# Responds to the RC2

Dust is an important aerosol type in the atmosphere and has significant impacts on environment and climate. Satellite is a very useful tool to detect dust aerosol as it can provide dust distribution of large spatial coverage with long-term duration. A unique lidar platform (CALIOP) can further provide the vertical distribution of dust aerosol. This study provides a 13-year global dust optical depth (DAOD) climatology derived from CALIOP and MODIS observations and presents some interesting results for global dust spatial distribution and temporal variations. The authors also investigate the reasons for the recent decline of dust activities in East Asia. The results demonstrate the reliability of the two datasets the authors have developed.

However, the authors seem to mention a lot of uncertainties in the dataset and it seems there is no answer for a better DAOD. I personally would like to see more convincing quantitative comparison of these two datasets, such as which one is better and it is possible to suggest a more reliable global DAOD. I suggest the authors make more clear conclusions relative to the comparison.

**Reply:** We thank the reviewer for constructive and insightful comments. We have addressed these comments in the revision. An item-to-item reply to the reviewer's comments is provided below.

Before addressing specific comments/questions, 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.

**Major Comments:**

Q1. Section 2 and 3: I am curious about the systematic difference between CALIOP and MODIS. In my understanding, the main reasons may be in the algorithms used to generate the product and the difference may be minimized if calibrated to the same data sources. I am wondering if there is some way to minimize the difference between different dataset. The authors seem to mention a lot of uncertainty and it may be helpful to separate the contributions from these factors. First, is it possible to compare the two dataset at the same time and close location (although the sample number may be small)? Second, after doing this comparison, the difference of monthly/seasonal mean can be due to the sampling and aggregate methods. I think the authors can provide a map of observation numbers for different months/seasons and a month with more temporal coverage is more likely to have a more reliable statistical result.

**Reply:** Thanks for the question.

First, this work is to present a climatological DAOD dataset derived from CALIOP observations and its comparison with MODIS-based DAOD dataset. Due to the spatial and temporal limit of CALIOP sampling, the DAOD is initially derived as monthly mean level 3 product. Therefore, the best comparison we could do in this study is in monthly mean level.

Second, in our CALIOP DAOD retrieval, we calculated monthly mean dust extinction coefficient at each altitude for each grid and then derived column integrated monthly mean DAOD. Refer to your suggestion, we added sample numbers at each altitude for each grid in our CALIOP monthly mean DAOD dataset.

Q2. Section 2.2: the comparison of nighttime CALIOP and daytime MODIS product is made based on the consideration "Kittaka et al., 2011 shows that daytime and nighttime global seasonal-mean AOD distributions for JJA 2006 from CALIOP are generally similar in both outflow and source regions (see their Figure 1)." (Lines 242- 244). First, Kittaka's conclusions are based on the global distribution, while this present study is specifically on dust source regions and dust outflow regions. Kittaka's conclusions should not be simply applied to present study. Second, previous studies have shown significant diurnal variations of dust event frequency in dust sources regions (e. g, Figure 17 of Yue, X., H. Wang, Z. Wang, and K. Fan (2009), Simulation of dust aerosol radiative feedback using the Global Transport Model of Dust: 1. Dust cycle and validation, J. Geophys. Res., 114, D10202, doi:10.1029/2008JD010995.).

**Reply:** Thanks for the insight.

It is correct that Kittaka's result may not be simply applied to this study, which mainly focuses on dust source and outflow regions.

To justify our comparison between CALIOP nighttime DAOD with MODIS daytime DAOD.

First, 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.

Second, Xu et al. 2009 (denoted as Xu2009) indeed shows that dust mobilization is more active during the local daytime than nighttime. However, more frequent dust uplift does not mean higher DAOD in the atmosphere. DAOD also depends on dust dry/wet deposition. Figure 16 (a) in

Xu2009 shows diurnal variation of global mean dust uplift, dry/wet deposition and dust burden. They conclude that dust burden shows the least variation with a standard deviation of only 1% of its mean value. Although they did not discuss DAOD diurnal variation in the paper, we assume that DAOD has similar magnitude of variation.

