

## Response to [RC2: egusphere-2025-5824](#)

*Authors employ two-stage Universal Kriging (UK) method for the synergistic fusion of aerosol optical depth dataset from MODIS and MISR, and ground-based ARFINET data over the Indian subcontinent. The seasonal fused maps of AOD integrates more than 80% of the ground-based observations, highlighting the impacts of number of ground measurements in the fusion process. Integrating Machine Learning (ML) approach with the Residual Kriging is found to capturing stable spatial patterns under limited or sparse coverage of ground observations. The paper feels lengthy, but informative and presented with sufficient details (i.e., text, maps, and plots).*

We sincerely appreciate the insightful and constructive comments of the reviewer. We have carefully addressed all the queries providing point by point responses to each of them. For clarity, the reviewer's comments are shown in bold green text, and our responses are provided in blue text. The relevant texts have also been incorporated into the revised manuscript.

### General Comments:

**Query-1:** *One primary concern with this paper is that the fusion approach has been applied to the monthly mean MODIS/MISR aerosol products, which are already providing spatially extensive distribution of AOD in the first place. The improvements demonstrated by authors add AOD data over very northern parts of India, around Kashmir region, where AOD is very low.*

**Response:** We thank the reviewer for highlighting this important point. We have utilized monthly data sets in the fusion framework, which is designed to operate under practical observational constraints, such as differences in sensor characteristics (e.g., spatial coverage, revisit frequency, and collocation with ground observations), which limit consistent data availability at daily timescales. Hence, the analysis is conducted at the monthly scale to improve spatial representativeness, reduce sampling gaps, and enhance statistical robustness.

Details are included in the revised manuscript.

**Line 262-281:** “The geostatistical data fusion method used in this study combines spatial data from multiple sources (satellite and ground-based, as detailed in Sections 2.1 and 2.2) with varying resolutions, accuracies, and types of measurements. The aim is to enhance the overall understanding and prediction of spatial variables (e.g., AOD) to produce a more accurate and comprehensive representation of columnar AOD, with an emphasis on reducing inter-sensor biases through integration with ground-based observations. For this, we have adapted UK framework, where data interpolation relies on unknown functions (e.g., satellite derived AOD) represented as trend models with spatial autocorrelation through variogram analysis. Building on this framework, the fusion methodology is designed to operate under practical observational constraints, such as differences in sensor characteristics (e.g., spatial coverage, revisit frequency, and collocation with ground observations), which limit consistent data availability at daily timescales. Hence, the analysis is conducted at the monthly scale to improve spatial representativeness, reduce sampling gaps, and enhance statistical robustness. Notably, the monthly satellite AOD products also retain sensor-specific biases and inter-product inconsistencies. Thus, the fusion approach presented here is not primarily aimed at gap-filling, but at generating a more accurate and internally consistent AOD dataset by integrating complementary information from multiple sensors and ground-based observations. Thus, even at the monthly scale, the proposed method adds value by reducing

retrieval uncertainties and improving the reliability of aerosol distributions, which is critical for climate studies and radiative forcing assessments.”

*Query-2: Another concern is about the choice of satellite sensors. MISR’s repeat overpass occurs every 4 days, limiting the spatial coverage and its ability to capture daily changes in aerosol loading. MODIS flies on Terra (morning overpass) and Aqua (early afternoon overpass). The Dark Target and Deep Blue combined AOD product used in the present work is available from both satellites. Utilizing these two MODIS sensors in the fusion process would have offered more complete spatial coverage on daily basis, in addition to the diurnal variations in aerosol patterns.*

**Response:** We thank the reviewer for this important and valuable suggestion.

We agree that incorporating both Terra and Aqua MODIS observations could improve daily spatial coverage and provide insights into diurnal variability. However, the present study is focused on developing a robust multi-sensor fusion framework by combining datasets with consistent overpass times and viewing geometries. Although MODIS AOD provides very good spatial coverage, its retrievals exhibit higher uncertainty over the heavy aerosol loading and high surface reflectance areas (Tian et al., 2018, 2019, Farhat et al., 2019). In contrast, MISR AOD demonstrates greater accuracy over terrains and highly reflective land cover regions due to its multi-angle observation capability (Garay et al., 2017); however, it has a lower temporal resolution with a revisit time of four days. Details regarding the utilization of MODIS and MISR data are included in the revised manuscript.

