Responses to Reviewer #1 Comments and Suggestions

Start review of acp-2021-418

Title: 15-year variability of desert dust optical depth on global and regional scales.

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We would like to thank the Reviewer for the comments and suggestions that give us the opportunity to revise and improve the quality of our manuscript. According to these, the submitted manuscript has been modified and updated appropriately. The changes are displayed in the marked copy.

General Comments:

The authors have analyzed dust optical depth (DOD) trends from the MIDAS dataset for all major global dust source regions in some detail in this paper. I think that this paper makes a useful contribution to the literature and provides a generally comprehensive global view of trends in dust optical depth. However, I have a few issues with the manuscript that the authors should explore in order to make the analysis more convincing and also easier to read and comprehend.

First, how are we to gauge the reliability of the DOD trends without showing some verification versus AERONET sites for example? For example the Gkikas et al. (2021) paper on this dataset shows significant regional biases in DOD for MIDAS versus several AERONET sites in their Figure 4d. You should include at least two trend analyses from AERONET data to compare with your MIDAS inferred trends of DOD. The SDA retrieval from AERONET (O'Neill et al, 2001, 2003) separates the AOD into fine and coarse modes and trends of coarse mode AOD from AERONET could be compared to the MIDAS trends of DOD.

Thank you for this valuable comment. Following your suggestion, we have added in the revised manuscript an evaluation analysis for MIDAS and AERONET DOD trends and also some information about AERONET. For the calculation of AERONET DOD trends, the coarse mode AOD from AERONET SDA is used.

2.2 AERONET

On a regional basis, the reliability of MIDAS DOD trends has been evaluated using ground-based measurements from AERONET (Holben et al., 1998). AERONET provides information for the spectral columnar AOD using direct spectral solar irradiance. In addition, *the physical and optical properties of aerosols can be derived by applying the Dubovik and King (2000) inversion algorithm. DOD ground-based measurements can be approached using AERONET retrievals, however, an aerosol classification scheme is mandatory. Through MIDAS evaluation procedure, the discrimination of dust load from non-dust aerosol species has been performed in terms of the Ångström wavelength exponent at 440-870 nm ($AE_{440\text{-}870\ nm}$) and the difference between single scattering albedo at 440 nm ($SSA_{440\ nm}$) and 675 nm ($SSA_{675\ nm}$). $AE_{440\text{-}870\ nm}$ has been used as an indicator of particles size (coarse or fine aerosols) in numerous aerosol classification studies (Basart et al., 2009; Mielonen et al., 2009; Lee et al., 2010; Giles et al., 2012; Hamill et al., 2016; Zheng et al., 2017; Che et al., 2018; Logothetis et al., 2020). In addition, the aerosols origin can be acquired using either the difference between SSA at different wavelengths or specific spectral SSA thresholds. In Gkikas et al. (2021a), the pure dust conditions have been succeeded using a very restricted threshold limit of $AE_{440\text{-}870}$ nm (≤ 0.75) along with a positive difference of $SSA_{675\ nm} - SSA_{440\ nm}$. Despite the favorable dust conditions retrieved through the SSA retrievals, the data availability strongly decreases causing difficulties in trend calculations. In the current study, the evaluation of MIDAS DOD trends is performed by using the AERONET coarse mode AOD at 500 nm, derived from the spectral deconvolution algorithm (SDA) (O'Neill et al., 2001, 2003). The performance of the SDA algorithm, in terms of segregating the fine and coarse aerosol modes, has been justified against ground-based observations (Kaku et al., 2014). Only quality assured data (cloud-screened), including pre-field and post-field calibrations (Level 2.0, L2) from AERONET Version 3 (V3) (Giles et al., 2019) are used. It should be mentioned that cAOD does not represent profoundly the dust load due to the presence of sea-salt particles."*

"3.1.3 Evaluation of MIDAS trends vs. AERONET

The validity of the computed MIDAS DOD trends is thoroughly analyzed in this section. For evaluation purposes, the coarse mode AOD, hereafter referred as cAOD, retrieved through the AERONET SDA algorithm is applied. The two datasets are collocated by spatially averaging MIDAS DODs included in an area of 3x3 pixels around each AERONET site, and also temporally combined using solely the same daily values. DOD and cAOD trends are calculated using the methodology described in Sect. 2.3. Figure 4a illustrates the geographical distribution of the AERONET stations (in total 41) satisfying the defined temporal criteria (see Sect. 2.3) and finally used in the assessment analysis. According to Fig. 4b, a good linear correlation ($R = 0.86$) of the derived trends is observed accompanied with low bias ($MBE = -0.04x10^{-2}$). In order quantify the performance of MIDAS in capturing the cAOD trends, the total accuracy (TA) of the correct trends (identical sign) is calculated. More specifically, TA is defined as the percentage of the stations with correct trends sign (the sum of B1 and A2 quadrants numbers in Fig. 4c divided by the total number of stations). MIDAS trends can capture the correct cAOD trends signs with a TA of 80.5% (Fig. 4c). In addition, the percentages of each quadrant in Fig. 4c shows the number of the correctly detected stations per sign. The overwhelming majority of the AERONET stations encompassed negative trends (30 out of 41 stations). MIDAS trends capture the 26 out of those 30 (86.7%) stations denoted with negative cAOD trends. Lastly, there are only 11 sites with positive cAOD trends, and MIDAS proved able to detect them at 7 out of 11 (63.6%) stations.

Table S1 provides the point-to-point trend results for each collocated MIDAS-AERONET sites. It should be mentioned that among the revealed stations, few indicate dust particles as the predominant aerosol type. Based on Logothetis et al. (2020), the station of Solar Village, Arabian Peninsula, is primarily a "dusty" site revealing significantly high percentages of coarse absorbing particles. Across this station, the trends between AERONET cAOD (0.0126 yr^{-1}) and MIDAS DOD (0.0107 yr^{-1}) are in good agreement in terms of magnitude, but both are non-significant at the 95% confidence level. Similar findings are also observed in the "dusty" site of Tamanrasset, Algeria, showing increasing cAOD and DOD trends of 0.0062 yr^{-1} and 0.0044 yr^{-1}, respectively. One of the advantages of MIDAS is that it provides the dust aerosols burden information in downwind regions of the planet. For instance, most of the stations located in South Europe receive dust particles transported towards the Mediterranean from Sahara and Middle East deserts, encompassing identical trend signs (Fig. 4a). Moreover, there are many downwind regions across different regions of the globe with similar trends magnitude such as Ispra, Italy (cAOD= −0.0013 yr^{-1}, DOD= −0.0015 yr^{-1}), Kanpur, India (cAOD= −0.0027 yr^{-1}, DOD= −0.0029 yr^{-1}), SERC (cAOD= −0.0023 yr^{-1}, DOD= −0.0020 yr^{-1}) in US, Shirahama, Japan (cAOD= −0.0020 yr^{-1}, DOD= −0.0012 yr^{-1}), and XiangHe, China (cAOD= −0.0028 yr^{-1}, DOD= −0.0018 yr^{-1}).