Third, using the CALIOP daytime DAOD dataset would not change the conclusion of this study: that is CALIOP DAOD is systematically lower 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 high-quality nighttime CALIOP DAOD dataset in our analysis.

Line 647, in Summary and Conclusions: it seems the trends and interannual variability of DAOD are similar. I don’t see the advantages and limitations clearly for each dataset. Please clarify.

**Reply:** Thanks for the question.

CALIOP and MODIS DAOD are systematically different. In most dust laden regions, CALIOP DAOD is statistically smaller than MODIS (Figure 5 in the paper). Even though the DAOD magnitude from two retrievals are very different as discussed in the previous sections, both CALIOP and MODIS show similar DAOD interannual variability and trends. Therefore, the interannual trend of DAOD is trustworthy since both retrievals show very similar trends.

**Specific comments:**

Q1. Line 21, abstract: add "(2007-2019)" after "the last two decades".

**Reply:** Done

Q2. Line 27, abstract: delete "and".

**Reply:** Done

Q3. Line 127: Self-consistent: Please briefly explain the word here, and not wait until Section 2.

**Reply:** The following sentence in the manuscript is a brief explanation of self-consistent by citing Yu et al. 2009 as an example.

For example, in MOIDS over-ocean DAOD retrieval, both AOD ($\tau$) and fine-mode AOD ($f\tau$) are assumed to be composed of marine aerosol, dust and combustion aerosols, i.e.,

$$\tau = \tau_m + \tau_d + \tau_c \ , \quad (2)$$

$$f\tau = f_m\tau_m + f_d\tau_d + f_c\tau_c \ , \quad (3)$$

Where the subscripts m, d, and c represent marine aerosol, dust and combustion aerosol, respectively. 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 $\tau_m$.In this study, $f_m, f_d, f_c$ were determined from MODIS 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). In this case, the self-consistent means that the selection of $f_m, f_d, f_c$ are also from MODIS retrieval rather than from other sources such as AERONET. The self-consistent use of MODIS data could minimize the introduction of additional biases due to discrepancies in FMF between MODIS and AERONET.

Q4. Lines 131-132: is it any critical difference for dust between these version and previous version? This is important, as it may indicate the results shown in this study may be different from previous versions because of version updates.

**Reply:** There are numerous updates from V3 to V4 for CALIOP retrievals and similarly from V5 to V6 for MODIS retrievals, including instrument calibration updates, algorithm adjustments and modifications of QA flags. It is impossible and beyond the scope of this study to keep track of all these changes and investigate the impacts on DAOD retrievals. In this study, we use the latest versions of CALIOP and MODIS retrievals and report the corresponding DAOD results. Interested readers can compare our results and previous studies based on earlier versions of retrievals. The differences can be investigated, if significant, in future studies.

Q5. Line 155: please provide some supporting information for "70% agreement".

**Reply:** The '70% agreement' is also supported by the reference paper in the following sentence. Therefore, we combine the two sentences in the revised version as 'The comparison between aerosol subtypes in CALIOP level 2 V2.01 and NASA Aerosol Robotic Network (AERONET) aerosol types shows that 70% of the CALIOP and AERONET aerosol types are in agreement and best agreement is achieved for dust and polluted dust (Mielonen et al., 2009).'

Q6. Lines 162-163: if 40 sr is too low, is it possible to increase this value and update the product? What is the lidar ratio?

**Reply:** In CALIOP Version 4 product, the greater lidar ratio of 44sr is used for dust aerosols. We cannot update the product with a use of the new lidar ratio because the CALIOP retrieval uses the lidar ratio to first correct light attenuation and then convert the attenuation-corrected backscatter to the extinction. Extinction does not have a linear relationship with lidar ratio. Lidar ratio is defined as Extinction-to-backscatter ratio. This explanation of lidar ratio is added in the revised manuscript.

