

## **Visibility-derived aerosol optical depth over global land from 1980 to 2021**

### **Response to RC2**

We thank the referee for the constructive and helpful comments. We carefully thought about the comments and made corresponding revisions to the manuscript, which have substantially improved the manuscript.

#### **1. Main modifications to the content:**

- (1) Simplified the introduction.
- (2) Modified the introduction of meteorological data (section 2.2).
- (3) Modified the temporal matching method with AERONET in section 2.5. Added expected error (Eq. 14).
- (4) Added error analysis at global, regional, and site scales (sections 3.3.1-3.3).
- (5) Added uncertainty analysis with AERONET AOD (section 3.3.4).
- (6) Added trend analysis for India (Section 3.6).
- (7) Improved dataset files.

#### **2. Modifications to the chart:**

- (1) Modified the Figure 5.
- (2) Merged the original Figures 6 and 7 into Figure 6.
- (3) Added Table 1, evaluation results for each region.
- (4) Added Figure 7, evaluation results at site scale.
- (5) Added Figure 8, uncertainty analysis.
- (6) Added Figure 12, average AOD for different latitude ranges.
- (7) Added India in Figures 1 and 13-15.

*This manuscript describes the dataset of global land AOD from 1980 to 2021 derived from visibility data (VIS\_AOD) using the machine learning method. The Aqua MODIS AOD data were used as the training dataset and the resulted VIS\_AOD were evaluated with AOD from Terra MODIS and AERONET, and the trends of annual and seasonal mean VIS\_AOD over several regions were assessed.*

*The most significant value of the dataset is that it provides the global AOD over land for the time before the EOS satellite era (i.e., before 2000). With that, I recommend the manuscript to be published on ESSD. However, I do have several comments that should be addressed in the revision before it is accepted for publication.*

#### **Major comments:**

**Comment 1:** *Introduction: The introduction section is unnecessarily too long. I read paragraphs after paragraphs and still did not get what this paper was about until near the end of page 5. I suggest significantly shorten the introduction to briefly introduce aerosols, tell the readers why AOD is important, what the limitation of available satellite and AERONET data records are, and what this paper is about.*

**Response 1:** Thank you for your suggestion. We removed content unrelated to AOD. We have mainly simplified the first, fourth, and eighth paragraphs in the introduction.

**Comment 2:** *Limitation of the VIS\_AOD: fundamentally, visibility observations are at the surface, but AOD is a column integrated quantity. Considering PBL height is necessary in converting the surface quantity to column AOD but it is not sufficient, because aerosols are frequently located above the PBL, especially in the cases of large fires and transported plumes. In addition, different aerosol species have different optical properties, and the aerosol composition in the vertical column could be quite different from that near the surface. It is thus necessary to discuss the limitations and uncertainties or errors associated with the VIS\_AOD products.*

**Response 2:** Thank you for your suggestion. We used 15-minute AERONETAOD (550nm) and re-evaluated VIS\_AOD using expected error ( $\pm(0.05+0.15^*AOD)$ ). We have discussed the limitations in and the uncertainties in section 3.3.4, and errors in section 3.3.1-3.3.3.

**Comment 3:** *Validation: AERONET AOD is considered as a “ground truth” because of the direct measurements and globally unified, rigorous standard calibration. AERONET AOD has been used extensively for satellite retrieval validations, including the Terra and Aqua MODIS products. The correlation coefficients of VIS\_AOD vs. AERONET AOD is only 0.51 for coincidental data, which is much lower than that of MODIS AOD vs. AERONET ( $R=0.86$ , Levy et al., 2013 for MODIS C6 AOD products). The VIS\_AOD quality and uncertainties again need to be assessed with the AERONET AOD.*

**Response 3:** Thank you for your suggestion. We matched 15-minute AERONET AOD at 550nm and re-evaluated VIS\_AOD using expected error ( $\pm(0.05+0.15^*AOD)$ ). The VIS\_AOD quality and uncertainties have been assessed with the AERONET AOD in section 3.3.3 and 3.3.4. In this study, we used all the available globally AERONET AOD data which cover a period of 20 years.