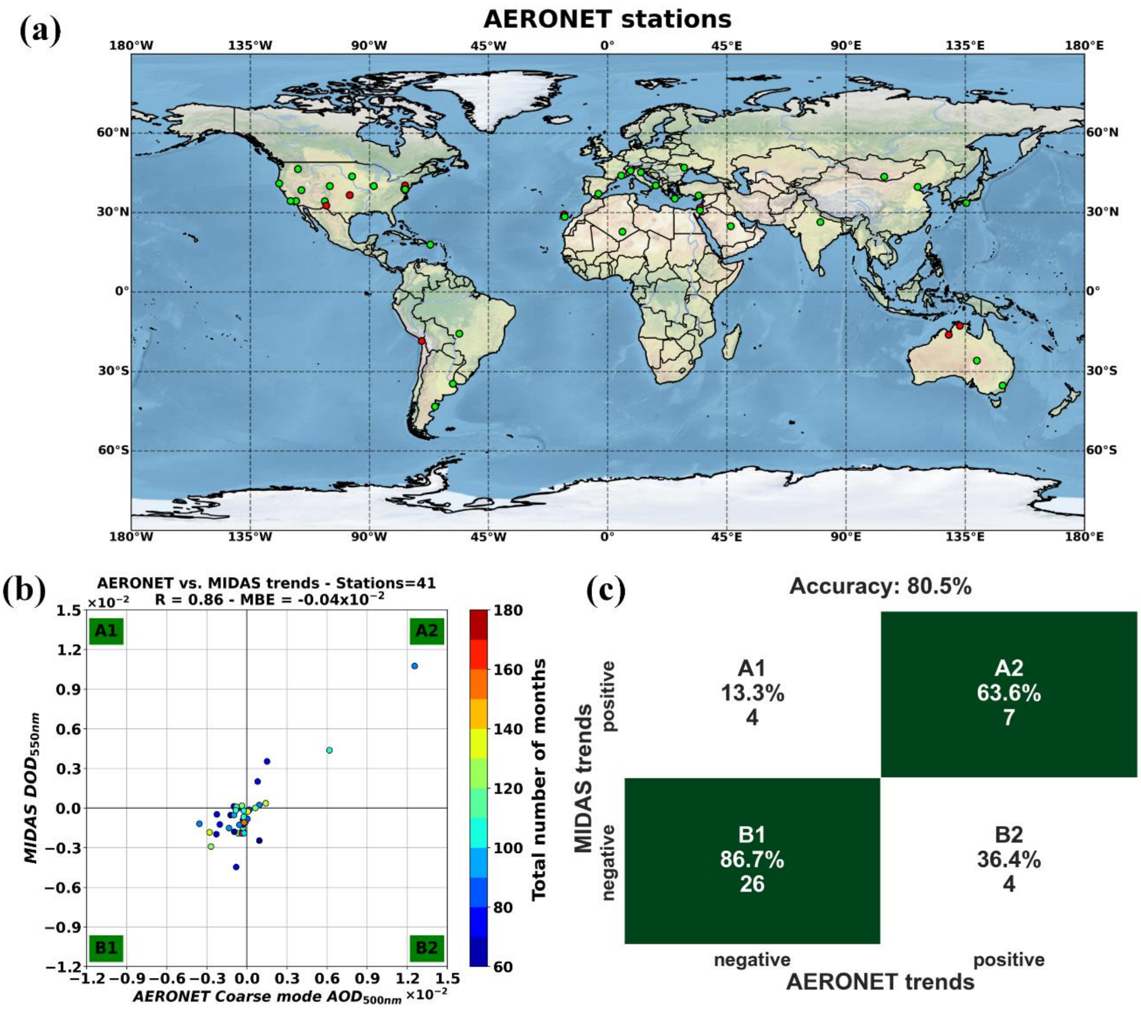

Figure 4: (a) Geographical location of the available AERONET stations in which the temporal trends of DOD and cAOD are calculated. Green and red dots refer the stations with the similar and different trend sign, respectively. (b) Scatter plot between MIDAS DOD and AERONET cAOD trends. The color bar indicates the total number of months. (c) Confusion matrix of possible trend signs among the two datasets."

Second, throughout the manuscript I found it difficult and confusing to have to look at the supplemental document file in order to confirm principal conclusions made in the primary manuscript. The way this paper is currently written it requires quite frequent switching between reading the 2 document files in order to understand the author's arguments. I strongly urge the authors to move some/many of the figures that are in the supplemental section into the main paper.

Following the reviewer's comment, we have moved many figures from the supplementary material to the revised manuscript. In addition, we have transferred the Table S1 to the revised manuscript (revised Table 2). We are strongly dedicated that the revised manuscript provides all the important information to the reader, including 18 Figures and 3 Tables. We have retained only the additional information in the supplementary file.

Third: The very localized (relatively small area) of the large negative trends in DOD shown for the Bodele Depression (Figure 9) suggest the possibility of a surface reflectance artifact in the satellite retrievals and therefore possibly a trend in surface reflectance and not of dust concentrations. Since this is the largest single dust source on the planet then why is the strong negative trend in DOD over such a small area? It is well known that the dust plumes from the Bodele are advected by winds over very long distances. You need to explain in the text why the strong decrease in DOD is so limited to the very site of this dust source itself.

Thank you for your comment. Similar trend patterns have been also shown in other studies using various aerosol satellite products such as MODIS/Terra (Che et al. (2019) – period: 2001-2016; Voss and Evan (2020) – period: 2001-2018; Gui et al. (2021) – period: 2007-2019), MODIS/Aqua (Voss and Evan (2020) – period: 2003-2018), MISR (Che et al. (2019) – period: 2001-2016), SeaWiFS (Hsu et al. 2012 – period: 1998-2010; Pozzer et al. (2015) – period: 2001-2010) and reanalysis datasets like MERRA-2 (Che et al. (2019) – period: 2001-2016).

Recently, Shi et al. (2021) investigated the seasonal changes of dust emissions across this region. Based on their study, over the period 2001-2012, dust emissions in the broader area of the Bodélé Depression were decreased in summertime, which was attributed to the increased rainfall, caused by the positive trends of the Sahara heat lows (SHL), the warm phase of Atlantic Multi-decadal Oscillation (AMO) and the decreasing trends in terms of occurrence and intensity of nocturnal low-level jets' (NLLJ).

Briefly speaking, those patterns in this small area are mainly explained by the relevant meteorological conditions instead of the surface reflectance changes that could influence the reliability of the MODIS AOD retrievals, thus resulting in suspicious tendencies. Although the investigation of relationship between DOD and meteorological factors is beyond the scope of this paper, and it will be a part of future study, we will discuss some preliminary results here.

In order to better understand the reasons for the decreasing DOD trends across Bodélé Depression, we investigated the correlation between the monthly MIDAS DODs and two meteorological variables, such as the wind speed (WS) at 10 m and the accumulated precipitation (STP) along with the volumetric soil water (Layer: 0-7 cm) (VSM), using the ERA5 reanalysis dataset at 0.1° x 0.1° spatial resolution. Figure R1 displays trend analysis of the aforementioned parameters over the area of Bodélé Depression. The solid black box depicted in Fig. R1a refers to the area that is presented in Fig. 13. Based on Fig. R1a, except of the small area where strong negative trends are documented, there are also many scattered pixels of negative trends in the surrounding area (16 – 19°N - 15 – 20°E). According to Figs. R1b-d, it is evident that DOD values are related to temporal variability of applied parameters. Through time, dust amounts are strongly related to meteorology as well as geophysical factors. For instance, the increase of STP and VSM levels increases the wet dust deposition and decreases the dust erosion, causing the reduction of dust load. On the other hand, the increase of WS acting in favor of dust erosion thus increasing the dust amount.

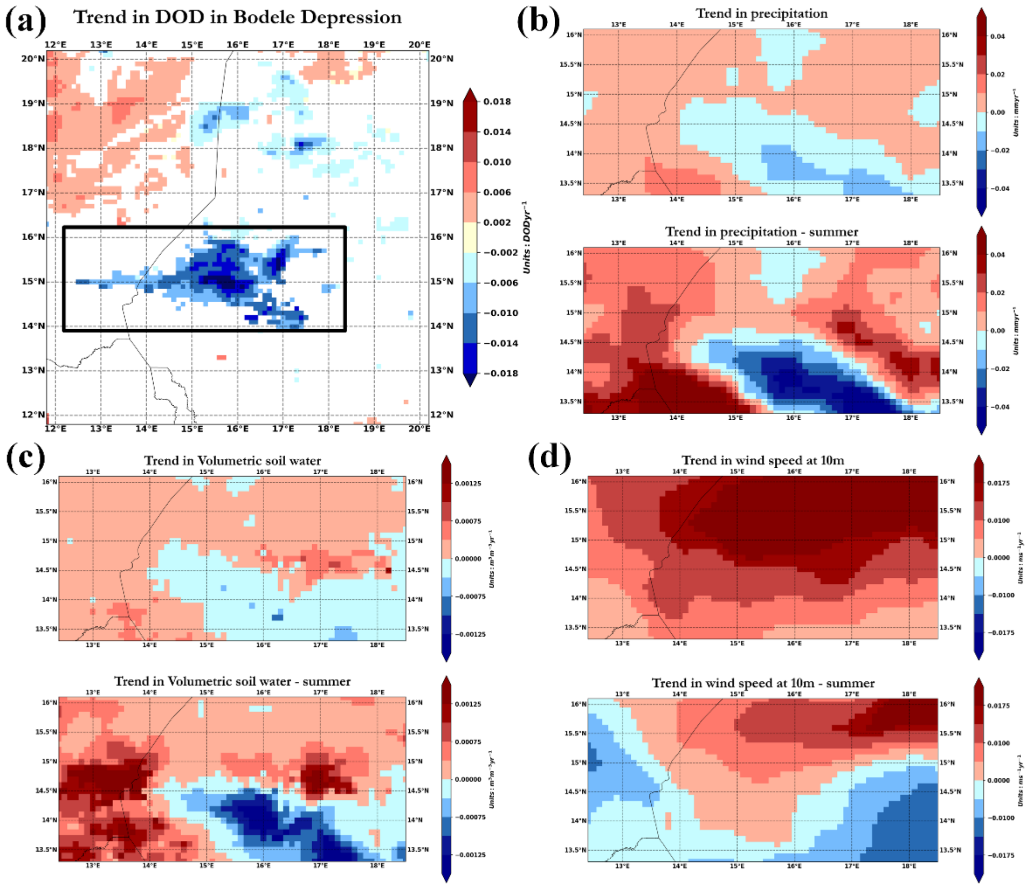

Figure R1: Geographical distribution of long-term (a) DOD trends, and long-term along with summertime trends of (b) total precipitation, (c) volumetric soil water and (d) wind speed at 10m across Bodélé Depression.