Q7. Line 174: I don't understand "or" here. Please clarify.

**Reply:** Sorry for the confusion. It means that some of these studies consider 'dust' subtype as dust; others consider both 'dust' and 'polluted dust' subtypes as dust.

Q8. Sections 2.1 and 2.2: is it possible to make a table and put the comparison of key features of CALIOP and MODIS in it?

**Reply:** Section 2.1 and 2.2 describe CALIOP and MODIS dust retrieval methods, respectively. We added more detailed information for MODIS dust retrieval over ocean and land. Table 1 in the manuscript is the summary of key features of the two DAOD retrievals (see below).

Table 1. Summary of DAOD retrievals from MODIS and CALIOP

| **Sensors** | **Retrieve Scope** | **Relevant variables used to derive DAOD** | **References** |
|---|---|---|---|
| MODIS | Ocean | AOD, fine-mode AOD | Yu et al. (2009, 2020) |
| MODIS | Land | AOD, SSA at 470nm, Angstrom exponent | Pu and Ginoux et al. (2018) |
| CALIOP | Globe | Profiles of backscatter, extinction, depolarization ratio | Yu et al. (2015a) |

Q9. Line 242: Kittaka et al. (2011) also analyze the AOD including all aerosol types. I am wondering whether their conclusions applied to specific dust source regions and dust- effect regions.

**Reply:** Exactly, Kittaka et al. 2011 analyze the AOD including all aerosol types. In the revised manuscript, 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 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. The bottom line is that CALIOP daytime and nighttime difference may not be physical.

Q10. Line 248: "in hoping that": this statement may be misleading. I think the key point is that observations do shows some significant diurnal of dust events in the source regions mainly because of the wind speed difference. Please clarify.

**Reply:** Thanks for the insight.

As discussed in our reply to the Q2 in the major comments. Xu et al. 2009 (denoted as Xu2009) shows that dust mobilization is more active during the local daytime than nighttime. However, more frequent dust uplift does not mean higher DAOD in the atmosphere. DAOD also depends on dust dry/wet deposition. Figure 16 (a) in Xu2009 shows diurnal variation of global mean dust uplift, dry/wet deposition and dust burden. They conclude that dust burden shows the least variation with a standard deviation of only 1% of its mean value. We believe that DAOD would have a variation similar to dust burden.

For some DAOD diurnal variation studies based on CATS observations, there is a significant difference between daytime and nighttime CATS AOD quality, because CATS daytime observation has a higher lidar calibration uncertainty at 1064nm and is subject to solar contamination. To account for this day-night inconsistency in CATS AOD quality, the diurnal variability is examined separately for daytime and nighttime periods. Therefore, the true daytime-nighttime DAOD difference is still not fully understood.

To justify our comparison between CALIOP nighttime DAOD with MODIS daytime DAOD. 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.

Q11. Line 268: I am wondering whether this new data includes all the algorithms mentioned in previous paragraph.

**Reply:** Yes, the three retrieval methods (global CALIOP, MODIS over ocean and MODIS over Land) introduced in section 2 are all used in this study.

Q12. Line 272: how about the sampling over land? Is there a minimum number required for deriving monthly statistics?

**Reply:** Thanks for the question. For MODIS overland retrieval, there is no minimum of the number of samples to derive monthly values.

Q13. Lines 279-280: is there any measure to keep the ocean and land product consistent with each other?

**Reply:** For MODIS, the observations are consistent over ocean and over land. However, different aerosol retrieval algorithms are used for over ocean (Dark Target) and over land (Deep Blue) due to their different surface characteristics. Therefore, MODIS-based DAOD retrieval methods, which make use of parameters retrieved from MODIS aerosol retrievals, are also different for over ocean and over land (see details in section 2).

For CALIOP, we use a consistent algorithm to retrieve DAOD over land and ocean.

Q14. Section 3.1: this section is too long. Consider adding subtitle or dividing it into two sections.

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

Q15. Lines 313-314: I don't think it is because of more frequent miss but it is an expected result of using a threshold to detect dust.