**Comment 4:** *Analysis of AOD variations: It is poorly done. There are many unsubstantiated claims, inconsistent explanations, etc. Section 3.5 requires major revision. See my specific comments below.*

**Response 4:** Thank you for your suggestion. We have made an adjustment and improvement for the analysis of AOD variations in section 3.5 and 3.6.

*Specific comments:*

**SC1:** Line 39: “*aerosol particles are primarily discharged from the Earth’s surface*” – this is not correct. An overwhelming majority of inorganic aerosols (e.g., sulfate, nitrate) are form in the atmosphere via photochemical reactions of their gaseous precursors.

**SC1 Response:** Thank you for your correction. We have made modifications. Aerosol particles are directly emitted into the atmosphere or formed through gas-particle transformation.

**SC2:** Line 40-43, cited references: *There are many previous publications for the related topic, yet only single citation is listed as if that is the only reference or the original one. This is not appropriate. At least you should add “e.g.” in front of the references and add a few more.*

**SC2 Response:** Thank you for your suggestion. We have added references.

**SC3:** Line 67-68: *What are the major deficiencies? How they contribute to the uncertainties of climate forcing?*

**SC3 Response:** Thank you for your suggestion. We have made modifications. The uncertainties are caused by the deficiencies of the global descriptions of aerosol optical properties (such as scattering and absorption) and microphysical properties (such as size and component), and the impact on cloud and precipitation, further affecting the estimation of aerosol radiative forcing.

**SC4:** Line 144: “*inherent limitation of long temporal coverage*” - *How long is the solar radiation data that can be used to infer AOD? From the reference cited in line 140, the first one started at least in 1978 or before.*

**SC4 Response:** This part is not related to visibility-based AOD, and we have deleted it.

**SC5:** Line 148-151: *How do the observations of extinction, water vapor, and gas molecules at the surface help you in this work?*

**SC5 Response:** Thank you for your suggestion. We have made modifications. We reduced the sensitivity of particulate matter to humidity by calculating dry visibility. The optical depth of gas molecules is a quantity related to position and elevation, and is considered a constant (Li et al. ,2020).

**SC6:** Line 179-180: *The challenges listed in this paragraph (lines 171-178) exists everywhere on local, regional, and global scales. Why does the AOD can be done from visibility data regionally less challenging than globally? You are doing global anyway in this study.*

**SC6 Response:** Thank you for your suggestion. We have adjusted this sentence.

**SC7:** Figure 1 on page 6: *Why India is not included in the trend analysis? It is an important region that has undergone rapid changes.*

**SC7 Response:** Thank you for your suggestion. We have added India (region 12 in Figure 1) and analyzed the trend in India in Figures 13-15.

**SC8:** Line 217-218, Figure 1 caption: *The order of these two regions is reversed in the figure caption. Northeast Asia is labeled 11 and Eastern China 12 on the figure.*

**SC8 Response:** Thank you for your correction. We have made an adjustment.

**SC9:** Line 229, eq.1: *I wonder what advantage is to harmonic mean instead of other ways to calculate the mean.*

**SC9 Response:** We have added the advantages of harmonic mean in section 2.2:  
(1) The extinction coefficient is directly proportional to the reciprocal of visibility, so the result of harmonic averaging is more reasonable.  
(2) Harmonic averaging can capture the decrease in visibility faster than arithmetic averaging. For example, data with 6 1-minute intervals, 10,10, 1,1,1,1 km. The arithmetic average result is 4km, and the harmonic average result is 30/21km.  
(3) Daily representativeness. Combining (1) and (2), daily averages is more representative on the daily scale.

**SC10:** Line 248-251: the sentence “Because...are adopted” sounds strange: Because three variables (RH, pressure, wind speed) are related to aerosol properties, five variables are adopted. Explain why you also adopt TMP and WS.