Across this region, increasing STP and VSM trends are documented, showing that the reduction of DOD levels is strongly related to the increase of STP and VSM. It should be mentioned that across this area the levels of WS and VSM provide a seasonal pattern, recording relatively low levels through the seasons of the year. During summer, the Intertropical Convergence Zone (ITCZ) location moves to higher latitudes and rapidly affects the amounts of WS and VSM across Bodélé Depression. The revealed summertime STP and SVM trends are higher in terms of magnitude. In addition, positive trends have also been documented for WS. Generally, the increase of WS acting in favor of dust erosion thus increasing the dust amount. However, the level of increased WS may not lead to changes of dust amount across Bodélé, due to small WS changes.

To our knowledge, there is not observed changes of the surface reflectance that could influence the true level of MODIS AOD and providing suspicious tendencies, like those of Klingmüller et al. 2016 study in the area of Aral Sea, where the substantial trends in terms of magnitude are revealed and proved to be related to the land cover changes caused by the drying of the Aral Sea. In a future work, the role of meteorological variables on the configuration of MIDAS DOD trends will be performed as well as the investigation of potential changes in underlying surface conditions that could influence the calculated AOD/DOD trend calculations. Nevertheless, we decided to demonstrate to the Reviewer a part of our preliminarily results across the Bodélé Depression.

Also the white areas around the blue negative trends are assumed to be near zero in Figure 9, although the color bar at the bottom shows yellow color for near zero trends, not white. Can you explain the discrepancy in the color bar and the map.

Thank you for the comment. The following lines are included in the caption of the revised Figure 2 to explain more explicitly the color bar.

"The pixels with: 1) non-significant trends, 2) the temporal criteria are not met and 3) not available data are colored as white (blank) in each map of trend analysis. Neutral trends, ranging between −0.002 and 0.002 DOD yr^{-1}*, are colored with light yellow (or cream) (the central color of the color bar). Figs S3a, S3b and S4 present the differences between the aforementioned colors at fine, coarse spatial resolution as well as for the seasonal trends, respectively. Based on those Figs, the pixels with not available data are colored with gray color while those of failing to meet the availability criteria are colored with greenish."*

Detailed comments:

1. **Lines 141-142: Some quantification is needed here rather than calling the MIDAS dataset 'trustworthy' and rather than just saying '…a quite high level of agreement' exists with other datasets.**

After following the reviewer's suggestion, we think that the revised manuscript contains sufficient information providing also some evaluation metrics.

2. **Lines 206-207: It seems that this sensitivity analysis is important. Therefore I think the authors need to include some discussion and figures in this paper in order to support their conclusions.**

Thank you for the comment. A specific paragraph (Section 3.1.1) has been added in the revised manuscript to describe the reasons of using the geometric mean instead of arithmetic mean.

"*The overwhelming majority of the published AOD/DOD trend analysis studies have been relied on arithmetic mean in order to produce coarser spatial (e.g. 1° x 1°) and temporal (e.g. monthly values) resolutions. In this study, a sensitivity analysis on the aggregation method (i.e. arithmetic vs geometric mean), has been performed by utilizing the daily coarse spatial resolution (1° x 1°) MIDAS DODs. Figure 1 depicts the frequency histogram of MIDAS DODs in log scale using all the available data over the period 2003–2017. It is apparent that the shape of the DOD distribution is close to a log-normal distribution (Fig. 1). The latter considers the extreme dust episodes which force the distribution curve to be right-skewed. Arithmetic mean is about 4 times higher than the geometric mean, highlighting the importance of which* *metric is more representative of the population and how this can affect the results for specific applications (e.g. radiative forcing). When geometric standard deviation is considered, 65.43% of DOD values range between 0.002 and 0.027 while 81.04% encompassed within –0.033 and 0.099 for arithmetic mean, indicating an overstating of the variability (Sayer and Knobelspiesse, 2019). The averages and the standard deviations are calculated using weighted aggregation exrpessions with the weighting factors in terms of latitude (see Sect. 2.3). An additional point, revealing that the selection of normal statistics can lead to a misrepresentation of the population for a positive-definite quantity (i.e. dust optical depth), is that the lower bound (−0.033) is negative, which has not any physical meaning.*

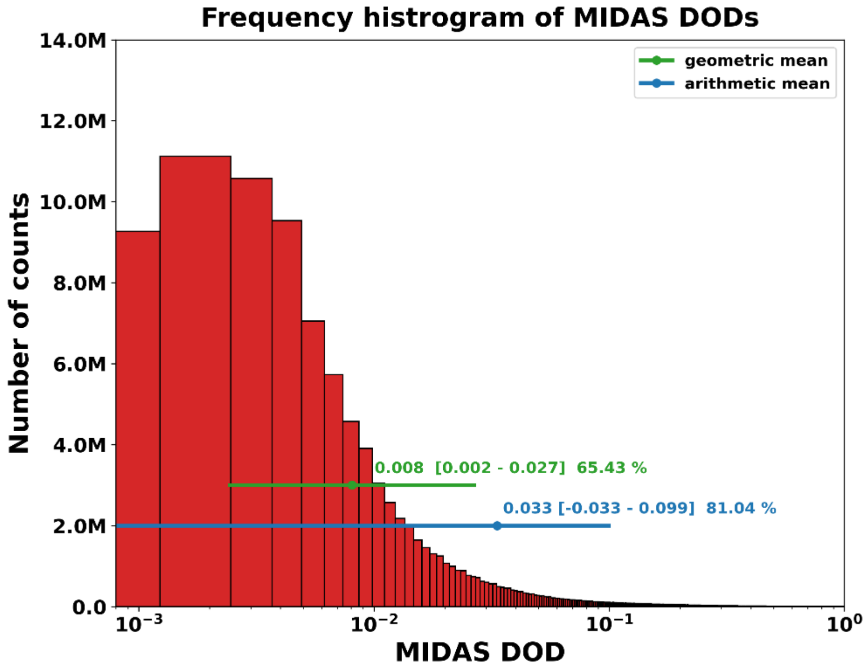

Figure 1. Frequency histogram of MIDAS DODs reported at 1° x 1° spatial resolution over the period 2003 – 2017. The computed geometric mean (green) and arithmetic mean (blue) are given along with ranges corresponding to geometric mean/geometric standard deviation and geometric mean*geometric standard deviation for the geometric mean and ± standard deviation for the arithmetic mean.

In agreement with Sayer and Knobelspiesse (2019), the calculated trends for AOD and DOD are consistent in terms of sign between fine (Fig. 2) and coarse (Fig. 3) spatial resolution data. However, in terms of magnitude this is not the case. Figure S1, S2 depicts the frequency histograms of the deviations between the arithmetic and geometric trends. When geometric AOD/DOD averages are considered, the deseasonalized trends are suppressed by up to 91.77% with the respect to the corresponding levels obtained from the arithmetic means, regardless the underlying surface type. The only exception is found for AOD at 1° spatial resolution and across oceanic territories (Fig. S2c) where geometric trends overestimate those of arithmetic by 71.63%.”

3. **Lines 210-213: This is not obvious in Fig 1 below. As a reader it is difficult to have to look at a different supplemental document in order to confirm conclusions made in the primary manuscript.**

Following your comment, we have decreased the bonding between the manuscript and the supplement material by decreasing the total number of supplement figures.

4. **Line 221: Please define the blank or white areas on the Fig 1 maps since white is not shown in the color bar scale.**

Please see our previous reply (above the third major comment).