**Line 248-255:** “The MODIS and MISR datasets used in this study are both acquired from the Terra satellite platform and therefore have nearly identical overpass times. This temporal consistency ensures improved compatibility in the fusion process and minimizes uncertainties associated with diurnal variability in aerosol loading. In contrast, inclusion of MODIS observations from the Aqua satellite, which has a different overpass time, would introduce additional variability related to diurnal aerosol evolution that requires explicit treatment. Addressing such effects is beyond the scope of the present methodology-focused study and will be considered in future work.”

**Line 312-316:** “AOD observations in this study were aggregated to a monthly scale to ensure more consistent spatial coverage and improve the reliability of multi-sensor fusion analysis. Due to the differences in spatial coverage and revisit characteristics of MODIS and MISR as well as temporal gaps in data availability from ground-based instruments (Figs. S3a, 3b, 3c), daily datasets often contained substantial spatial gaps over the study domain.”

**Line 645-649:** “when dust loading is dominated by coarse and non-spherical particles (in May), MISR demonstrates relatively better performance than MODIS (as shown by scatter plots). This difference may be attributed to the advantage of MISR’s multi-angle observation capability, consistent with findings from Middle Eastern validation studies (Farahat, 2019; Garay et al., 2017).”

*Query-3: Additionally, an application of the UK-ML approach on daily AOD fields would have added more value than the presented monthly scale, at which the satellite aerosol products fill the gaps and provide more extensive spatial coverage.*

**Response:** We fully agree with the reviewer’s suggestion that applying the UK/RK-ML approach to daily AOD fields could provide additional insights into short-term aerosol variability. However, such an analysis would require denser and more consistent

observational coverage than currently available. In this context, as discussed in our responses to Query-1 and Query-2, the use of monthly averaged AOD products was motivated by the need to ensure sufficient spatial coverage and reliable collocation between satellite (MODIS and MISR) and ground-based (ARFINET/AERONET) observations. At daily timescales, the differences in sensor characteristics—such as MISR’s limited repeat cycle and spatial coverage, as well as inconsistencies in collocation with ground observations—result in sparse and uneven data availability over large regions.

We have included the above message in the revised manuscript.

**line 262-281:** “The geostatistical data fusion method used in this study combines spatial data from multiple sources (satellite and ground-based, as detailed in Sections 2.1 and 2.2) with varying resolutions, accuracies, and types of measurements. The aim is to enhance the overall understanding and prediction of spatial variables (e.g., AOD) to produce a more accurate and comprehensive representation of columnar AOD, with an emphasis on reducing inter-sensor biases through integration with ground-based observations. For this, we have adapted UK framework, where data interpolation relies on unknown functions (e.g., satellite derived AOD) represented as trend models with spatial autocorrelation through variogram analysis. Building on this framework, the fusion methodology is designed to operate under practical observational constraints, such as differences in sensor characteristics (e.g., spatial coverage, revisit frequency, and collocation with ground observations), which limit consistent data availability at daily timescales. Hence, the analysis is conducted at the monthly scale to improve spatial representativeness, reduce sampling gaps, and enhance statistical robustness. Notably, the monthly satellite AOD products also retain sensor-specific biases and inter-product inconsistencies. Thus, the fusion approach presented here is not primarily aimed at gap-filling, but at generating a more accurate and internally consistent AOD dataset by integrating complementary information from multiple sensors and ground-based observations. Thus, even at the monthly scale, the proposed method adds value by reducing retrieval uncertainties and improving the reliability of aerosol distributions, which is critical for climate studies and radiative forcing assessments.”

