**Authors' Response**

We sincerely appreciate Referee #1's insightful comments and valuable suggestions, which have helped us improve the clarity and scientific presentation of our manuscript. We have carefully considered all the points raised and made the corresponding revisions.

Below, we provide a point-by-point response to all comments and describe the corresponding changes made to the manuscript. For clarity, the Referee's comments are shown in black, while our responses are shown in red.

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**General comments:**

This manuscript presents a global assessment of the uncertainty in clear-sky surface solar radiation associated with uncertainties in aerosol optical depth (AOD) from the ECMWF Atmospheric Composition Reanalysis 4 (EAC4). The authors derive an empirical AOD expected-error relationship from collocated EAC4 and AERONET observations, propagate the resulting AOD uncertainty to global horizontal irradiance (GHI) and direct normal irradiance (DNI) using radiative kernels derived from radiative transfer simulations, and evaluate the resulting clear-sky irradiance estimates against BSRN observations. The analysis covers a relatively long period (2003–2024) and provides global and seasonal distributions, as well as an analysis of selected high-AOD AERONET sites.

The topic is relevant to both atmospheric radiation and solar-resource assessment, and the manuscript addresses an aspect that has received comparatively less attention than either the validation of surface solar radiation products or the quantification of aerosol radiative effects. In particular, the distinction between the sensitivity of GHI and DNI to AOD uncertainty is potentially valuable. The use of a computationally efficient radiative kernel/LUT approach also provides a potentially useful framework for extending uncertainty calculations to global datasets.

The manuscript is generally well structured, and I consider the scientific question worthwhile and the proposed framework potentially useful. Some aspects of the methodology and interpretation, however, would benefit from clarification and revision to further strengthen the work. The main points are detailed below.

**Specific comments:**

- The manuscript derives an expected-error relationship from the differences between EAC4 and AERONET AOD and subsequently refers to this quantity as "EAC4 AOD uncertainty". The authors should discuss more explicitly the distinction between an empirical expected error relative to AERONET and the intrinsic uncertainty of the EAC4 reanalysis AOD. The EAC4–AERONET differences can contain contributions from AERONET measurement uncertainty, representativeness differences, spatial and temporal collocation errors, systematic model errors, and errors in aerosol speciation and vertical distribution. Therefore, the terminology should be carefully defined throughout the manuscript.

The manuscript should also clarify whether AERONET observations are assimilated, directly or indirectly, into EAC4. If there is any dependence between the two datasets, the degree of independence of the comparison used to derive the expected error should be discussed.

We thank the Referee for this important comment. We agree that the expected-error relationship derived from EAC4–AERONET differences should not be interpreted as a direct estimate of the intrinsic uncertainty of the EAC4 reanalysis. As clarified in Sect. 2.4, our approach provides an empirical, AOD-dependent uncertainty estimate based on the statistical distribution of differences between EAC4 and AERONET observations. These differences may also include contributions from spatial and temporal representativeness errors, collocation uncertainties, and limitations in the representation of aerosol properties and their vertical distribution. Therefore, the estimated uncertainty should be interpreted relative to the AERONET observational reference, rather than as an uncertainty arising exclusively from the EAC4 reanalysis system.

Regarding the independence of the datasets, AERONET observations are not directly assimilated into EAC4, which assimilates satellite-derived AOD observations (Langerock et al., 2024). Therefore, AERONET provides an independent ground-based reference for the evaluation of EAC4 AOD.

To clarify these points, we have added the following text to Sect. 2.2 of the revised manuscript:

"AERONET observations are not directly assimilated into EAC4, which assimilates satellite-derived AOD observations (Langerock et al., 2024). Therefore, AERONET provides an independent ground-based reference for the evaluation of EAC4 AOD."

Furthermore, we have added the following clarification to Sect. 2.4:

"It should be noted that the EAC4–AERONET differences do not exclusively represent errors in the EAC4 AOD, but may also include contributions from spatial and temporal representativeness differences, collocation uncertainties, and limitations in the model representation of aerosol properties and their vertical distribution. Consequently, the derived EE should be interpreted as an empirical estimate of EAC4 AOD uncertainty relative to AERONET observations, rather than a direct measure of the intrinsic uncertainty of the reanalysis."