5. **Line 228-230: It seems strange and unlikely that for such a large dust source as the Bodele that the decreasing trend is confined only to the exact location of the depression itself since it is well known that this dust is advected in various directions out of the basin.**

The response of the Reviewer's comment has been answered above (Third major comment)

6. **Line 236-238: Please explain here what spatial resolutions were examined by de Meij et al (2012). Again I find it extremely difficult to have to switch back and forth between the main and supplemental documents in order to follow some of your main points in this paper.**

We have modified the sentence mentioned by the Reviewer in the revised manuscript as follows:

"De Meij et al. 2012 have investigated the differences between the fine daily MODIS AOD (L2; at 0.1° x 0.1° spatial resolution) and the coarse monthly MODIS AOD (L3; at 1° x 1° spatial resolution) in trend calculations utilizing the Collection 5 (C005) retrievals. According to their study, a good agreement was found between the L2 and L3 AOD trends over specific areas (i.e. Central Mediterranean, North-East America, and East Asia)."

7. **Lines 253-261: I think that a table comparing the two data sets (Voss and Evan (2020) and the current study) is warranted here.**

We have followed the suggestion of the Reviewer and in the revised manuscript we have added the following table (Table 1), presenting the DOD trend ranges between the two datasets over 15 regions of interest.

Table 1: Comparison of the computed DOD trends between the current study and the Voss and Evan (2020) over 15 regions of interest.

Regions	Latitude (°)	Longitude (°)	Current study (DOD yr^{-1})	Voss and Evan (2020) (DOD yr^{-1})
Desert areas				
West Sahara	21 – 26 N	12 – 16 W	–0.010 - – 0.002	–0.010 - –0.002
Central Sahara	15 – 30 N	10 W – 15 E	0.002 - 0.010	0.002 - 0.010
East Sahara	18 – 30 N	15 – 30 E	–0.006 - – 0.002	–0.006 - – 0.002
Bodélé Depression	13 – 16 N	12 – 18 E	–0.018 - – 0.002	–0.018 - – 0.002
Middle East	10 – 35 N	35 – 50 E	0.002 - 0.018	0.002 - 0.021
Thar Desert	24 – 30 N	68 – 76 E	–0.018 - – 0.002	–0.021 - – 0.002
Gobi Desert	37 – 45 N	90 – 110 E	–0.006 - – 0.002	–0.010 - – 0.002
Downwind areas				
Sub-Sahel	0 – 13 N	60 W – 20 E	Non-significant	0.002-0.018
Mediterranean Basin	30 – 45 N	10 W – 30 E	–0.006 - – 0.002	–0.002 - 0.002
Region surround Caspian Sea	35 – 60 N	45 – 60 E	Non-significant	0.002 - 0.021
Tropical Atlantic Ocean	0 – 15 N	20 – 60 W	Non-significant	0.002 - 0.006
South Atlantic Ocean	30 S – 0	13 W – 13 E	Non-significant	–0.006 - 0.006
North Pacific Ocean	40 – 60 N	140 E – 120 W	Non-significant	–0.010 - – 0.010
North Pacific and North America	15 – 40 N	140 E – 75 W	–0.002 - 0.002	–0.002 - 0.002
South Pacific Ocean	45 – 15 N	160 E – 80 W	–0.002 - 0.002	–0.002 - 0.002

8. **Lines 265-266: Please be clear here what the filtering criteria are. Again here, the readability of this paper is reduced significantly by frequently referring to supplemental figures in a different file.**

In order to clarify the applied temporal filters of this section, the following sentence has been added in the revised manuscript:

"*More specifically, the two applied temporal filters include the: 1) the calculation of the monthly averages when at least 6 days are available and 2) the trend calculation only in grid cells with higher than 60 available months (5 years).*"

Line 282-283: Yes this is obviously true, however you did not really present any evidence for erroneous trends. Why conduct this exercise if you cannot show clearly why a lack of temporal filtering is problematic? Or maybe I have missed your point, in which case it would be worth trying to clarify this.

Thank you for the comment. Find below few key-points, trying to justify our choice to perform this sensitivity analysis.

When our trend analysis was conducted without any temporal filtering:

1) We have found two new regions with suspicious statistically significant DOD trends: India and Southeast China (Figs 5b).

2) We have detected a quite large number of pixels with slightly positive AOD trends across the oceanic area between 30.0ºS and 60.0ºS which has not any physical explanation (Figs 5a).
3) A strong declining AOD tendency has been revealed across southeastern China (Figs 5a) whereas is absent for filtered AOD trends (Figs. 2a).

In order to further support the importance of this sensitivity analysis, we have performed the evaluation analysis of Sect. 3.1.3 but without any temporal filtering. The below lines are added in the revised manuscript:

"Despite the increase in monthly data availability, trend analysis without temporal filtering may lead to erroneous and not representative results either for AOD or DOD. In order to investigate in detail the last statement, a sensitivity analysis is performed using in total 76 AERONET stations (Fig. S9a). Through the evaluation analysis of MIDAS DOD trends (Sect. 3.1.3), the AERONET stations have been selected based on their data availability. More specifically, only the stations with at least 10 years of data have been retained in MIDAS evaluation procedure. Then, the total number of sites has been decreased from 76 (here) to 41 due to temporal filtering (see Sect. 3.1.3). Based on Fig. S9b, the unfiltered temporal trends between MIDAS and AERONET documented a profoundly lower linear correlation (R=0.51) while the data points are more sparse. When trends are calculated without any temporal filtering, the TA of the correct trends has been decreased from 80.5% (Fig. 4c) to 73.7% (Fig. S9c)."

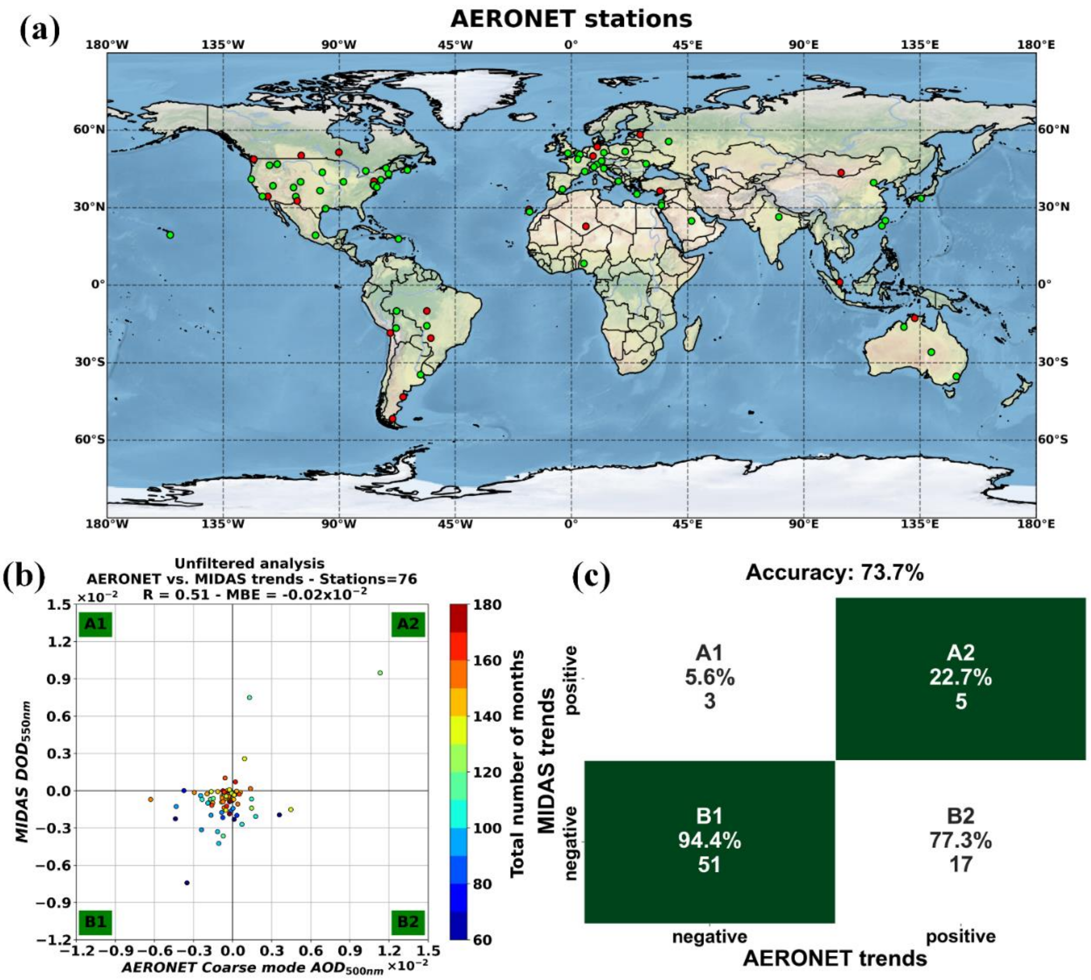

Figure S9: Same as Fig. 4 for unfiltered trend analysis.