### *Specific Comments:*

*Query-4: Abstract: Satellite and ground-based datasets should be introduced first in the abstract, followed by Universal Kriging and ML approaches. (a) The abstract doesn’t give an impression of how UK-ML approaches improve spatial distribution of AOD. (b) Have authors validated the fused AOD dataset? Although, ground-based ARFINET data is used in the fusion, the AOD still can be validated against available AERONET sites in India. (c) Also, it is unclear how the suggested fusion approach optimally uses either MODIS, MISR, and ARFINET AOD datasets. Abstract should address these concerns.*

**Response:** Complied with thanks. The abstract is revised introducing the satellite (MODIS, MISR) and ground-based (ARFINET/AERONET) datasets, followed by a clearer description of the UK/ RKML methodology and its advantages. We have included validation details of fused AOD with both ARFINET and AERONET ground based observations.

The abstract clearly highlights the key advancement—namely, the improved spatial stability and reliability of AOD distributions achieved through the RK-ML approach compared to UK, the methodological details are included in the revised manuscript:

### *Advantages RK-ML:*

The primary objective of this study is the fusion of AOD datasets to improve both the magnitude and spatial reliability of AOD across different regions. Our analysis shows that the UK method exhibits limitations under sparse ground-based observations, often resulting in less stable and spatially inconsistent patterns. In contrast, the RKML approach produces a more robust and consistent spatial distribution.

This improvement arises from the methodological framework: UK relies on a deterministic trend model and is therefore sensitive to the distribution of observations. In RKML, a machine learning model (SVR) first captures the nonlinear relationship between satellite and ground-based AOD, and Ordinary Kriging is then applied to the residuals. Because the residuals are small and have near-zero mean, the Kriging step introduces minimal corrections, particularly in regions far from observations. As a result, RKML preserves a stable and realistic AOD distribution, even under sparse observational conditions.

### *Validation of fused AOD:*

The fused AOD dataset has been validated using a leave-one-out cross-validation (LOOCV) approach. This method was chosen considering the limited number of ground-based stations and their uneven spatial distribution across India. LOOCV allows each station to be independently evaluated while maximizing the use of available observations, making it more suitable than K-fold cross-validation or region-based holdout strategies under sparse and heterogeneous sampling conditions.

During LOOCV, we have utilized both ARFINET and AERONET data from ground-based observations. However, it may be noted that during the study period, the number of available AERONET stations within Indian region was limited, and the temporal coverage was not consistent for the selected months.

### *Fusion approach:*

In the proposed fusion framework, satellite-derived AOD products (MODIS and MISR) are incorporated as explanatory variables (or trend components), while ground-based observations (ARFINET/AERONET AOD) are treated as the reference (response variable). Conceptually, this is analogous to a regression-based approach in which satellite datasets provide spatially continuous information, and ground observations are used to constrain and correct the estimates. The fusion method combines these datasets by leveraging both the large-scale spatial patterns captured by MODIS and MISR. In this framework, ground-based observations play a critical role in bias correction, whereas MODIS and MISR provide spatial continuity and help capture regional variations. The integration of these complementary strengths enables the fused AOD product to achieve improved spatial reliability compared to using any single dataset independently. Furthermore, the approach is optimal in the geostatistical sense, as it provides the best linear unbiased estimate (BLUE) by minimizing estimation variance while incorporating satellite-derived predictors.

The revised abstract is included below:

“Synergistic fusion of aerosol parameters from multi-sensor measurements is crucial for integrating diverse data sources and generating consistent representations of aerosol distribution for accurate climate impact assessment. In this study, satellite observations from MODIS (Moderate Resolution Imaging Spectroradiometer) and MISR (Multi-angle Imaging SpectroRadiometer) are combined with ground-based measurements from Multi-Wavelength solar Radiometer (MWR) and CIMEL sun-photometers from the ARFINET and AERONET respectively to generate fused Aerosol Optical Depth (AOD) fields over India. The primary