- Equation (4) in the manuscript removes a fixed AERONET uncertainty of 0.01 in quadrature. This assumes, among other things, that the quoted AERONET uncertainty can be treated as a one-standard-deviation random uncertainty and that it is independent of the EAC4 error. The use of a constant value should also be justified given the different wavelengths, aerosol regimes, stations, and loading conditions involved. Furthermore, the AERONET AOD is not directly available at 550 nm and is obtained through spectral interpolation. The uncertainty introduced by this interpolation should either be quantified or explicitly justified as negligible relative to the EAC4–AERONET differences.

We thank the Referee for this comment. A constant AERONET AOD uncertainty of 0.01 was adopted as a first-order approximation based on the reported accuracy of quality-assured AERONET measurements at visible wavelengths (Giles et al., 2019; Sinyuk et al., 2020). Its removal in quadrature assumes that the AERONET measurement uncertainty can be represented as an independent random contribution, expressed in terms of one standard deviation, to the EAC4–AERONET differences. Although the actual AERONET uncertainty may vary among individual observations, wavelengths, stations, and aerosol conditions, the use of a constant value provides a simplified treatment of the observational uncertainty across the global dataset.

To clarify these assumptions, we have revised the corresponding paragraph in Sect. 2 of the manuscript as follows:

"To obtain the uncertainty of EAC4 AOD ($\sigma_{AOD,EAC4}$), the contribution of AERONET measurement uncertainty ($\sigma_{AOD,\,AER}$) was removed in quadrature. A constant AERONET AOD uncertainty ($\sigma_{AOD,AER}$) of 0.01 was adopted as a first-order approximation based on the reported accuracy of quality-assured AERONET measurements at visible wavelengths (Giles et al., 2019; Sinyuk et al., 2020). This approach assumes that the AERONET measurement uncertainty can be represented as an independent random contribution, expressed in terms of one standard deviation, to the EAC4–AERONET differences. Although the actual AERONET uncertainty may vary among wavelengths, stations, and aerosol conditions, the use of a constant value provides a simplified treatment across the global dataset. The resulting EAC4 AOD uncertainty ($\sigma_{AOD,EAC4}$) is given by:.."

To assess the influence of this assumption, we examined the effect of the quadrature subtraction over an EAC4 AOD range of 0–1.00, using increments of 0.05 up to AOD = 0.50 and increments of 0.25 thereafter (Table R1). The resulting reduction in the expected error decreases from approximately 12.1% at AOD = 0 to 3.7% at AOD = 0.05 and 1.8% at AOD = 0.10, becoming less than 1% for AOD values of 0.20 and above. These results indicate

that the quadrature correction has a relatively limited influence on the derived uncertainty, particularly under moderate and high aerosol-loading conditions.

**Table R1: Sensitivity of the derived AOD uncertainty to the quadrature subtraction of the assumed AERONET uncertainty (0.01).[1]**

| EAC4 AOD | EE | Corrected EE | Difference | Reduction (%) |
|---|---|---|---|---|
| 0.00 | 0.0210 | 0.0185 | 0.0025 | 12.06 |
| 0.05 | 0.0369 | 0.0355 | 0.0014 | 3.74 |
| 0.10 | 0.0528 | 0.0518 | 0.0010 | 1.81 |
| 0.15 | 0.0687 | 0.0680 | 0.0007 | 1.07 |
| 0.20 | 0.0846 | 0.0840 | 0.0006 | 0.70 |
| 0.25 | 0.1005 | 0.1000 | 0.0005 | 0.50 |
| 0.30 | 0.1164 | 0.1160 | 0.0004 | 0.37 |
| 0.35 | 0.1323 | 0.1319 | 0.0004 | 0.29 |
| 0.40 | 0.1482 | 0.1479 | 0.0003 | 0.23 |
| 0.45 | 0.1641 | 0.1638 | 0.0003 | 0.19 |
| 0.50 | 0.1800 | 0.1797 | 0.0003 | 0.15 |
| 0.75 | 0.2595 | 0.2593 | 0.0002 | 0.07 |
| 1.00 | 0.3390 | 0.3389 | 0.0001 | 0.04 |

Furthermore, to assess the influence of spectral interpolation, an additional consistency test was performed using AERONET observations from Lampedusa (2003–2024). AOD at 500 nm was estimated from AOD at 440 nm using the 440–675 nm Ångström exponent and compared with direct measurements at 500 nm. For 141,741 observations, the mean absolute difference was 0.0029, while 96.6% of the differences were within ±0.01. The mean absolute difference between measured AOD at 500 nm and estimated AOD at 550 nm was 0.012. These results suggest relatively small interpolation-related discrepancies at this station, although the test does not directly quantify the interpolation uncertainty at 550 nm.