**SC10 Response:** Thank you for your suggestion. We have made modifications in section 2.2. In addition to hourly visibility (VIS), some automatically observed variables closely related to aerosol properties were selected, including relative humidity (RH), dew point temperature (DT), temperature (TMP), wind speed (WS) and sea-level pressure (SLP). Temperature affects atmospheric stability and the rate of secondary particle formation, and humidity influences the size and hygroscopic growth, and wind speed and pressure significantly impact the transport and deposition.

**SC11:** Line 257-259: What happens when RH is out of that range (30-90%)?

**SC11 Response:** We have given an explanation in the manuscript, as follow: When the relative humidity is less than 30%, the dilution effect of aerosols is very low or even negligible. When the relative humidity is greater than 90%, research shows that it is impossible to distinguish whether it is fog or haze, or both exist at the same time, and even precipitation.

**SC12:** Line 262-263: Please give reasons for using different methods calculating means for different variables.

**SC12 Response:** We have provided an explanation in SC9 Response.

**SC13:** Line 279: Explain why these three variables are needed.

**SC13 Response:** We have provided an explanation in section 2.3.

**SC14:** Line 355-359: The language used in these lines are unclear and confusing. Does “good weather conditions” mean low AOD and clear sky? Does “AOD values are concentrated around the average value” mean AOD variability is small? Does “bad weather” mean heavy pollution events? What does “data imbalance” mean? Balance with what? How large is AOD that can be described as “large AOD”?

**SC14 Response:** We have made modifications in section 2.6.2. When it is clear, the AOD value is small, the variability of AOD is small ( $AOD < 0.5$ ), and the data is concentrated near the mean value. When heavy pollution, the AOD value is large ( $AOD > 0.5$ ). Compared to clear sky, the AOD sequence will show “abnormal” large values with low frequency, which is the imbalance of AOD data. The processing of imbalanced data. (1) AOD sequences are classified into three types based on percentile (0-1%, 2% -98%, 99%). (2) When the mean of the third type of AOD is greater than 5 times the standard bias of the second type, it is considered an imbalanced sequence. These data, with a total amount less than 5% of the sample, are imbalanced data. (3) Then synthetic samples are generated with the upper limit 10% of the samples.

**SC15:** Line 432-433: Explain the symbols in Eq. 14-16.

**SC15 Response:** We have made supplement.

**SC16:** Section 3.3: How is the daily value obtained? Do you match the time and location of observations between AERONET and MODIS? How is your evaluation of MODIS vs. AERONET compared to many published MODIS validation papers?

**SC17 Response:** We have made modification in section 2.5. In the previous comparative analysis, time and location were not considered when matching AERONET with satellite AOD. At present, the matching with AERONET AOD (550nm) is at least two times within 1 hour ( $\pm$  30 minutes) of satellite transit time.

**SC17:** *Line 492: when comparing with satellite daily, monthly, and yearly data, do you match the time and location to do the means at these time scales?*

**SC18 Response:** We have made supplements. We matched the time and location with satellite at daily, monthly, and yearly scales.

**SC19:** *Line 494-501, validation of VIS\_AOD with MODIS and AERONET: Because you use Aqua AOD to train the visibility-based ML model, the comparison between VIS\_AOD and Aqua AOD is not an independent validation. Please clarify.*

**SC19 Response:** Thank you for your correction. We have clarified that Aqua AOD is not an independent validation in section 3.3.

**SC20:** *Line 510-513: AERONET AOD is considered “ground truth” and is more accurate than MODIS because it is a direct measurement, not a retrieved product. All satellite AOD products have been evaluated with AERONET for their quality. Maybe you should train your model with AERONET AOD instead of Aqua MODIS AOD. In fact, AERONET AOD should be the standard data product to evaluate the model error.*

**SC20 Response:** Thank you for your suggestion. We have attempted AERONET AOD as the target value for the model. However, the AERONET site is sparse and the observation period is inconsistent, making it insufficient for gridding. Therefore, we chose MODIS AOD to train the model and AERONET AOD as standard data to evaluate model errors.

