a = 0.01$ and relative bias $of\ B_r = 26.7\%$. On the other hand, CALIOP DAOD is generally biased low with $B_a = -0.02$ and $B_r = -27.9\%$. For over-ocean dust retrievals, between 2007 and 2019, there were 7755 MODIS, CALIOP monthly mean DAOD retrievals collocated with 311 AERONET sites located within a 1-degree MODIS and CALIOP grid cell (Figure 3 in the revised manuscript). MODIS DAOD is biased high compared with AERONET COD with absolute bias $B_a = 0.01$ and relative bias $B_r = 18.1\%$. On contrary, CALIOP is generally biased low with $B_a = -0.02$ and $B_r = -35\%$.We estimate that the absolute expected error of MODIS DAOD is 0.65×$DAOD_M$+0 over land and 0.50×$DAOD_M$+0 over ocean, the absolute expected error of CALIOP DAOD is 0.52×$DAOD_C$+0.02 over land and 0.54×$DAOD_C$+0.02 over ocean. This analysis has been added in section 3.2.

Q4. Line 352-4: Here and in the rest of this section, the suggestion is made that CALIPSO's lower sampling frequency could be a cause for the systematically lower DAOD from CALIPSO than from MODIS. I think this is incorrect. A lower sampling frequency is just as likely to produce an overestimate of DAOD as an underestimate, so producing a systematic underestimation of a factor of two for many different regions is in my view implausible. Please correct this.

- Line 370-1: I think this statement is similarly statistically incorrect. Why would episodic sampling of dust events produce a systematically lower DAOD, especially when you have 12 years of data and so many total retrievals?

Reply: This is a good point. Statistically, CALIOP's lower frequency indeed is not a reasonable explanation for its systematically lower DAOD than MODIS. We corrected our statement in this part as below:

The CALIOP-based DAOD is rather low in regions that are known to be dusty in certain seasons, such as southwestern United States, South America, Australia and South Africa. These regions do stand out in MODIS DAOD maps (the second column in Figure 5). Then we plot DAOD-to-TAOD ratio based on DAOD and TAOD retrievals from two sensors (the last two columns in Figure 5). These regions indeed show up in the DAOD-to-TAOD ratio plot based on both sensors (i.e., the last two columns in Figure 5). This implies that in those regions both sensorspecific methodologies are able to distinguish dust aerosol from sensor-detected total aerosol to some extent so that the DAOD to TAOD ratio stands out in those regions for both sensors.

In addition, the conditionally sampled DAOD product is kept in the revised manuscript as an independent part instead of using this as an explanation of low CALIOP-DAOD, because the comparison between climatological and conditional DAOD could provide important information about frequency and intensity of dust events.

Other comments:

Q1. The abstract notes a climatological record over the last two decades, but the period spanned is really 2007-2019. Please correct.

Reply: Thanks. We corrected it as 'from 2007 to 2019'.

Q2. Lines 242-4: Yu et al. (2021) recently did a detailed analysis of the diurnal variability of dust AOD that should be mentioned here. And can you roughly estimate the error you expect from the difference in daytime and nighttime distributions based on Yu et al. and Kittaka '11? I think this should be small (~10%?) relative to your other errors.

Reply: Thanks for the suggestion and the reference. We added a paragraph to Section 2.1 to discuss why we use nighttime observation for CALIOP DAOD retrievals. We cited Yu et al. 2021 in this section. We would like to note here that, Yu et al. (2021) actually found a significant day-night inconsistency in their CATS AOD retrievals after comparisons with collocated AERONET retrievals (see their discussion in section 3.1). Because of this, they concluded that "*To account for this day–night inconsistency in CATS data quality, the diurnal variability in dust and dust mixture characteristics is currently examined separately for daytime and nighttime periods*". In other words, their daytime and nighttime DAOD, even though plotted together, are NOT directly comparable. But you are right that, the contrast between daytime and nighttime DAOD based on these plots is roughly 10-15%, which is smaller than other uncertainties in CALIOP retrievals as analyzed in section 3. Again, it has to be emphasized that this contrast is partly due to the day–night inconsistency in CATS data quality.

Q3. Line 247-9: This statement seems a bit vague. Could you be specific as to how large you expect the solar noise to be? If that's larger than 10% then the statement would sound less subjective to the reader.

