Authors' Response

We thank Referee #2 for the careful evaluation of our manuscript and for the constructive comments and suggestions. We have revised the manuscript accordingly.

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.

This work presents an approach for estimating the uncertainty of the aerosol optical depth (AOD) provided by the ECMWF Atmospheric Composition Reanalysis 4 (EAC4) and for assessing its impact on clear-sky solar irradiance. The approach relies on a linear parameterization of the AOD estimation uncertainty as a function of the EAC4 AOD, followed by the propagation of this uncertainty into solar irradiance estimates using a radiative-kernel approach.

The topic is highly relevant for a wide range of applications in which the accuracy of clear-sky solar irradiance estimates is important, particularly for solar resource assessment. The proposed framework is interesting and provides a potentially useful contribution to the quantification of aerosol-related uncertainties in surface solar radiation estimates. Overall, I find the approach promising and the topic relevant to the scope of the journal. However, several aspects of the methodology and their underlying assumptions would benefit from further clarification and discussion, as detailed in the comments below.

General comments:

1. The proposed approach relies on several assumptions regarding the spatial and temporal "stationarity" of the AOD uncertainty. In particular, the linear relationship between AOD and its estimation error is assumed to be spatially homogeneous and to remain valid for periods other than the one used to derive the regression.

This assumption may be particularly important under extreme or unusual aerosol conditions, for which the actual AOD uncertainty could differ substantially from that predicted by the model. It would therefore be useful to clarify more explicitly what type of uncertainty is being quantified by the proposed approach. As currently formulated, the resulting uncertainty appears to represent a statistical or climatological characterization of the AOD estimation error, rather than an uncertainty that dynamically responds to the specific atmospheric conditions at a given time and location.

This distinction is important for interpreting the resulting uncertainty in the propagated solar irradiance estimates and should be discussed more explicitly in the manuscript.

We thank the Referee for this important comment. We agree that the nature of the uncertainty quantified by the proposed approach and the assumptions underlying its application should be more explicitly stated. The AOD uncertainty used in this study represents a statistical characterization of the EAC4 AOD error derived from the distribution of differences between EAC4 and AERONET observations over the 2003–2024 period. The fitted relationship describes the expected magnitude of the AOD error as a function of the EAC4 AOD itself and is subsequently applied globally and throughout the study period. Therefore, although the estimated uncertainty varies in space and time through the corresponding EAC4 AOD values, the coefficients of the uncertainty parameterization are fixed and do not explicitly account for additional dependencies on aerosol type, geographical region, season, or other atmospheric conditions.

We agree that this distinction is particularly relevant under unusual or extreme aerosol conditions, for which the actual EAC4 AOD error may deviate from that represented by the global statistical relationship. Indeed, the normalized-error distribution presented in Fig. S1 already indicates broader tails than an idealized Gaussian distribution, suggesting that the adopted linear parameterization does not fully capture the largest error cases. We have therefore revised Sect. 2.4 to clarify the statistical nature of the derived AOD uncertainty and the assumptions of spatial and temporal applicability of the fitted relationship. We have also added a discussion of this limitation and its implications for the interpretation of the propagated GHI and DNI uncertainties.

Specifically, to clarify the statistical nature of the derived AOD uncertainty and the assumptions underlying its spatial and temporal applicability, we have added the following explanation to Sect. 2.4 of the revised manuscript:

"This formulation provides a statistically derived, AOD-dependent estimate of uncertainty for EAC4, allowing the estimated uncertainty to increase with aerosol loading. The parameterization represents the statistical distribution of EAC4–AERONET differences over the 2003–2024 period rather than a dynamically estimated uncertainty for individual atmospheric conditions. Although the resulting uncertainty varies in space and time according to the corresponding EAC4 AOD, the fitted coefficients are applied uniformly across the study domain and period and therefore do not explicitly account for possible dependencies of the EAC4 error on geographical region, season, aerosol type, or other atmospheric conditions. Consequently, the estimated uncertainty should be interpreted as an expected statistical uncertainty conditional on EAC4 AOD."

2. The evaluation of the proposed uncertainty model remains limited. In particular, the evaluation using BSRN appears to focus on the accuracy of the EAC4 clear-sky irradiance itself, rather than on the ability of the proposed uncertainty model to characterize the actual errors.

A comparison between the observed EAC4 clear-sky irradiance errors and the uncertainty estimated by the proposed approach would therefore be highly relevant. Such an analysis would help assess whether the estimated uncertainties are consistent with the actual distribution of errors and, in particular, whether they provide an adequate characterization of the uncertainty under different atmospheric conditions.