**Reply:** Thanks for the comment. We corrected our statement here. We deleted the statement of more frequent miss of dust by CALIOP.

This part is to discuss DAOD in regions that are known to be dusty in certain seasons, such as southwestern United States, South America (Patagonian Desert), Australia, and South Africa. In those regions, CALIOP-based climatological DAOD is rather low.

The low DAOD based on CALIOP in these regions could be the results of two factors. One is that the low aerosol detected by CALIOP (this could be indicated by TAOD comparison between CALIOP and MODIS in Figure 7), the other one is the different algorithm used for CALIOP and MODIS to distinguish dust aerosol from other types of aerosol. We found that 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 means that in those regions both sensor-specific 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.

Q16. Line 368: I don't think this can suggest dust activities occur relatively small scales. Since a threshold is applied in conditionally DAOD, it is easily to understand conditionally DAOD have much higher values than climatological DAOD.

**Reply:** Thanks for the insight.

In this study, climatological DAOD includes all cloud-free cases in the average of dust extinction and DAOD regardless of the presence of dust, while conditional DAOD is calculated by only averaging those cases where dust is detected (i.e., DAOD and dust extinction are non-zero).

The comparison of climatological and conditional DAOD could provide useful information on the intensity and frequency of dust events. For example, if we consider an extreme case in which dust aerosol is persistently lofted in the atmosphere. Then climatological DAOD would be the same as conditional DAOD in this case, because dust aerosol is always present in the satellite observations. Whereas, if dust events occur quite infrequently then the conditional DAOD would be much larger than climatological DAOD.

Therefore, in regions with a large difference between climatological and conditional DAOD (3$^{rd}$ column in Figure 6), dust activities are highly episodic or occur in relatively small scales, so that there are many cloud-free dust-free cases detected by CALIOP.

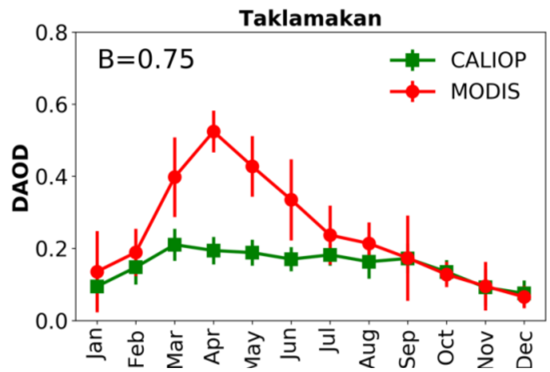
Q17. Line 401: I can't see this "exception". Please check.

**Reply:** Thanks for the comment. In Figure 7 in the revised manuscript, cloud fraction during the winter (DJF) in the Northwest of Pacific Ocean region in the 1$^{st}$ row and 4$^{th}$ column is greater than 0.9. In this circumstance, we expect that MODIS DAOD is larger than CALIOP DAOD. The 1$^{st}$ row and 2$^{nd}$ column shows that MODIS DAOD is similar or even smaller than CALIOP DAOD. This is an exception.

Q18. Lines 446-448: this can explain the secondary peak of DAOD in summer for MODIS, but it can't explain the difference of two datasets. Please clarify.

**Reply:** This is a great point. Thanks.

We further analyze DAOD interannual variability over Taklamakan Desert to check if the statement here is reasonable. The figure below shows that MODIS DAOD in Taklamakan Desert peaks in middle spring (April) and decreases in summer. Therefore, MODIS doesn't capture the secondary maximum dust activity over Taklamakan, the high DAOD over NWP retrieved from MODIS observations in summer therefore is mainly attributed to cloud contamination.




Q19. Line 480-495: it seems the authors suggest a true DAOD should fall between CALIOP and MODIS. If so, please explicitly state this in the text.
**Reply:** Yes, thanks for the suggestion. In Section 3 of the revised manuscript, after comparing our DAOD with AERONET COD, we conclude that it is highly probable that the true DAOD falls between MODIS and CALIOP DAOD.