- The temporal and spatial collocation procedure between EAC4 and AERONET should be described in sufficient detail to make the analysis reproducible. In particular, the authors should specify the temporal matching window and whether the EAC4 value is taken from the nearest grid cell or obtained by spatial interpolation. This is especially important given the 0.75° EAC4 grid and the point-like nature of AERONET observations. Spatial representativeness errors may be significant in regions with strong aerosol gradients.

We thank the Referee for this comment. The spatial and temporal collocation procedure applied in the present study follows the methodology described in Moustaka et al. (2026), which was already referenced in the manuscript. Nevertheless, to improve clarity, we have added the following clarification to the revised manuscript:

“Prior to the uncertainty analysis, the performance of EAC4 against 178 AERONET stations worldwide was evaluated by Moustaka et al. (2026), demonstrating generally very good agreement with the observations (R = 0.84, RMSE = 0.12, MAE = 0.07, RMB = 1.0, and IOA = 0.9, based on 1,657,564 collocated data pairs; see Moustaka et al. (2026) for further details on the collocation procedure).”

We also agree with the Referee that spatial representativeness differences may affect the comparison, particularly in regions characterized by strong aerosol gradients. Another example concerns high-altitude stations, where the mean elevation of the corresponding EAC4 grid cell may be considerably lower than the actual station elevation, potentially resulting in differences in the atmospheric column represented by the observations and the reanalysis. However, this is a well-known limitation when comparing point-based ground observations with spatially averaged quantities from gridded reanalysis products, numerical models, or satellite retrievals, rather than an issue specific to the present analysis.

[1] EE = 0.021 + 0.318 × AOD; corrected EE = $\sqrt{(EE^2 - 0.01^2)}$. The percentage reduction is calculated relative to the uncorrected EE. All AOD values are dimensionless.

- The choice of 500 observations per AOD bin and the use of a linear relationship between expected error and EAC4 AOD should be justified. The authors should assess whether the resulting coefficients (a) and (b) are sensitive to the bin size and whether alternative functional forms provide significantly different uncertainty estimates, particularly at high AOD. This is important because the subsequent global uncertainty field and all propagated GHI/DNI uncertainties are directly dependent on this parameterization.

We thank the Referee for this comment. The selection of 500 observations per bin was intended to provide a balance between a sufficiently large sample for estimating the 68th percentile of the absolute EAC4–AERONET differences and adequate resolution across the AOD range. The linear relationship was adopted as a simple empirical representation of the dependence of expected error on aerosol loading.

Following the Referee's suggestion, we performed additional sensitivity tests using 250, 500, 1,000, and 2,000 observations per bin. The resulting linear coefficients showed only minor variations, with the intercept ranging from 0.02098 to 0.02165 and the slope from 0.31413 to 0.31782. The corresponding differences in the propagated AOD uncertainty were generally below 1% across the examined AOD range, reaching approximately 1% at AOD = 2.

We also compared the original linear relationship with a second-order polynomial fit. For the original 500-observation bins, the quadratic fit slightly reduced the RMSE of the binned expected errors from 0.00732 to 0.00714. However, the differences in the resulting AOD uncertainty estimates remained relatively small, ranging from approximately −3.4% to +1.0% over the examined AOD range of 0.05–2.0. The quadratic relationship therefore did not provide a substantial improvement that would justify introducing additional complexity into the uncertainty parameterization.

These results support the robustness of the original parameterization and the retention of the linear relationship adopted in the manuscript.