9. Line 288: Please give a short summary of this methodology. As this paper currently is written a reader needs to jump from one document to another (either previously published papers or your supplemental document) to understand what is being done or discussed.

The applied methodology of the calculated seasonal trends as well as their statistical significance levels are described in the manuscript. More specifically, the manuscript includes the following text:

"*The detection of the statistical significance of the calculated trends based on Weatherhead et al. (1998) cannot be applied here due to the 9-month gap among the seasons. Therefore, an alternative approach is followed by calculating the seasonal trends using a simple linear regression model on the DOD anomalies and identifying the statistically significant trends based on the two-sided Student's t-test. The null hypothesis of the t-test assumes a non-significant temporal trend under a defined confidence level (here is 95%).*"

10. Lines 322-323: Every satellite data set easily detects trans-Atlantic dust transport. Why reference only your current database?

We have added several published studies focusing on dust transatlantic transport. More specifically, we have revised the text as follows:

"*Numerous studies have notified the Saharan transatlantic transport (Peyridieu et al., 2013; Alizadeh-Choobari et al., 2014c; Prospero et al., 2014; Gläser et al., 2015; Fréville et al., 2020; Gkikas et al., 2021b).*"

11. Lines 326-327: OK I applaud the honesty here but this decreases my confidence somewhat in the trend analysis maps. Comparison of these trends with some verification versus AERONET sites would be useful.

We have followed the suggestion of the Reviewer and an evaluation analysis is included in the revised manuscript. The response of this comment has been explicitly given in comment 1 of the review. In addition, we have also performed a seasonal trend analysis using an AERONET station across the aforementioned region. More specifically, the following lines have been added in the revised manuscript:

"In order to investigate the reliability of MIDAS DOD in the above region, the seasonal trend analysis is implemented at the AERONET station of llorin, Nigeria. It worths mentioning that this station has not been included in evaluation analysis of Sect. 3.1.3, due to the low number of months (N=48<60). However, 32 out of 48 months lie in boreal winter, enabling the application of the methodology during this season. Both datasets represented increasing and statistically significant cAOD (0.011 yr^{-1}, $|\omega/\sigma_\omega|=2.43$) and DOD trends (0.021 yr^{-1}, $|\omega/\sigma_\omega|=3.74$). As expected, MIDAS revealed higher in magnitude trends than cAOD (approximately 2 times higher)."

12. Line 339: I think you might mean "tends to be getting dustier" since Table S1 is a table of trends.

Corrected in the revised manuscript.

13. Lines 404-405: It seems that some mention should be given to the statistical significance and uncertainties of these measured/computed global AOD and DOD trends.

In the revised manuscript we have added the below text:

"*In this study, significant AOD trends of 0.00052 yr^{-1} and 0.00051 yr^{-1} are revealed over GLB-O and GLB respectively (Fig. 11b), using geometric mean at fine spatial resolution*."

In addition, the statistical significance and the uncertainties of DOD/AOD trends for all regions (including the global trends) are presented in Table 3 and Fig. 8.

14. Line 468: Please provide some explanation of the strong land-sea gradient in the DOD over the southern portion of the Red Sea shown in Figure 11b.

This behavior is common for MODIS due to the different retrieval algorithms applied above land and sea surfaces. Due to the fairly bright landmasses and the predominance of weak-to-moderate aerosol loadings, there is minimal contrast between surface and atmosphere leading to systematic algorithm uncertainties, which can explain the lower land DODs than those recorded in the Red Sea.

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Responses to Reviewer #2 Comments and Suggestions

Start review of acp-2021-418

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We would like to thank the Reviewer for the helpful evaluation of the manuscript and providing us the opportunity to revise and improve the quality of our manuscript. Detailed responses are presented in the marked copy.

A general note for the Reviewer: It seems, based on the point to point Reviewer comments (comment lines), that a different submitted manuscript has been evaluated (up-to question 18). After the initial submission, based on the first comments from the reviewers, we had updated our manuscript with a new paragraph in the introduction in order to support the novelty as well as the scientific contribution of our study. Thus, the corrected submission has different numbering of the lines. However, we detected all pointed comments of Reviewer #2. Below, the old lines are referred to the updated submission and not to the initial one.

<u>**General Comments:**</u>

The authors describe trends in dust aerosol optical depth and aerosol optical depth as calculated from the MIDAS fine resolution dataset. They conduct several sensitivity studies including assessing differences between the geometric and arithmetic mean, variation in start year and timeseries length, filtering, impact of spatial resolution, and regional trends. Overall, I believe that this contributes meaningfully to the existing literature on this topic as it evaluates a new dust dataset and conducts sensitivity tests that have been under-utilized in previous satellite-derived dust climatology studies. However, I believe some additional analysis and revision to the manuscript is necessary.

While the authors present comparisons to several other dust datasets, many of them are also based on MODIS AOD and are therefore not independent from the MIDAS dataset. Additional comparison with datasets that do not incorporate MODIS data are warranted eg. CALIPSO DOD, AERONET, ground-based dust measurements. At a minimum, more acknowledgement in the text of the lack of independent comparison is necessary.

We follow the Reviewer's suggestion and in the revised manuscript we have added an evaluation analysis of MIDAS DOD trends. We used, as reference data, ground-based measurements from AERONET network and more specifically the coarse mode AOD from AERONET SDA algorithm. The following evaluation analysis is presented in Section 3.1.3.

“2.2 AERONET

On a regional basis, the reliability of MIDAS DOD trends has been evaluated using ground-based measurements from AERONET (Holben et al., 1998). AERONET provides information for the spectral columnar AOD using direct spectral solar irradiance. In addition, the physical and optical properties of aerosols can be derived by applying the Dubovik and King (2000) inversion algorithm. DOD ground-based measurements can be approached using AERONET retrievals, however, an aerosol classification scheme is mandatory. Through MIDAS evaluation procedure, the discrimination of dust load from non-dust aerosol species has been performed in terms of the Ångström wavelength exponent at 440-870 nm ($AE_{440\text{-}870\ nm}$) and the difference between single scattering albedo at 440 nm ($SSA_{440\ nm}$) and 675 nm ($SSA_{675\ nm}$). $AE_{440\text{-}870\ nm}$ has been used as an indicator of particles size (coarse or fine aerosols) in numerous aerosol classification studies (Basart et al., 2009; Mielonen et al., 2009; Lee et al., 2010; Giles et al., 2012; Hamill et al., 2016; Zheng et al., 2017; Che et al., 2018; Logothetis et al., 2020). In addition, the aerosols origin can be acquired using either the difference between SSA at different wavelengths or specific spectral SSA thresholds. In Gkikas et al. (2021a), the pure dust conditions have been succeeded using a very restricted threshold limit of $AE_{440\text{-}870\ nm}$ (≤ 0.75) along with a positive difference of $SSA_{675\ nm} - SSA_{440\ nm}$. Despite the favorable dust conditions retrieved through the SSA retrievals, the data availability strongly decreases causing difficulties in trend calculations. In the current study, the evaluation of MIDAS DOD trends is performed by using the AERONET coarse mode AOD at 500 nm, derived from the spectral deconvolution algorithm (SDA) (O'Neill et al., 2001, 2003). The performance of the SDA algorithm, in terms of segregating the fine and coarse aerosol modes, has been justified against ground-based observations (Kaku et al., 2014). Only quality assured data (cloud-screened), including pre-field and post-field calibrations (Level 2.0, L2) from AERONET Version 3 (V3) (Giles et al., 2019) are used. It should be mentioned that cAOD does not represent profoundly the dust load due to the presence of sea-salt particles.”