Reply: It is hard to isolate the uncertainty induced by solar noise from all other uncertainty sources. However, we think our choice of using nighttime CALIOP observations is still valid.

First, based on our discussion in the above question Q2, we know that it is very difficult to extract true daytime and nighttime DAOD difference from lidar observations. The diurnal variation of DAOD in Yu et al. 2021 are actually investigated for daytime and nighttime separately due to the significant difference in data quality.

Second, we also retrieve DAOD based on CALIOP daytime observations and further analyze the difference between CALIOP daytime and nighttime DAOD datasets (Figure S1). We found that CALIOP daytime DAOD is generally much greater than nighttime DAOD in open ocean regions where dust aerosol is not expected to appear (see the third column in Figure S1). This means CALIOP daytime DAOD has a much lower quality than nighttime DAOD, which is mainly due to solar contamination in daytime CALIOP observations. Considering the low data quality of CALIOP daytime DAOD dataset, we choose to use the nighttime CALIOP product that is free of solar noise.

Third, using CALIOP daytime DAOD dataset would not change our result in this study, specifically CALIOP DAOD would be still systematically smaller than MODIS DAOD. CALIOP daytime DAOD is generally smaller than nighttime in dust-laden regions. Generally, CALIOP

nighttime DAOD is smaller than MODIS DAOD especially in some dust-laden regions. If we change to use CALIOP daytime DAOD, then its difference with MODIS DAOD would be even larger.
Considering all aforementioned issues, we decide to use higher quality nighttime CALIOP DAOD dataset in the analysis.

Q4. Line 270-2: This sentence is unclear. Could you include a supplementary graph on how sensitive your results are to this criterion of 10 retrievals per month?

Reply: Figure 1 below shows the impact of requiring a minimum of 10 DAOD retrievals in a month on the derived seasonal mean DAOD over ocean. The first column shows seasonal mean DAOD (2007~2019) directly from MODIS retrieval. The second column shows the seasonal mean DAOD of MODIS retrievals with a minimum of 10 DAOD retrievals in a month. The third column is the difference between the first two columns. Over dust dominant regions such as the North Atlantic Ocean, there is no impact. However, over some heavy cloudy regions such as the North Pacific Ocean, DAOD in column 1 is significantly higher than column 2 during MAM and JJA. In those regions, MODIS dust retrieval could bias high due to cloud contamination, screening out infrequent sampling of DAOD could minimize the cloud contamination in those regions to some extent.