focus of this study is to develop a fusion framework over India, involving the evaluation and comparison of two approaches Universal Kriging (UK) and novel hybrid geostatistical-machine learning approach (RK-ML). Both methods share the same geostatistical foundation (variogram-based spatial-modelling) but differ in how the mean structure of AOD is estimated. In UK, satellite-derived AOD serves as deterministic trend for spatial prediction and is effective when ground based observations are well distributed, whereas RK-ML considers SVR-predicted AOD as prior and applies Ordinary Kriging to interpolate residuals from real-time ground observations, maintaining a near-zero residual mean away from observations which reduces distortion under sparse and uneven data conditions. Our results highlight seasonal fused AOD maps (winter, pre-monsoon, and post-monsoon) over India. Leave-One-Out Cross-Validation (LOOCV) is adopted as an evaluation strategy for assessing model performance, showing that the 95% confidence interval ( $\pm 2\sigma$ ) of the fused AOD captures over 80% of ground observations, indicating effectiveness in capturing regional aerosol variability. RK-ML demonstrates more stable spatial patterns and improved LOOCV performance compared to UK, particularly in regions with limited ground-based coverage.”

**Introduction:**

**Query-5:** *The use of AERONET AOD measurements is mentioned here (2nd paragraph), but not in the abstract.*

**Response:** We have revised the abstract to explicitly include the use of both ARFIENT and AERONET observations in the study.

**Section 2.1 Ground-based AOD:**

**Query-6:** *Which agency operates ARFINET? ISRO? This should be cited here.*

**Response:** We have updated the citations in the section 2.1.

Line 168-170: “The ground-based AOD is primarily obtained from ARFINET observations, having continuous measurements across the Indian region since 1985 maintained under ISRO-GBP (Gogoi et al., 2009; Babu et al., 2013).”

**Query-7:** *Are the measurements from MWR made simultaneously across all ten narrow wavelength filters?*

**Response:** Yes, the measurements can be approximated as simultaneous. In exact sense, the difference between consecutive filters is ~4-5 sec and consecutive measurement from same filter is on two minute lag. A sample table of acquisition file is given below.

Date:1/ 4/ 2016					
H:MM:SS	Filter number	Voltage (mV)	H:MM:SS	Filter number	Voltage (mV)
Round-1			Round-2		
82304	1	129	82504	1	87
82309	2	433	82509	2	296
82314	3	142	82514	3	92

82318	4	1042	82518	4	735
82323	5	513	82523	5	391
82328	6	618	82528	6	496
82332	7	825	82532	7	665
82337	8	949	82537	8	750
82342	9	239	82542	9	189
82347	10	1084	82547	10	865

**Query-8: Does the variance of the Langley intercept cause an uncertainty of ~ 5% in AOD derivation?**

**Response:** We are sorry for the lack of clarity on Langley intercept. The details regarding the estimation of AOD based on Langley technique (LI) is included in the revised manuscript and the uncertainty caused by variation in LI is discussed (as given below):

**Line 190-201:** “The accuracy of AOD estimates from MWR is based on the accuracy of the estimate of LI. Since, LI is also a parameter of indirect calibration of the instrument, the temporal variability of LI is examined to ensure performance of the system and qualify usable data. Typically LI varies within 5% of the mean and up to 10% in worst cases. Fluctuations are more pronounced at shorter wavelengths than at longer ones. Owing to these variations, total AOD uncertainty ranges from 0.02 to 0.03, increasing at shorter wavelengths (<500 nm) and during high AOD conditions (>0.5), which are mainly limited to the pre-monsoon season. Importantly, these errors are primarily statistical and uncorrelated across channels, rather than systematic (e.g., dark current, detector offsets, and molecular scattering/absorption modelling which are <0.1%). The instrument details, AOD retrieval method, and error budget have been discussed elsewhere Gogoi et al., 2009; Babu et al., 2013; Kompalli et al., 2010; Moorthy et al., 2007).”