“3.1.3 Evaluation of MIDAS trends vs. AERONET

The validity of the computed MIDAS DOD trends is thoroughly analyzed in this section. For evaluation purposes, the coarse mode AOD, hereafter referred as cAOD, retrieved through the AERONET SDA algorithm is applied. The two datasets are collocated by spatially averaging MIDAS DODs included in an area of 3x3 pixels around each AERONET site, and also temporally combined using solely the same daily values. DOD and cAOD trends are calculated using the methodology described in Sect. 2.3. Figure 4a illustrates the geographical distribution of the AERONET stations (in total 41) satisfying the defined temporal criteria (see Sect. 2.3) and finally used in the assessment analysis. According to Fig. 4b, a good linear correlation ($R = 0.86$) of the derived trends is observed accompanied with low bias ($MBE = -0.04x10^{-2}$). In order quantify the performance of MIDAS in capturing the cAOD trends, the total accuracy (TA) of the correct trends (identical sign) is calculated. More specifically, TA is defined as the percentage of the stations with correct trends sign (the sum of B1 and A2 quadrants numbers in Fig. 4c divided by the total number of stations). MIDAS trends can capture the correct cAOD trends signs with a TA of 80.5% (Fig. 4c). In addition, the percentages of each quadrant in Fig. 4c shows the number of the correctly detected stations per sign. The overwhelming majority of the AERONET stations encompassed negative trends (30 out of 41 stations). MIDAS trends capture the 26 out of those 30 (86.7%) stations denoted *with negative cAOD trends. Lastly, there are only 11 sites with positive cAOD trends, and MIDAS proved able to detect them at 7 out of 11 (63.6%) stations.*

Table S1 provides the point-to-point trend results for each collocated MIDAS-AERONET sites. It should be mentioned that among the revealed stations, few indicate dust particles as the predominant aerosol type. Based on Logothetis et al. (2020), the station of Solar Village, Arabian Peninsula, is primarily a "dusty" site revealing significantly high percentages of coarse absorbing particles. Across this station, the trends between AERONET cAOD (0.0126 yr^{-1}) and MIDAS DOD (0.0107 yr^{-1}) are in good agreement in terms of magnitude, but both are non-significant at the 95% confidence level. Similar findings are also observed in the "dusty" site of Tamanrasset, Algeria, showing increasing cAOD and DOD trends of 0.0062 yr^{-1} and 0.0044 yr^{-1}, respectively. One of the advantages of MIDAS is that it provides the dust aerosols burden information in downwind regions of the planet. For instance, most of the stations located in South Europe receive dust particles transported towards the Mediterranean from Sahara and Middle East deserts, encompassing identical trend signs (Fig. 4a). Moreover, there are many downwind regions across different regions of the globe with similar trends magnitude such as Ispra, Italy (cAOD= −0.0013 yr^{-1}, DOD= −0.0015 yr^{-1}), Kanpur, India (cAOD= −0.0027 yr^{-1}, DOD= −0.0029 yr^{-1}), SERC (cAOD= −0.0023 yr^{-1}, DOD= −0.0020 yr^{-1}) in US, Shirahama, Japan (cAOD= −0.0020 yr^{-1}, DOD= −0.0012 yr^{-1}), and XiangHe, China (cAOD= −0.0028 yr^{-1}, DOD= −0.0018 yr^{-1}).

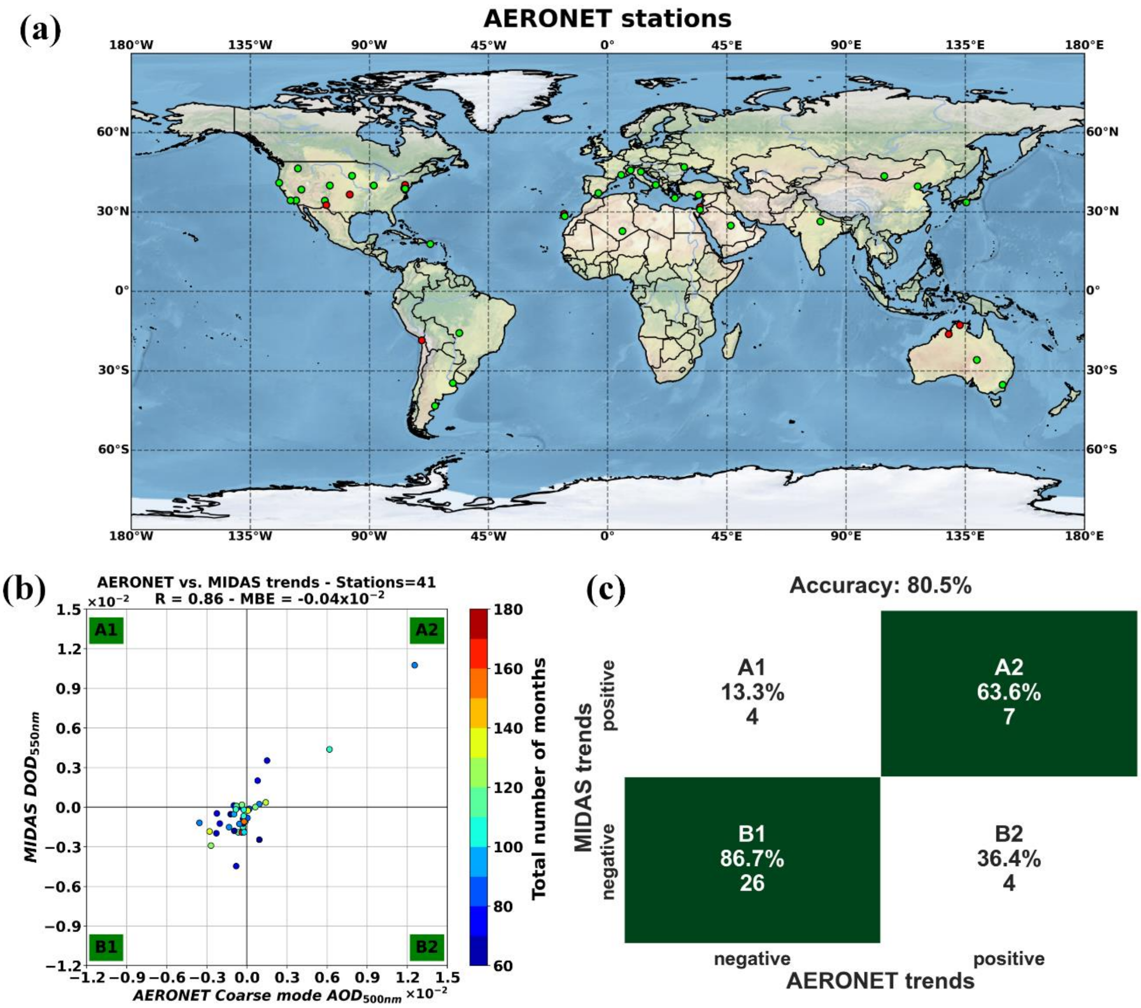

Figure 4: (a) Geographical location of the available AERONET stations in which the temporal trends of DOD and cAOD are calculated. Green and red dots refer the stations with the similar and different trend sign,

respectively. (b) Scatter plot between MIDAS DOD and AERONET cAOD trends. The color bar indicates the total number of months. (c) Confusion matrix of possible trend signs among the two datasets.”

The discussion of the differences resulting from the use of the geometric vs. arithmetic mean of DOD is important and that analysis should be presented completely in the body of the paper.

We agree with Reviewer’s opinion and we have added the following paragraph in Section 3.1.1 to support our analysis.