Section 2.4 of the manuscript was revised as follows:

“A linear model was then fitted to describe the dependence of EE on EAC4AOD:

$$EE = a + b \cdot \mathrm{AOD}_{\mathrm{EAC4}}, \quad (2)$$

where $a$ and $b$ are regression coefficients, and $AOD_{EAC4}$ denotes the median EAC4 AOD within each equal-population bin. To assess the sensitivity of the derived EE relationship to the bin size and the selected fitting function, additional tests were performed using 250, 500, 1,000, and 2,000 observations per bin, as well as a second-order polynomial fit. The fitted linear coefficients showed only minor variations across the different bin sizes, resulting in differences in the estimated AOD uncertainty generally below 1% over the examined AOD range. The quadratic fit slightly reduced the RMSE of the binned EE estimates from 0.00732 to 0.00714 compared with the linear fit, while the resulting differences in AOD uncertainty remained within approximately −3.4% to +1.0% for AOD values between 0.05 and 2.0. These results indicate that the derived uncertainty estimates are relatively insensitive to the selected bin size and fitting function, supporting the use of the original linear parameterization.”

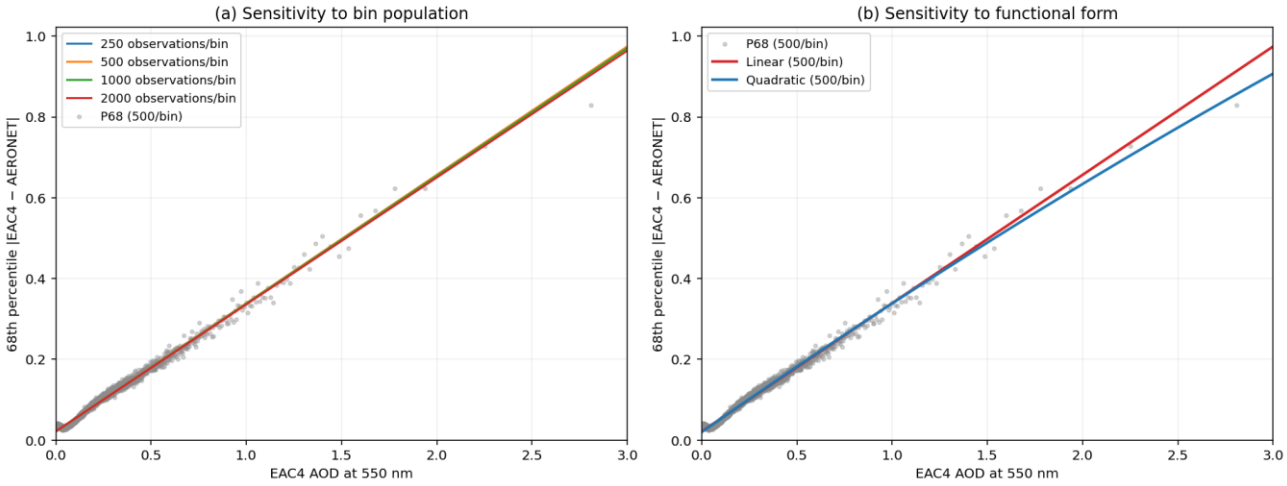



**Figure R1: Sensitivity of the empirical EAC4 AOD expected-error parameterization to (a) the number of observations per AOD bin (250, 500, 1,000, and 2,000) and (b) the selected functional form (linear and quadratic), using 1,666,328 EAC4–AERONET collocated observations from 178 stations. Grey markers indicate the 68th percentile of the absolute AOD differences calculated using 500 observations per bin.**

- The radiative-transfer calculations combine 3-hourly EAC4 AOD with monthly climatological SSA and Ångström exponent, monthly EAC4 TCWV and TCO, monthly surface albedo, and hourly solar geometry. The authors should discuss the implications of this temporal inconsistency. In particular, aerosol optical properties such as SSA and Ångström exponent can exhibit substantial short-term and seasonal variability and may be correlated with aerosol type and AOD. Using monthly climatologies may therefore affect both the baseline irradiance and the calculated AOD sensitivity, especially for DNI. The consistency between the AeroCom SSA/AE climatology and the aerosol representation in EAC4 should also be discussed.

We thank the Referee for this important comment. We agree that aerosol optical properties, particularly SSA and the Ångström exponent, can exhibit substantial temporal variability and may be correlated with aerosol loading and aerosol type. Consequently, the use of monthly climatological values cannot fully represent short-term variations in aerosol optical properties, particularly during specific aerosol events.