Q20. Line 523-524: broad East Asian region (ESA defined in Figure 4): I can't find ESA in Figure 4. Please clarify.
**Reply:** Thanks. The typo was corrected.

Q21. Line 531: change "DOAD" to "DAOD".
**Reply:** Done. Thanks

Q22. Line 535: I don't think it is "much weaker".
**Reply:** Yes, we change 'much weaker' to 'weaker'. We think the correlation of DAOD is weaker for MODIS because on one hand correlation coefficient is smaller for MODIS (R=0.53) than CALIOP (R=0.6), on the other hand P-value for MODIS (p=0.07) is higher than the threshold 0.05, which means the trend is not statistically significant.
In the revised manuscript, we changed the sentence as 'In spring, the correlation of DAOD from two regions is good based on CALIOP ($R = 0.6$ , $p = 0.03$), while a weaker correlation ($R = 0.53, p = 0.07$) was found based on MODIS.'

Q23. Line 538: please explain a little bit why EVI, MERRA2 near surface (at 10m) wind speed and precipitation are reliable for this analysis. Probably cite some references which have already demonstrated this.
**Reply:** Here we cited three papers (Qian et al. 2002, Kurosaki & Mikami, 2003, Lee & Sohn, 2011) to indicate the dependence of dust events on precipitation, surface wind speed and vegetation, respectively.

Q24. Line 541: add “p>0.05” after “precipitation”, as the determination of significance depends on the level of significance. I guess here you are using p=0.05 as a threshold.

**Reply:** (p>0.05) was added. Thanks.

Q25. Line 601: please expand DPR.

**Reply:** DPR (Depolarization ratio) was added in the revised manuscript.

Q26. Line 603: I am wondering how the uncertainty is defined. Please add a definition.

**Reply:**

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%.

The DAOD uncertainty induced from DPR is updated in the revised manuscript. The DAOD uncertainty map and uncertainty definition are added in the supplement as Figure S6.