“*The overwhelming majority of the published AOD/DOD trend analysis studies have been relied on arithmetic mean in order to produce coarser spatial (e.g. 1° x 1°) and temporal (e.g. monthly values) resolutions. In this study, a sensitivity analysis on the aggregation method (i.e. arithmetic vs geometric mean), has been performed by utilizing the daily coarse spatial resolution (1° x 1°) MIDAS DODs. Figure 1 depicts the frequency histogram of MIDAS DODs in log scale using all the available data over the period 2003–2017. It is apparent that the shape of the DOD distribution is close to a log-normal distribution (Fig. 1). The latter considers the extreme dust episodes which force the distribution curve to be right-skewed. Arithmetic mean is about 4 times higher than the geometric mean, highlighting the importance of which metric is more representative of the population and how this can affect the results for specific applications (e.g. radiative forcing). When geometric standard deviation is considered, 65.43% of DOD values range between 0.002 and 0.027 while 81.04% encompassed within –0.033 and 0.099 for arithmetic mean, indicating an overstating of the variability (Sayer and Knobelspiesse, 2019). The averages and the standard deviations are calculated using weighted aggregation exrpessions with the weighting factors in terms of latitude (see Sect. 2.3). An additional point, revealing that the selection of normal statistics can lead to a misrepresentation of the population for a positive-definite quantity (i.e. dust optical depth), is that the lower bound (−0.033) is negative, which has not any physical meaning.*

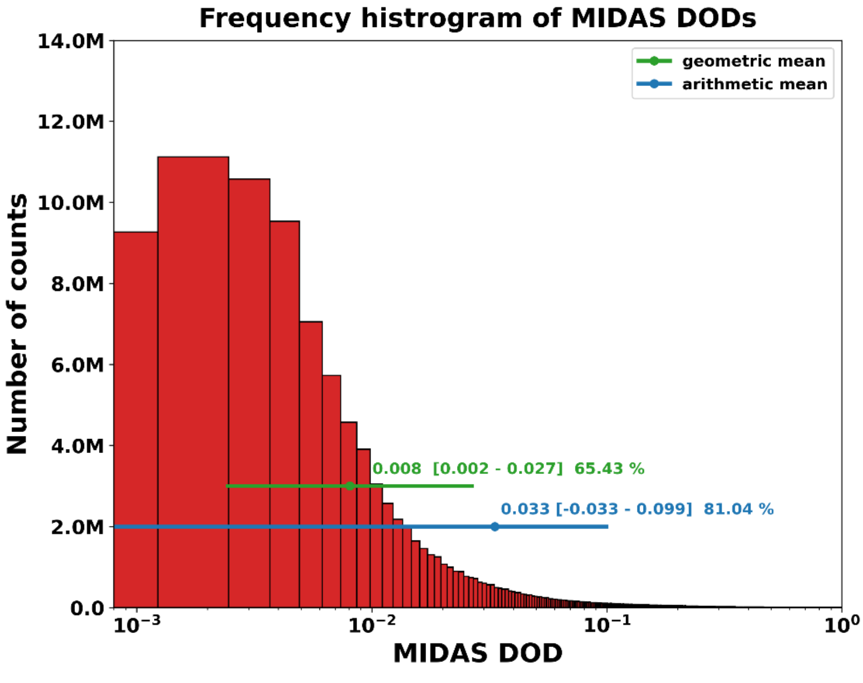

Figure 1. Frequency histogram of MIDAS DODs reported at 1° x 1° spatial resolution over the period 2003 – 2017. The computed geometric mean (green) and arithmetic mean (blue) are given along with ranges

corresponding to geometric mean/geometric standard deviation and geometric mean*geometric standard deviation for the geometric mean and ± standard deviation for the arithmetic mean.

In agreement with Sayer and Knobelspiesse (2019), the calculated trends for AOD and DOD are consistent in terms of sign between fine (Fig. 2) and coarse (Fig. 3) spatial resolution data. However, in terms of magnitude this is not the case. Figure S1, S2 depicts the frequency histograms of the deviations between the arithmetic and geometric trends. When geometric AOD/DOD averages are considered, the deseasonalized trends are suppressed by up to 91.77% with the respect to the corresponding levels obtained from the arithmetic means, regardless the underlying surface type. The only exception is found for AOD at 1° spatial resolution and across oceanic territories (Fig. S2c) where geometric trends overestimate those of arithmetic by 71.63%."

In the methods section, more discussion of the uncertainty, strengths, and weaknesses of the MIDAS data should be included. Some of the methods were not completely described.

Some modifications on the revised manuscript have been applied. We think that we are providing sufficient information to the reader without overloading the relevant section since most of the discussion is better suited to Gkikas et al., (2021).

I also believe the authors should elaborate more on the motivation for this work. There have already been several studies on dust optical depth trends using MODIS-derived datasets. Please discuss why this one is a valuable contribution beyond being a different spatial resolution.

After the initial submission of the paper an additional paragraph discussing on the novelty of the current study is added in the introduction. The modified aforementioned paragraph in the revised manuscript is presented below:

"This study's main objective is to investigate the dust temporal variations at global, regional, and seasonal scales, using the newly MIDAS DOD product from 2003–2017. A few aspects regarding the innovative points of this research are highlighted below to support the scientific contribution to the relevant research field. First, in contrast to the existing studies, this trend analysis relies on fine spatial resolution data, making it feasible to depict in detail the spatial patterns of the DOD variations. Such information can be critical for interpreting the perturbations of the radiation fields, environmental impacts, and health effects attributed to dust particles. One more advantage of the high resolution DOD analysis is the flexibility of the final grid size selection depending on data availability, which is a critical aspect when satellite observations are used. MIDAS data can be easily upscaled at coarser spatial resolutions in order to match spaceborne observations, which have been commonly used in other trend analyses available in the literature (Hsu et al., 2012; Yoon et al., 2014; Notaro et al., 2015; Pozzer et al., 2015; Klingmüller et al., 2016; Alfaro-Contreras et al., 2017; Che et al., 2019; Guo et al., 2019; Voss and Evan 2020; Song et al., 2021). In addition, fine spatial resolution data ensure a more realistic collocation with ground-based measurements for validating the obtained DOD trends. Second, quite a few studies concentrate on pure DOD (Xi and Sokolik 2015; Guo et al., 2019; Lakshmi et al., 2019; Voss and Evan 2020; Song et al., 2021) rather than AOD to analyze the trends of mineral particles' load. Even though the consideration of the latter parameter is quite reasonable across deserts, its representativeness over downwind

areas is questionable due to the coexistence of other aerosol types. Such types can also affect the DOD trend uncertainty. In MIDAS, this issue is addressed by the adjustment of MODIS AOD to DOD in terms of the MERRA-2 dust fraction, while in other studies, aerosol size and natural optical properties, which their quality above land is downgraded, are used in parallel. Third, taking advantage that MIDAS provides DOD and quality assured AOD, their trends are discussed jointly for assessing the contribution of dust burden temporal variations to those of the total aerosol load. It should be mentioned that this is the first study assessing the effect of DOD to total AOD trends across the major desert dust areas of the planet, highlighting the potential role of desert dust particles in past, present, and future AOD trend studies. Fourth, the investigation of the potential impact on trends' magnitude, sign, and statistical significance when different DOD aggregations (i.e. arithmetic mean vs. geometric mean) are considered among various spatial and temporal scales. Fifth, the DOD interannual variations are discussed for the entire study period on a seasonal basis and sub-periods for detecting alternations on DOD trends within the period of interest."

The manuscript needs substantial editing for grammar. There were uncapitalized proper nouns, improperly used or missing articles, and generally confusing sentences throughout the text. I have included some of these in my detailed comments but this list is far from exhaustive.

We would like to thank the Reviewer for giving us the opportunity to correct our submitted manuscript. Overall, the manuscript has been corrected in many points and highlighted with yellow color.

Detailed comments:

15. **Line 21: Changed to "The effect of DOD on the total aerosol optical depth (AOD) change is determined by calculating the…"**

Thank you. This sentence has been revised as:

"*The effect of DOD on the total aerosol optical depth (AOD) change is determined by calculating the calculating the DOD to AOD trends ratio*".

16. **Line 23: change to "…Gobi Deserts) the ratio value is approximately 0.6."**

Thank you. We did the correction.

[old lines: xxx-xxx; revised lines xxx-xxx]

17. **Line 28: remove "which sounds a critical aspect when satellite-based measurements are utilized."**

Done.

18. **Line 31: Change to "are a major contributor to the atmospheric aerosol…"**

Thank you. We did the correction

19. Line 48: Capitalize "Van der Does"

Thank you for the correction. However, in the literature the name is written with lowercase v.

20. Line 52: South America

Done

21. Line 108: remove "it" in "it is reasonable"

This sentence has been changed in the initial submitted manuscript.

22. Line 111: change language "taking advantage that" to something grammatically correct

This sentence has been changed in the initial submitted manuscript.

23. Line 141: Please elaborate on the "highly accurate" MODIS AODs by providing information on error statistics and validation studies

MIDAS implements the MODIS aerosol products in which AOD is derived using the Dark Target (DT) and Deep Blue (DB) algorithms. Globally, these products have been thoroughly validated against AEronet RObotic NETwork (AERONET), providing a very good agreement either over oceanic areas for DT (R=0.880; MAE=0.055; RMSE=0.083) or over land for DT (R=0.920; MAE=0.066; RMSE=0.107) and DB (R=0.904; MAE=0.062; RMSE=0.107) (Wei et al., 2019b).