**Query-9: A map of ARFINET operating sites would be desirable.**

**Response:** Complied with, a map showing all ARFINET sites is included in the revised manuscript (**Fig. S1a**).

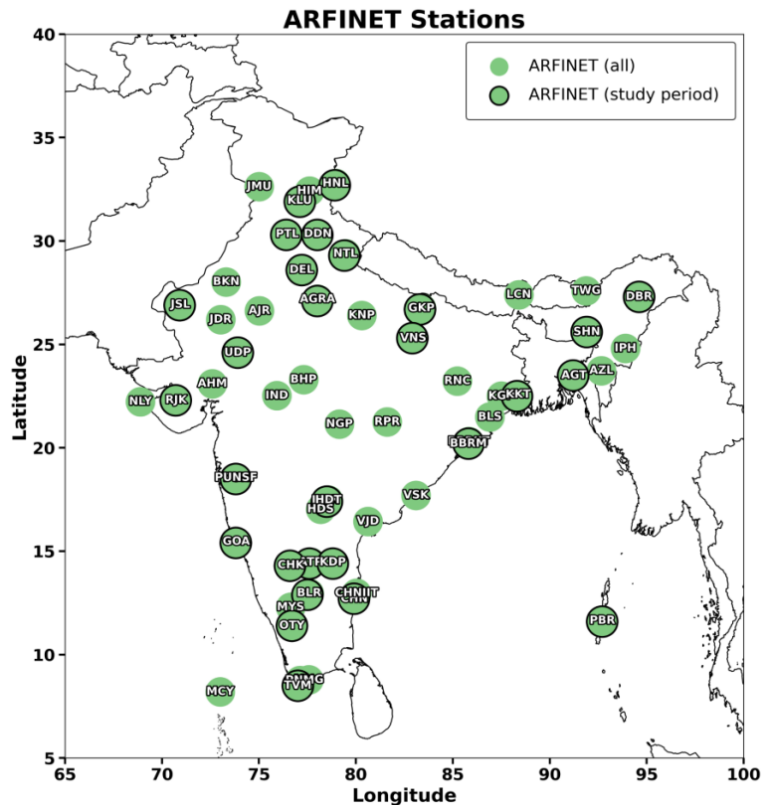


Figure – S1a. ARFINET(Aerosol Radiative Forcing over India NETwork) stations all over different parts of India (green circles represent stations while circles with black outline are the stations used for current study)

**Section 2.2 Satellite retrieved AOD:**

**Query-10:** Note that Dark Target and Deep Blue algorithm retrieve AOD using two different respective algorithms. The combined product is derived by selecting the best retrieval from either of the algorithms (i.e., DT over darker surfaces and DB over semi-arid and arid surfaces).

**Response:** We thank the reviewer for highlighting this important point. We have included the specific details of Dark Target and Deep Blue retrieval algorithms and in the revised manuscript to better explain that the combined AOD product that is generated by selecting the most appropriate retrieval from either algorithm (i.e., Dark Target over darker surfaces and Deep Blue over semi-arid and arid surfaces).

**Line 225-233:** “The merged AOD product combines only high-quality Dark Target (DT; QA = 3 over land, QA > 0 over ocean) and Deep Blue (DB; QA = 2 and 3) retrievals to provide global 10 km coverage. Over land, selection is based on Normalized Difference Vegetation Index (NDVI), with DB used for bright (arid, semi-arid) surfaces (NDVI ≤ 0.2), DT for vegetated (darker) regions (NDVI ≥ 0.3). In transitional zones, the higher-QA retrieval or their average is applied, while over ocean only DT is used. Although this approach improves spatial coverage and usability, uncertainties may arise in averaged regions and due to assumptions about algorithm performance across surface types (Sayer et al., 2014).”

### **2.3.2 Variogram Analysis:**

***Query-11: Fig S1: the detrending process is not well understood. Did author use long-term MODIS AOD datasets over India? Does this include all four seasons?***

**Response:** Thanks for suggesting this important point. We have elaborated the discussion on detrending process in the revised manuscript. The detrending applied in this study refers specifically to removing large-scale, systematic spatial trend in the data, such as the variations arising out of the changes in elevation or latitude-based variations.