In the present study, the 3-hourly EAC4 AOD is used to represent the temporal variability in aerosol loading, while monthly climatological SSA and Ångström exponent values provide the corresponding background aerosol optical properties for the radiative-transfer calculations. This approach was adopted to enable a consistent global, multiyear analysis while limiting the number of varying input parameters.

We acknowledge that the use of monthly climatological aerosol optical properties may influence both the estimated clear-sky irradiance and its sensitivity to AOD, particularly for DNI. Furthermore, the AeroCom climatology and EAC4 aerosol representation are not necessarily fully consistent in terms of aerosol composition and optical properties. Consequently, the radiative-transfer calculations should be interpreted as estimates based on the prescribed aerosol optical properties rather than a fully time-resolved representation of aerosol optical variability.

Importantly, the objective of the present study is to quantify the contribution of EAC4 AOD uncertainty to clear-sky GHI and DNI uncertainty, rather than to provide a comprehensive uncertainty budget accounting for all atmospheric and surface inputs. The potential influence of temporal variability in SSA and the Ångström exponent, as well as inconsistencies between aerosol datasets, is therefore acknowledged as a limitation of the adopted approach.

We have added the following clarifications to Section 4 of the revised manuscript::

“In addition to evaluating the irradiance estimates themselves, the propagated AOD-related uncertainties were assessed against the observed absolute EAC4–BSRN irradiance differences. The observed error distributions increased systematically with the estimated uncertainty, particularly for DNI. When the collocations were

stratified by aerosol loading, both the propagated uncertainty and the observed irradiance discrepancies increased with AOD. These results provide an independent assessment that the AOD-based uncertainty framework captures the systematic increase in irradiance discrepancies associated with increasing aerosol loading. However, the propagated uncertainties represent only the contribution from AOD, whereas the observed EAC4–BSRN differences additionally include uncertainties associated with other atmospheric and surface inputs, radiative transfer modelling, representativeness, measurements, and clear-sky classification. Furthermore, the use of monthly climatological SSA and AE does not account for their short-term variability or their potential correlations with aerosol loading and type. Differences between the aerosol optical properties represented by the AeroCom climatology and the aerosol composition in EAC4 may also introduce additional inconsistencies. These limitations can influence both the calculated irradiances and their sensitivity to AOD, particularly for DNI, and should therefore be considered when interpreting the propagated AOD-related uncertainties."

- Equation (5) expresses the propagated uncertainty as the absolute value of the sensitivity multiplied by the AOD uncertainty. However, in Eq. (7), the absolute value is not used. Since increasing AOD will generally produce a negative perturbation in both GHI and DNI, the kernel is expected to be negative. Please check the consistency of the equation.

We thank the Referee for identifying this inconsistency. The absolute value of the radiative kernel was by mistake omitted from Eq. (7). We confirm that the absolute value was correctly applied in the actual uncertainty calculations, and therefore this typographical error does not affect any of the presented results. Equation (7) has now been corrected to ensure consistency with Eq. (5).

- The BSRN comparison is useful, but it primarily evaluates the clear-sky irradiance estimates generated by the LUT/RTM framework. It does not directly validate the magnitude of the propagated uncertainty estimates. A particularly useful additional analysis would be to compare the observed model–measurement residuals with the predicted propagated uncertainties.

We thank the Referee for this valuable suggestion. We agree that the original BSRN comparison primarily evaluated the accuracy of the EAC4-derived clear-sky irradiance estimates rather than directly assessing the propagated AOD-related uncertainties. This point was also raised by Referee #2, and we have therefore extended the BSRN evaluation to address this concern.

Specifically, for each of the 553,184 collocated clear-sky EAC4–BSRN observations, we compared the absolute irradiance difference, $|F_{EAC4} - F_{BSRN}|$, with the corresponding AOD-propagated irradiance uncertainty estimated using the radiative-kernel approach. The collocations were grouped into 20 equal-population bins according to the estimated uncertainty, and the 68th percentile of the observed absolute differences was calculated for each bin. The results showed that the magnitude of the observed irradiance differences generally increased with increasing propagated uncertainty for both GHI and DNI, with a particularly strong relationship for DNI (Spearman $\rho = 1.00$, compared with $\rho = 0.94$ for GHI, across the uncertainty bins).