**SC21:** *Y-axis title on Figure 7: It should be “Annual AERONET\_AOD”, not “Annual Terra\_AOD” for the lower right panel.*

**SC21 Response:** Thank you for your correction. We have removed Figure 7 and replaced it with Figure 6.

**SC22:** *Line 528: Clarify that the zonal and meridional AOD are over land only.*

**SC22 Response:** Thank you for your correction. We have clarified that the zonal and meridional AOD are over land only.

**SC23:** *Line 532: Like mentioned above, the evaluation between VIS\_AOD and Aqua MODIS AOD is not meaningful and not an independent evaluation.*

**SC23 Response:** We have made modification. We have indicated that Aqua AOD is not an independent validation, while Terra and AERONET are independent validation.

**SC24:** *Line 536: How to define “highly similar”: need to be quantitative and avoid subjective phrases.*

**SC24 Response:** Thank you for your correction. We have made modifications. The R between Aqua and Terra AOD are highly similar, with an R of is 0.980.

**SC25:** *Line 553: “good agreement” – this is another subjective phrase. The R between VIS\_AOD and AERONET AOD (remember, AERONET AOD is the actual*

*measurement, not a retrieval product) is 0.624, meaning it captures 39% of observed AOD. Is it good enough?*

**SC25 Response:** Thank you for your correction. We have deleted this sentence.

**SC26:** Line 561-562: “*High AOD values occur in the NH...*”, which contradicts with the numbers in line 559 (mean AOD of NH=0.158 and SH=0.173)!

**SC26 Response:** Thank you for your suggestion. We have made modifications. There are many regions with high AOD values over land in NH.

**SC27:** Line 566-568: *Figure 8 shows that lower AOD value is not just at 25S, but all latitude from 25S to 60S. In any case, Figure 8 does not support the higher SH AOD than NH AOD.*

**SC27 Response:** Thank you for your suggestion. We have made modifications. Lower AOD regions of the SH are from -25°N to -60°N.

**SC28:** Line 590-592: *Why should industrial activities intensify in JJA? Is there any data support that? Reasons for higher AOD in the summertime has a lot to do with the higher RH to promote aerosol growth, and more active photochemical production of aerosols from their precursor gases.*

**SC28 Response:** Thank you for your correction. We have made modifications. Under higher relative humidity in JJA, it promotes the growth of hygroscopic particle and the photochemical reaction of aerosol precursors, resulting in high aerosol loading.

**SC29:** Line 591-592: *SON is biomass burning season in South America and southern Africa, and the high AOD there and then is not due to “intensification of industrial activities”!*

**SC29 Response:** Thank you for your correction. We have made modifications. The occurrence of high AOD values is highly associated with the growth of hygroscopic particle and the photochemical reaction of aerosol precursors under higher relative humidity in Asia (JJA) (Remer et al., 2008) and Europe such as Russia (JJA), and biomass burning in South America (SON), Southern Africa (SON), and Indonesia (SON).

**SC30:** Line 593-594: “*the increased dust emission in Middle East region related to the transport of dust from the Sahara region*”: This sentence does not make any sense. How can transport of dust from Sahara cause the increased dust emission in Middle East?

**SC30 Response:** Thank you for your correction. We have made modifications. We replaced the Middle East with India

**SC31:** Line 595-596: *Monsoon systems are most active in summer, not autumn!*

**SC31 Response:** Thank you for your correction. We have made modifications. This may be related to the weakening of the monsoon.

**SC32:** Line 601-603: *Why does AOD in SH decrease much faster than that in NH?*

**SC32 Response:** Thank you for your suggestion. We have given an explanation. There is a decrease in the frequency of sandstorms and wildfires and an increase in precipitation, such as in Australia.

**SC33:** Line 603-604, MODIS trends: You should compare your trends for the same period 2003-2020 with the MODIS trends over land only.