**Lines 331-342:** “However, real-world environmental and geophysical data often exhibit large-scale spatial trends driven by physical and geographical factors, such as latitude, longitude, and elevation. In the case of AOD, these variables act as key spatial predictors that capture dominant regional gradients and can be used to model and remove the large-scale spatial trend. In the presence of strong spatial trends, variogram may become unbounded or exhibit unrealistically large ranges. These spatial trends violate the stationarity assumption which can lead to unbounded variogram. To address this spatial detrending of the data is performed, which isolates the local fluctuations or residuals from the spatial data set. This serves as an essential step in geostatistical analysis to ensure a well-defined and bounded variogram, enabling reliable estimation of sill, nugget, and range parameters for spatial covariance modeling. To validate this assumption, we obtained the frequency distribution of satellite AOD and their residuals (Fig. S4) after detrending.”

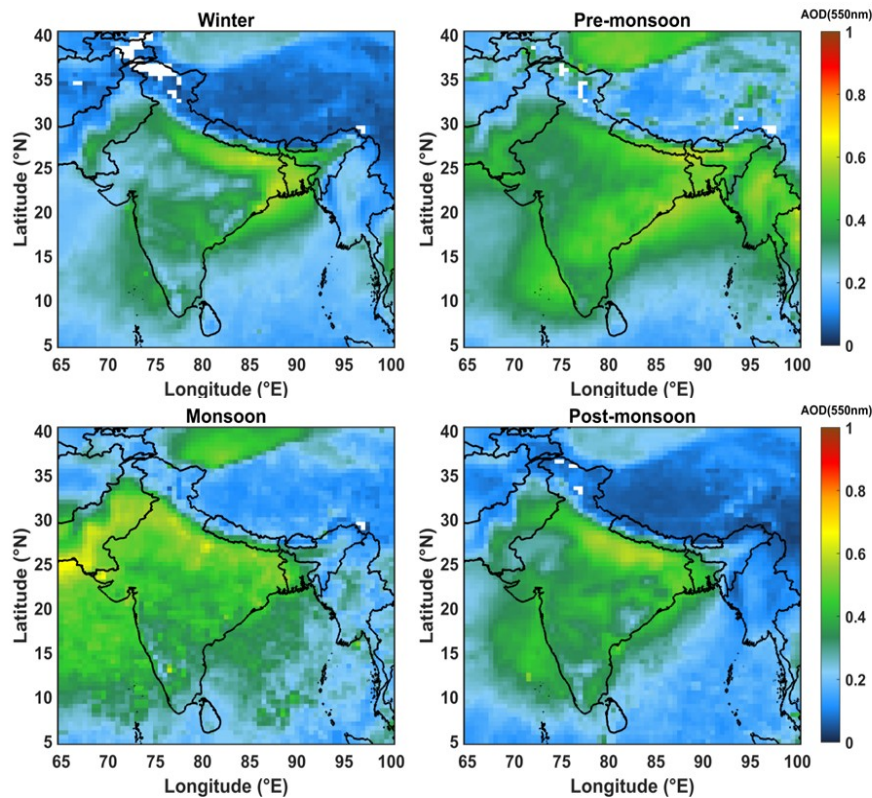
**Lines 344-348:** “Since the detrending in our study is purely a spatial operation, the temporal dimension is not explicitly considered and is effectively treated as constant during the detrending process. Consequently, the approach does not involve long-term datasets or explicitly account for seasonal variability (e.g., all four seasons).”

***Query-12: Figure 3: Similar long-term seasonal climatology maps from MISR are worth showing here to examine consistency or lack thereof.***

**Response:** Complied with. Following this recommendation, we have included the long-term seasonal climatology map derived from MISR, similar to the MODIS map, in **Figure 3b** to facilitate comparison and to examine the consistency between the two datasets.