We additionally examined the relationship as a function of aerosol loading by grouping the collocations into 15 equal-population bins according to EAC4 AOD. For GHI, the 68th percentile of the observed absolute differences increased from approximately 19 to 28 W m$^{-2}$ across the AOD bins, while the corresponding median propagated uncertainty increased from approximately 3 to 16 W m$^{-2}$. For DNI, the corresponding observed differences increased from approximately 37 to 139 W m$^{-2}$, accompanied by an increase in the median propagated uncertainty from approximately 24 to 81 W m$^{-2}$.

Importantly, the propagated uncertainties quantify only the contribution associated with EAC4 AOD uncertainty, whereas the observed EAC4–BSRN differences also include contributions from other atmospheric and surface inputs, radiative-transfer assumptions, spatial representativeness, measurement uncertainty, and clear-sky classification. Consequently, a one-to-one correspondence between the propagated uncertainty and the observed irradiance differences is not expected.

These additional analyses demonstrate that the proposed uncertainty framework captures the systematic increase in observed irradiance discrepancies with increasing estimated uncertainty and aerosol loading, particularly for

DNI, although it does not represent the total irradiance uncertainty. The corresponding results have been incorporated into Sect. 3.4 of the revised manuscript and Fig. S8 of the Supplement.

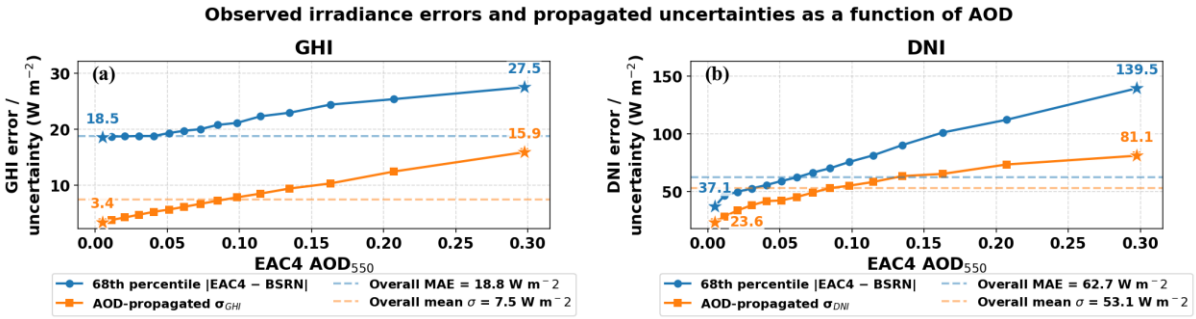



**Figure R2: Observed clear-sky irradiance errors and AOD-propagated uncertainties as a function of EAC4 $AOD_{550}$ for (a) GHI and (b) DNI. Collocations were divided into 15 equal-population bins according to EAC4 $AOD_{550}$. The 68th percentile of the absolute EAC4–BSRN difference (blue) and the median AOD-propagated irradiance uncertainty (orange) are shown for each bin. Dashed horizontal lines indicate the overall mean absolute error (MAE) and mean propagated uncertainty across all collocations, while stars highlight the values in the lowest- and highest-AOD bins. (same with Fig. S8)**

**Technical corrections:**

- Replace "AOD retrieval uncertainty" with "EAC4 AOD uncertainty" or equivalent terminology where appropriate, since EAC4 is a reanalysis rather than a retrieval product.

We thank the Referee for this suggestion. We agree that the term "AOD retrieval uncertainty" is not appropriate when referring to EAC4, as it is a reanalysis product rather than a retrieval product. We have therefore revised the terminology throughout the manuscript, replacing "AOD retrieval uncertainty" with "EAC4 AOD uncertainty" or equivalent wording where appropriate.

- Provide information of the ten high-AOD AERONET stations discussed in Section 3.3.

We thank the Referee for this suggestion. We have added a new table (Table S1) to the revised Supplement, providing detailed information on the ten AERONET stations characterized by the highest long-term mean AOD values over the 2003–2024 period. The table includes the station names, geographical coordinates (latitude and longitude), elevation, and mean AOD at 550 nm. We have also added an explicit reference to this table in Sect. 3.3 of the revised manuscript, complementing the spatial distribution of these stations already presented in Fig. S7.