**SC33 Response:** Thank you for your suggestion. We have made the modifications.

**SC34:** Line 607-608: “our study has the same downward signal as that in previous studies”: This is not true from the trend values presented just a few lines above. Your trends are over land only and they are in opposite directions to MODIS and SeaWiFS!

**SC35 Response:** Thank you for your correction. We have made the modifications.

**SC35:** Line 614-616: Are these two sentences or one? It seems the period should be replaced with a comma on line 615.

**SC36 Response:** We have made modification. It is one sentence.

**SC37:** Figure 10: (1) in the caption, symbols are different from what depicted in the legends on the first right panel. Is triangles representing NH (in caption) or SH (on legends)? If the yellowish lines with triangles are for NH, why the global means are much closer to SH, given that NH has much larger land surface? If they are for SH, why AOD in SH is much higher than that in the NH for all seasons and all times except in MAM after 2000? There is a lot of explanations to do.

**SC37 Response:** (1) The line types and markings in Figure 11 have been corrected. (2) The triangular yellow line represents SH, and the square red line represents NH. Figure 12 illustrates the multi-year average AOD in different latitude ranges for land, the NH, and the SH from 1980 to 2021.

**SC38:** Line 649: Again, I wonder why India is excluded.

**SC39 Response:** We have added **India** into this study.

**SC40:** Line 655-657: The large volcanic eruptions from El Chichon and Mt. Pinatubo do not appear in most regions, which are not correct. Is this because your training data are after 2002 that do not have any knowledge of major volcanic eruptions? Does this illustrate the limitation of visibility-based estimates of column AOD?

**SC40 Response:** Thank you for your suggestion. Volcanic eruptions also have a significant impact on tropospheric aerosols. The presence of tropospheric aerosols will affect visibility near the ground. Although the model does not have data from before 2002, visibility had the records and captured the characteristics of historical aerosols. We think that it is not a limitation of visibility-based estimation, but rather its advantage.

**SC41:** Line 658: It is AOD, not loading, that is shown in Figure 11.

**SC41 Response:** Thank you for your suggestion. It has been modified to ‘AOD level’.

**SC42:** Line 688: Why are these three numbers shown 4 significant digits after the decimal point, but all other numbers are with just 3?

**SC42 Response:** Thank you for your correction. We have ensured consistency in significant digits after the decimal point.

**SC43:** Line 703-804: Do you get the sign correctly or consistently? How can a negative number (-0.01/10a) be greater than a positive number (0.009/10a)?

**SC43 Response:** Thank you for your correction. It is a writing error and the negative sign was missed. It has been corrected to -0.009/10a.

**SC44:** Line 715: JJA is NOT the biomass burning season in West Africa.

**SC44 Response:** Thank you for your correction. We have made modifications.

**SC45:** Line 729: Wildfire is very seasonal. Does your seasonal trend support the conclusion of BC and OC decreasing?

**SC45 Response:** Thank you for your corrections. We have made modifications. It does not support the decreasing in BC and OC, and it is related to dust, biomass burning, and forest cover area.

**SC46:** Line 744: “Natural emissions were predominant in 1992 and 1997”: What is the base of such statement? Figure 12 and 13 hardly show any enhancement of AOD in these years.

**SC46 Response:** Thank you for your correction. We have deleted this sentence.

**SC47:** Line 749-750: Why should PBL height affect AOD, which is a column quantity? This is another unsubstantiated claim.

**SC47 Response:** Thank you for your correction. We have made modifications, ‘the reason for the high AOD in winter may be related to the transportation.’

**SC48:** Line 757-758: What does “high level of volatility” of AOD mean?

**SC48 Response:** We have made modifications, ‘larger positive anomaly accompanied by oscillations.’

**SC49:** Line 773: “201” should be 2021.

**SC49 Response:** Thank you for your correction. We have made modifications.

**SC50:** Figure 12: Discussions of the differences between VIS\_AOD and MODIS\_AOD should be explained.

**SC50 Response:** Thank you for your suggestion. We have made an explanation for the differences in section 3.3.4.