**Line 558-560:** “The spatial patterns of a decadal average satellite-based MODIS and MISR AOD (2011–2020; Fig. 3a, 3b) also shows persistent high AOD values in the IGP and its outflow regions across all seasons.”

**Line 578-583:** “Additionally, discrepancies between MODIS and MISR AOD are also seen owing to fixed and multi angle retrievals especially in Pre-monsoon period over the NW region, where MISR AOD is significantly different from MODIS. There are also some pockets where low AOD region observed by MODIS is alternatively represented as a region of higher AOD in MISR observations, particularly in proximity to the IGP outflow.”



**Figure 3b.** Long term (2011-2020) satellite based AOD (at 550 nm) from MISR over south-Asian region.

### **3.2 Inter-comparison of satellite-ground AOD**

*Query 13: Lines 466-473: This description appears belonging to Figures S7-S9, not S4-S6. Please check and verify. Also, add a brief discussion on satellite vs. ground AOD comparison (MISR underestimates ground AOD at moderate to high aerosol loadings).*

**Response:** We thank the reviewer for pointing this out. We have corrected the relevant text corresponding to Figs. S8–S10 and S11–S13 in the revised manuscript, quantitatively describing the association between satellite and ground-AOD.

**Line 621-629:** “The scatter plots (Supplementary Figs. S8-S10; the number of ground stations included in the correlation studies is given in Table 1) between MODIS/ MISR and ground-based AOD highlight moderate to strong correlations ( $\sim 0.8-0.9$ ) in winter (January) and post-monsoon (November), while moderate correlations ( $\sim 0.54-0.77$ ) between the two are observed in pre-monsoon (May). The RMSE between MISR and ground-based AOD is higher ( $\geq 0.2$ ) during winter and post-monsoon, whereas higher RMSE values between MODIS and ground-based AOD are observed during the pre-monsoon period. The prominent locations contributing to mean errors and weak correlations with ground observations are situated in the NW and IGP regions.”

**Line 630-637:** “The quartile-plots (Figs. S11-S13) highlight significant spatio-temporal variability in AOD, with both sensors displaying higher AOD over terrestrial regions, particularly in the IGP, its outflows, and South (Peninsular) and Central India. The third and fourth quartiles are more representative for AOD over land regions than in surrounding areas like oceans and elevated terrain. Data with respect to longitude and latitude show that higher AOD values are mostly confined to  $20^{\circ}-30^{\circ}\text{N}$  latitude and  $80^{\circ}-95^{\circ}\text{E}$  longitude. However,

MODIS consistently recorded significantly higher AOD values than MISR, with notable dissimilarities in quartile patterns over northern India during May.”

**Line 638-649:** “Both the correlation and quartile analyses highlight the advantages and limitations of MODIS and MISR observations. For example, MISR tends to underestimate high AOD conditions in urban regions compared to MODIS, even though it can effectively separate surface contributions under low aerosol loading, as also reported by Tao et al. (2020). Under high AOD conditions, the benefit of multi-angle measurements becomes limited, as thick aerosol layers smooth out surface reflectance signals (BRDF), potentially leading to an underestimation of AOD due to misattribution of aerosol contributions to surface reflectance. In contrast, when dust loading is dominated by coarse and non-spherical particles (in May), MISR demonstrates relatively better performance than MODIS (as shown by scatter plots). This difference may be attributed to the advantage of MISR’s multi-angle observation capability, consistent with findings from Middle Eastern validation studies (Farahat, 2019; Garay et al., 2017).”

**Query 14: Lines 495-503: This paragraph should go to the beginning of the section 3.2 (also change Figure numbers S7-S9 to S4-S6).**

**Response:** Changes have been made as suggested.

### **Section 3.3.3**

**Query 15: Up to this point, it was unclear whether daily or monthly MODIS/MISR dataset is used in the fusion process. It looks like monthly datasets are used. Please confirm.**

**Response:** Thanks for the suggestion, we have clearly mentioned the use of monthly data sets in the beginning (Section 2.3.1) while discussing about collocation approach.

-END