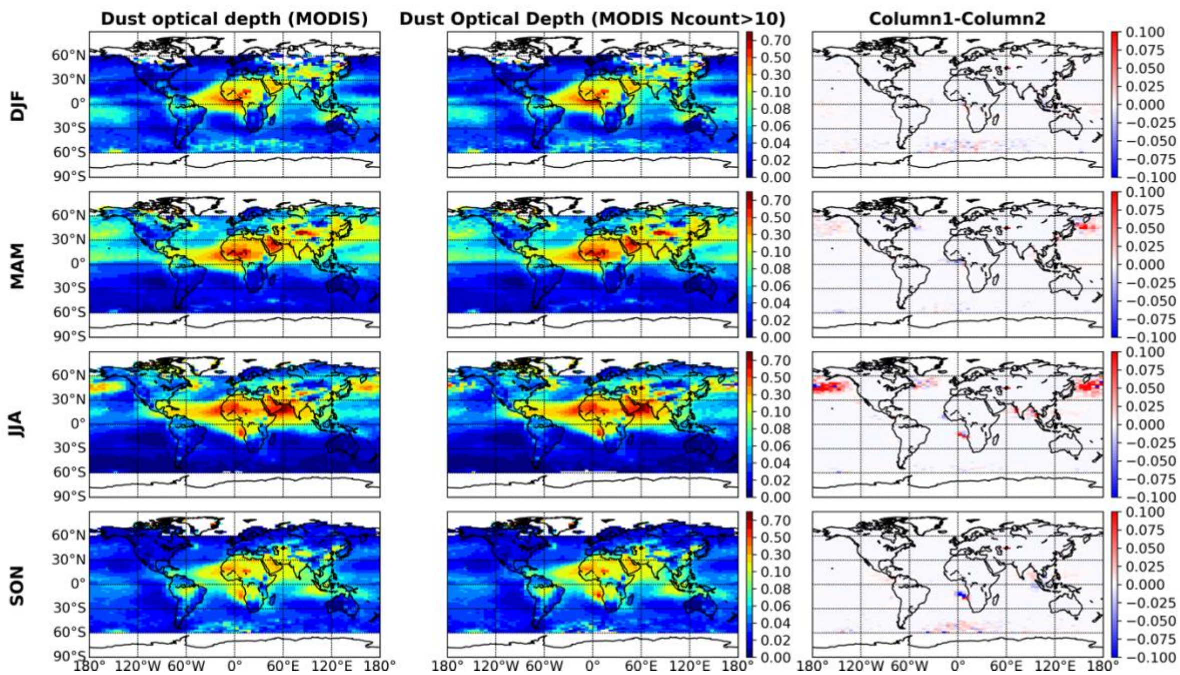

Figure 1 The first column shows seasonal mean DAOD (2007~2019) directly from MODIS retrieval. The second column shows the seasonal mean DAOD of MODIS retrievals with a minimum of 10 DAOD retrievals in a month. The third column is the difference between the first two columns.

Q5. Section 3.1 is very long and a bit difficult to read. I recommend adding sub-sections to improve readability.

Reply: Thanks for the suggestion. In the revised manuscript, we break the original Section into two sections as section 4.1 and 4.2.

Q6. Line 317-8: could you explain why the coarse size of dust contributes to the positive depolarization ratio?

Reply: We added two references at this point to explain that the linear depolarization ratio of dust particles depends on the dust particle size, one is based on theoretical studies (Gasteiger et al., 2011), the other one is based on an experimental basis (Järvinen et al., 2016).

Järvinen et al. 2016 shows that the strongest size-dependence was observed for fine-mode particles as their depolarization ratios increased almost linearly with particle median diameter from 0.03 to 0.3, whereas the coarse-mode particle depolarization values stayed rather constant with a mean linear depolarization ratio of 0.27.

Q7. Line 319-20: If DAOD over ocean is derived from TAOD and FMF, then how do you remove the AOD due to sea salt? See my comment above regarding a need for more detail on how the DAOD/AOD ratio is calculated for MODIS.

Reply: We added more details regarding MODIS DAOD retrievals over ocean and land in Section 2.2. The more detailed description could answer how to distinguish DAOD from others for over-ocean and overland retrievals (see answer for Q2 in main comments).

Q8. Is the global DAOD you report weighted by the area of each grid point? It'd be helpful to note this somewhere.

Reply: This is a great point. 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'. This description was added in the caption of Table 4.

Q9. Line 384-6: A recent paper by Huang et al. (2020) showed that Asian dust indeed gets more spherical during transport so might be good to include here.

Reply: Thanks for the suggestion. The reference paper is included.

Q10. Line 438-9: Please elaborate on how specifically the seasonal cycles of dust emission and transport are consistent with previous results.

Reply: More discussion about comparison with previous studies are added in the revised manuscript.

For example, Prospero et al. 2002 shows that dust activity peaks in May-July in North Africa and Middle East, while peaks in spring in China. These seasonal cycles are consistent with our results shown in the first row of Figure 6. Yu et al. 2015a shows that DAOD peaks in June-July-August in La Parguera, which is consistent with the seasonal cycle in CRB in this study.

Q11. Line 480-4: Here and elsewhere, the authors include some insightful explanations on how errors in cloud screening affect both CALIOP and MODIS retrievals. Are you able to quantify the difference in the AOD between CALIOP and MODIS that is due to these errors from simultaneous retrievals from both?

Reply: Thanks for the suggestion, but this is extremely difficult and beyond the scope of this study. Cloud screening process is designed and implemented by the operational algorithm teams, which is difficult for us to analyze. Moreover, our DAOD retrievals are at 2x5 degree resolution, so it is not possible to obtain "simultaneous retrievals" based on the current data. The current paper is already too long, we will leave this investigation to future study.

Q12. Line 592: should be "desert" not "dessert" :)

Reply: Thanks. The typo is corrected. :)

Q13. Line 610: what do you mean by appropriate, exactly?