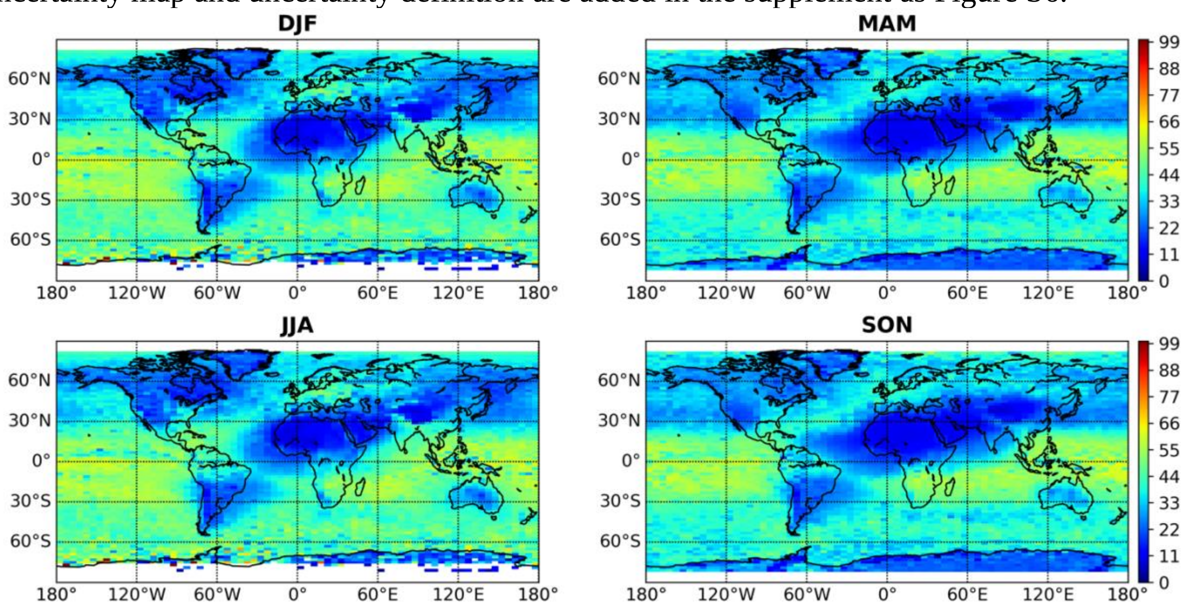



Figure S6. 2007~2019 Seasonal mean DAOD uncertainties induced by DPR assumptions. For each season in each grid, DAOD uncertainty is defined as $\frac{(DAOD^{high}-DAOD^{low})/2}{DAOD^{mean}}$%, where $DAOD^{high}$ is derived from high dust scenario with $\delta_d = 0.20$ and $\delta_{nd} = 0.02$, $DAOD^{low}$ is derived from low dust scenario with $\delta_d = 0.30$ and $\delta_{nd} = 0.07$, $DAOD^{mean}$ is the average of the two scenarios.

Q27. Line 618: is it also applied to this study? If so, I am wondering whether a true DAOD is even higher than MODIS DAOD. Please clarify.

Reply: We realized that this is not applied to this study. Our study is focusing on monthly mean climatological DAOD. Therefore, we did our own analysis to compare our monthly mean DAOD with AERONET monthly mean coarse mode AOD (COD).

First, 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. We suggest that the true DAOD are highly probable to 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 $0.65 \times DAOD_M + 0$ 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 part of analysis is added in Section 3.2 in the revised manuscript.

Q28. Line 640: it is possible that CALIOP misses some dust events. But this study is based on long-term statistics and the impacts should be eliminated if the observation number are substantial large. Do the authors suggest the impacts are not negligible in this study?

**Reply:** This is a great point. Thanks for pointing this out.
In the revised manuscript, we removed this statement.

Q29. Line 664: add "during 2007-2019" after "DAOD".

**Reply:** Done. Thanks

Q30. Line 780: avoid using "decadal trend" here as there are only 13 years indeed.

**Reply:** 'decadal trend' was changed to 'interannual trend'. Thanks.

Q31. Line 782: the symbol "+" can't be clearly seem.

**Reply:** The figure was updated with a larger '+'sign.

Q32. Line 805: it is also helpful to put together the time series of EVI vs DAOD, wind vs DAOD, precipitation vs DAOD with the year for x-axis. This can be put in the supplement for references.

**Reply:** The time series figure was added in supplement (Figure S10).

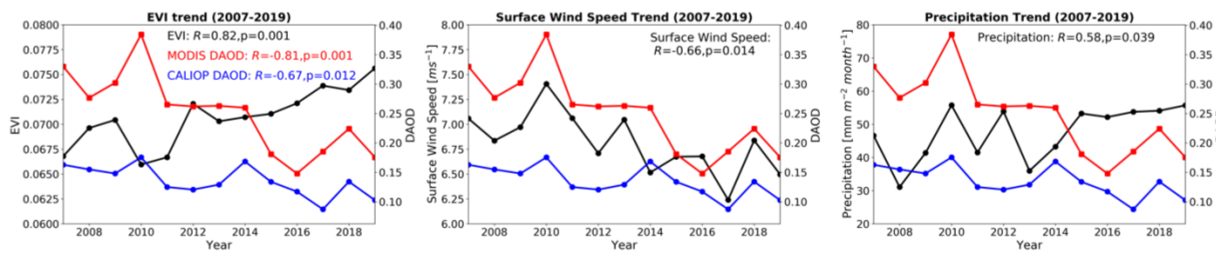



**Figure S10.** Inter-spring series of EVI, surface wind speed and precipitation along with inter-spring series of DAOD from MODIS (red curves) and CALIOP (blue curves). R is Pearson's linear correlation coefficient between each variables and time series. Positive R indicates the variable increase with time, and vice versa.

Q33. Lines 935-938: a duplicated reference.

**Reply:** Corrected. Thanks!

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