- Standardize capitalization of geographical terms such as "Southern Hemisphere" and "Northern Hemisphere".

We thank the Referee for pointing this out. We have revised the manuscript to ensure consistent capitalization of geographical terms, including "Northern Hemisphere" and "Southern Hemisphere", throughout the text.

- Check line 320 "indicate" -> indicates.

We thank the Referee for pointing this out. We revised the word from "indicate" to "indicates".

- Ensure consistent use of "clear-sky" throughout the manuscript.

We thank the Referee for this suggestion. We have checked the manuscript and standardized the use of "clear-sky" throughout the manuscript.

- Check consistency in the reporting of units, significant figures, and decimal places for AOD, uncertainty, and irradiance statistics.

We thank the Referee for this suggestion. We have carefully checked the consistency of units, significant figures, and decimal places throughout the manuscript. Units are reported consistently, while numerical values in the figures and tables are generally presented with greater precision to facilitate quantitative comparisons. In the

manuscript text, values are often rounded and reported as approximate quantities to improve readability and emphasize the main findings. We consider this distinction appropriate, as it does not introduce inconsistencies in the reported results.

- Figure 3 – Please consider if the colour scale used for the AOD uncertainty map should be changed. Since most uncertainty values are substantially below 1, using the same 0–1 scale as the AOD panel, greatly reduces the visual contrast of the uncertainty field. A separate, different scaled colour bar for Fig. 3b would allow the spatial variability of the estimated uncertainty to be assessed more clearly.

We thank the Referee for this suggestion. Following the Referee's recommendation, we have prepared an alternative version of Fig. 3 with separate colour scales for AOD and its estimated uncertainty, which is provided below (Fig. R3).

Although the separate scales enhance the visual contrast of the uncertainty field, we consider that the original representation, using a common colour scale, offers an important advantage by allowing a more direct comparison of the absolute magnitudes of AOD and its associated uncertainty. In particular, the use of identical colours for identical numerical values facilitates the interpretation of the uncertainty relative to the corresponding AOD values.

For this reason, we would prefer to retain the original version of Fig. 3 in the manuscript, while providing the alternative representation here for comparison.

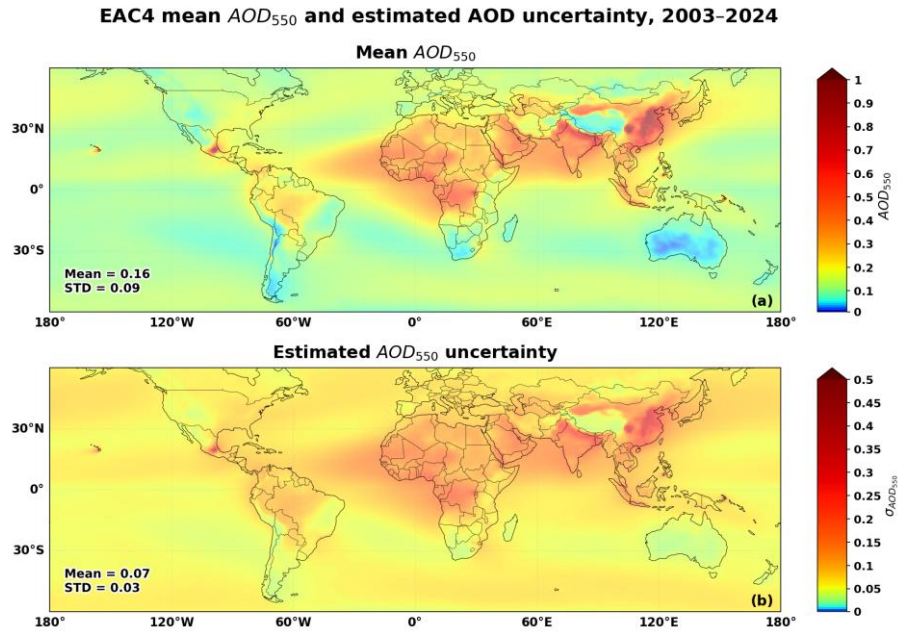



**Figure R3: Same with Fig. 3 but with different colorbars for the absolute AOD and its uncertainty as proposed by the Referee.**