Reply: Thanks for the question. This 'appropriate' could be explained by our description of MODIS DAOD retrieval in Section 2.2. For MODIS over-ocean DAOD retrieval, we have two equations Eq. (2) and (3) shown in the answer for Q2 in main comments. Based on Eq. (2) and (3), τ_d can be calculated from MODIS-retrieved τ and f, with appropriate parameterizations for f_m, f_d, f_c and τ_m. More specifically, the appropriate parameterizations here represent that f_m, f_d, f_c were determined from retrieved f in selected regions and seasons for which a specific aerosol type dominates, τ_m was parameterized as a function of wind speed (details can be found in Kaufman et al., 2005; Yu et al., 2009, 2020).

In addition, a reference was added in the revised manuscript for the parameterization values.

Q14. Line 614: here and elsewhere, could you define what you mean by "coarse mode", exactly? What particle size range does that refer to? Definitions differ for that differ in the literature.

Reply: This is a great question.

For AERONET product, the fine and coarse mode optical depths are defined optically (rather than in terms of a microphysical cutoff of the associated particle size distribution at some specific radius) and essentially depend on the fact that the coarse mode spectral variation is approximately neutral (O'Neill et al., 2003). In the paper, we mentioned that MODIS overland DAOD retrieval represents the coarse-mode fraction of dust only, the coarse mode here refers to the portion of the actual aerosol that exists at low-RH aerodynamic diameters larger than 1 µm (Anderson et al., 2005). The definition of coarse mode for AERONET and MODIS retrievals are added in the revised manuscript.

Q15. Line 615: although fine dust accounts for a small fraction of the mass, it accounts for a larger fraction of the DAOD, so this statement should be corrected.

Reply: This is a great point.

Based on the coarse-mode definition in MODIS overland retrieval (mentioned in Q14), basically MODIS overland retrieval exclude submicron dust aerosol. Then we double checked Kok et al. 2017 and corrected our statement.

This part is changed to 'The exclusion of submicron dust aerosol could induce around 3% underestimation of the global dust mass load and around 15% underestimation of the global DAOD (see Figure S1 in Kok et al. 2017).'

Q16. Line 616-8: this is helpful information. Could you be clear here what the bias is of the Aqua MODIS DAOD relative to AERONET, and what the error is? And since coarse mode includes sea salt, is this a one-to-one comparison?

Reply: Yes, the comparison with AERONET measurements is helpful information. Therefore, we added our own analysis regarding comparison between our monthly mean DAOD datasets with AERONET monthly mean coarse-mode AOD (COD) and further derived absolute expected error. 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.

Actually, comparison with AERONET COD is not one-to-one comparison because so far there is not a valid method to derive DAOD from AERONET measurements. However, over land, especially dust source regions, dust aerosols are predominantly in coarse mode, therefore, AERONET COD could be considered as a good proxy of DAOD over land. Over ocean, the exclusion of fine mode DAOD could be partially cancelled by the inclusion of coarse sea salt AOD in AERONET COD retrievals. Therefore, AERONET COD is considered as a proxy of DAOD over ocean as well.

Q17. Line 649: could you be quantitative here about the correlation? I think whether MODIS and CALIOP-based DAOD "correlate well" is subjective and I personally was surprised the correlation was not higher.

Reply: The coefficients of correlation (R values) are added in this part for each region to make this statement quantitative.

This part is changed to 'Through the comparison, we found generally CALIOP-based DAOD correlates well with MODIS-based DAOD over dust-laden regions such as Sahara (R=0.78), TAT (R=0.84), CRB (R=0.75) and ARB (R=0.85)'

Q18. Line 653: I think here k is the correlation and R^2 is the variance explained.

Reply: We change to use R instead of R^2 in the revised version. Correlation coefficient (R) is a parameter to indicate the degree of correlation between two variables. R ranges from -1 to $+1$. R= -1 means that there is a perfect negative relationship between the two variables. For every positive increase in one variable, there is a decrease of a fixed proportion in the other. R= $+1$ means that there is a perfect positive relationship between the two variables. For every positive increase in one variable, there is an increase of a fixed proportion in the other. R^2 is the coefficient of determination, which shows percentage variation in y-axis variable can be explained by the dependence of x-axis variable using the particular regression model.

We think the slope 'k' indicates how does one variable change with the other. For example, we have two variables x = [2,4,6,8,10] and y = [1,2,3,4,5]. Then we have y=0.5x. In this case, even though k = 0.5, but the two variables correlate very well with correlation coefficient R=1.

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

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