24. Line 141: Instead of saying "trustworthy", consider providing specific information about the uncertainty in the product, based on uncertainty in MODIS AODs and MDF

Please see our previous replies. We would like to avoid the repetition of parts which have been already discussed in detail in Gkikas et al. (2021). About the uncertainty, the formulas and the concept are given in the paper presenting MIDAS development.

25. Line 143: note that validation with MERRA-2 is not independent since the MDF is used in the calculation of MIDAS DOD

Please note that both in the submitted and the revised document we are talking about an intercomparison and not for validation. There are several reasons explaining that MERRA-2 DOD is not very similar with those of MIDAS. For instance, MERRA-2 assimilates MODIS bias-corrected MODIS AOD from Collection 5 instead of Collection 6.1 used in MIDAS. Moreover, MERRA-2 assimilates MODIS AOD and then the increments are distributed among the simulated five aerosol species. Focusing on dust, the mineral particles' load in the atmosphere is driven by the GOCART aerosol model and the GEOS-5 meteorological driver which are independent at a large degree by the derived MIDAS DOD. In addition, the MDF is regulated also by the non-dust aerosol species simulated in MERRA-2. It is reminded, that MERRA-2 assimilates MODIS AODs derived by the Dark Target algorithm (vegetated land and oceans) excluding the bright desert surfaces where the sources are located. In the aforementioned regions, spaceborne and ground-based AOD retrievals from MISR and AERONET, respectively, are assimilated.

26. Line 145: Describe how you minimize contribution of non-dust aerosol species

We have added the methodology that dust particles are separated with non-dust species in Section 2.2.

"Through MIDAS evaluation procedure, the discrimination of dust load from non-dust aerosol species has been performed in terms of the Ångström wavelength exponent at 440-870 nm ($AE_{440\text{-}870\ nm}$) and the difference between single scattering albedo at 440 nm ($SSA_{440\ nm}$) and 675 nm ($SSA_{675\ nm}$)."

[old lines: xxx-xxx; revised lines xxx-xxx]

27. Line 152: Change the language of "it has been justified the reliability of …" for grammatical reasons

We have revised the mentioned sentence as:

"*Summarizing, the reliability of the MIDAS DOD justified in Gkikas et al. (2021a) strengthens its applicability for investigating the temporal trends of dust aerosol burden over long-time periods and at various spatial scales.*"

[old lines: xxx-xxx; revised lines xxx-xxx]

28. 206: Please show this analysis in the supplementary material

We decided to perform this analysis in the main body of the revised manuscript (Section 3.1.1, Fig. 1).

29. Figure 1: Consider showing differences in trend between geometric mean and arithmetic mean instead of showing values

The differences between geometric-based and arithmetic-based trends are shown in Figures S1 and S2 over land and ocean respectively.

30. Lines 267-269: Please rephrase for clarity.

These lines have been deleted in the revised manuscript.

31. Line 298: Please indicate, with grey shading for example, where seasonal trends were not calculated due to data gap

In order to clearly present the data availability either for yearly or seasonal trends we have modified the Figures S4 and S14. Now, the pixels with not available data (data gap; gray color) or fail to meet the availability criteria (greenish color) are clearly presented for long-term (Fig. S3) and seasonal (Fig. S4) analysis. In these pixels the DOD trends are not calculated and are presented with white (blank) color in all maps (e.g. Fig. 2). Also, the following lines are included in the caption of the revised Figure 2 to explain more explicitly the color bar.

"The pixels with: 1) non-significant trends, 2) the temporal criteria are not met and 3) not available data are colored as white (blank) in each map of trend analysis. Neutral trends, ranging between −0.002 and 0.002 DOD yr^{-1}, are colored with light yellow (or cream) (the central color of the color bar). Figs S3a, S3b and S4 present the differences between the aforementioned colors at fine, coarse spatial resolution as well as for the seasonal trends, respectively. Based on those Figs, the pixels with not available data are colored with gray color while those of failing to meet the availability criteria are colored with greenish."

32. Line 310: Please provide some values in the text for these trends in order to make it easier to understand without flipping between the manuscript and the supplementary material. For example, "increase trends of up to X yr^-1" or similar language.

In order to reduce the bonding between the manuscript and the supplementary material, we have transferred this table to the revised manuscript.

33. Line 327: Rephrase the final sentence of this line to reflect that the MERRA-2 dust fraction in MIDAS overestimates dust as compared to the DOD values derived from CALIOP retrievals.

We have revised the pointed sentence as:

"However, the trend magnitude along the Gulf of Guinea as well as in the northern regions (from Ghana to Cameroon) seems to be unreliable due to the reduced performance of MDF, surface contamination in the received radiances by MODIS and to the co-existence of aerosols and clouds (Gkikas et al., 2021b)."

34. Line 337: Consider discussing the relationship between cyclone activity and dust eg. Pan et al. (2018) Journal of Climate; Evan et al. (2006) GRL

We followed the Reviewer suggestion and we have added the following text in the revised manuscript:

"In addition, dust aerosol burden originated form Sahara Desert is directly related to tropical cyclones (TCS) over Tropical Atlantic Ocean, but their relationship is not unambiguously clarified (Evan et al., 2006). Based on model simulations, Pan et al. (2018) investigated the role of dust aerosols for the genesis of TCs over tropical Atlantic basin, by comparison of dust and non-dust model simulations. They revealed that dust amount is directly related to TCs, revealing a bimodal pattern. More specifically, favorable conditions for TCs formation are documented by increasing the midlevel moisture and decreasing the vertical wind shear while

unfavorable conditions are encompassed by decreasing the low-level vorticity and potential intensity."

35. Line 400: Why not state the global trend over ocean for MIDAS DOD here?

At the beginning of paragraph (Section 3.3.1), we state that the global DOD trends both over land and ocean are small. In particular, the global (GLB), over land (GLB-L) and over ocean (GLB-O) DOD trends are also presented in Table 3 and Fig. 8a.

36. Line 413: 5 years is a very short period over which to calculate a trend.

We agree with Reviewer's reflection that 5 years is a very short period to calculate trends. The reason of choosing the short 5-year period in trend analysis is just to perform the sensitivity analysis under different periods, varying the number of years and the initial year. Nevertheless, we have added the following sentence in the revised manuscript:

"Nevertheless, the time window is very short to infer the amplitude of the calculated trends."

37. Line 460: change "do not contradict with" to "are consistent with"

Done.

38. Line 462: "resulting in"

Done.

39. Lines 567-568: Overestimate as compared to what? What are you considering to be the "truth" dataset/value? Also, please rephrase to correct grammar

In this study, the implications in the implementation between geometric mean and arithmetic mean to trend calculations is discussed (Section 3.1.1). According to Fig. 1, the shape of the DOD distribution deviates from an exact log-normal distribution but less than a normal one. Thus, we have concluded that the use of geometric mean for the temporal averaging of daily DOD values is most representative than the use of arithmetic mean. For this reason, we have used the geometric-based DOD trends as a reference DOD trend value. Lastly, we have revised the following text as:

"In addition, the sensitivity analysis on the different aggregation approaches revealed that the arithmetic-based trends are larger than those of the geometric-based ones (from 52.87 to 91.77%) all over the globe."

40. Line 574: "and globally"

Done.

41. 575: Redundant sentence

We have removed this sentence in the revised manuscript.

42. Figure 5: explain hatching in figure caption

Thank you. We have added that hatched pixels indicate the statistically significant trends.

43. Lines 582-583: Please rephrase for clarity and grammar

We have rephrased the pointed sentence as:

"In the majority of the regions of interest, including also downwind areas, the variations of the total aerosol load are driven by those of mineral particles."

44. Lines 588: Please explain further how these trend results could be incorporated into chemical models and why this is valuable

We have added in the revised manuscript the following text:

"Our results could be incorporated in chemical models, either for assessing the various impacts of dust and non-dust particles or for evaluating trends based on numerical simulations, and to further improve their calibration and forecast performance. Moreover, the obtained findings here can be used for the interpretation of the trends of the radiation fluxes at the surface and at the top of the atmosphere obtained by observations or atmospheric-aerosol models (Chaibou et al., 2020). The recently published Sixth Assessment Report (AR6) of the Intergovernmental Panel on Climate Change (IPCC) states that the increase of the global dust load causes a reduction of the effective radiative forcing (ERF) by $-0.25\ Wm^{-2}$ (Andrews et al., 2017; Forster et al., 2021). Therefore, fluctuations of the dust atmospheric load provide a valuable information in order to understand the associated impacts on past, current and future climate"

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