We thank the Referee for this valuable suggestion. We agree that the original BSRN evaluation primarily assessed the performance of the EAC4-derived clear-sky irradiance estimates, rather than directly evaluating the propagated AOD-related irradiance uncertainty. The validation of the irradiance estimates themselves was included because these clear-sky GHI and DNI products are also being used in an upcoming study focusing on clear-sky irradiance trends, in which the derived irradiance dataset will be made publicly available for use in future studies. An evaluation of the irradiance estimates against ground-based observations was therefore considered an important prerequisite for establishing the quality of the derived dataset.

Nevertheless, we fully agree with the Referee that, in the context of the present manuscript, which specifically focuses on the propagation of AOD uncertainty into clear-sky irradiance, a direct assessment of the propagated uncertainty is crucial. We have therefore extended the BSRN analysis to compare the observed clear-sky irradiance differences between the EAC4-derived estimates and BSRN observations with the corresponding propagated irradiance uncertainties estimated from the AOD uncertainty framework.

Specifically, for each of the 553,184 collocated clear-sky EAC4–BSRN observations, we calculated the absolute observed irradiance difference as $|F_{EAC4} - F_{BSRN}|$ and compared its distribution with the corresponding AOD-induced propagated uncertainty, σ_F, derived using the radiative-kernel approach. To assess whether the estimated uncertainty reflects changes in the magnitude of the observed errors, the collocations were grouped into equal-population bins according to the estimated σ_F, and the 68th percentile of the absolute EAC4–BSRN differences was calculated for each bin. A clear increase in the observed error magnitude with increasing estimated uncertainty was found for both irradiance components. The relationship was particularly strong for DNI, for which the 68th percentile of the observed error increased monotonically with the estimated uncertainty (Spearman $\rho = 1$ across the uncertainty bins). For GHI, a similarly increasing, although weaker, relationship was observed (Spearman $\rho = 0.94$ across the uncertainty bins).

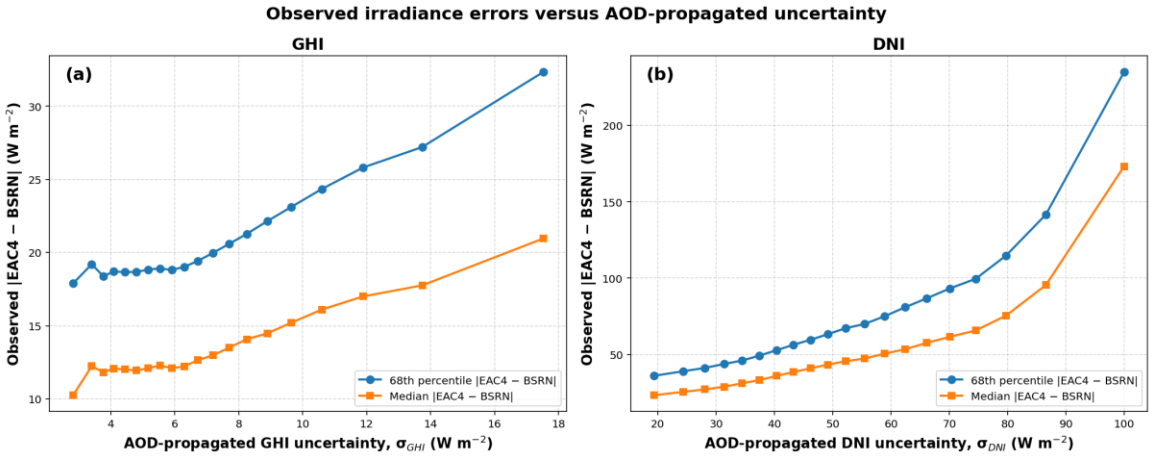

Figure R1: Relationship between the AOD-propagated irradiance uncertainty and the observed absolute EAC4–BSRN clear-sky irradiance differences for (a) GHI and (b) DNI. The 553,184 collocations were divided into 20 equal-population bins according to the propagated uncertainty. Symbols represent the median and 68th percentile of the absolute EAC4–BSRN differences within each bin.

We additionally examined the behaviour as a function of aerosol loading by grouping the collocations according to EAC4 AOD. For GHI, the 68th percentile of the observed absolute error increased from approximately 19 W m^{-2} under low-AOD conditions to approximately 28 W m^{-2} in the highest AOD bin, while the corresponding median AOD-propagated uncertainty increased from approximately 3 to 16 W m^{-2}. The response was considerably stronger for DNI, for which the 68th percentile of the observed error 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}. These results indicate that the proposed AOD-dependent uncertainty framework captures the systematic increase in observed irradiance discrepancies with increasing aerosol loading, particularly for DNI.

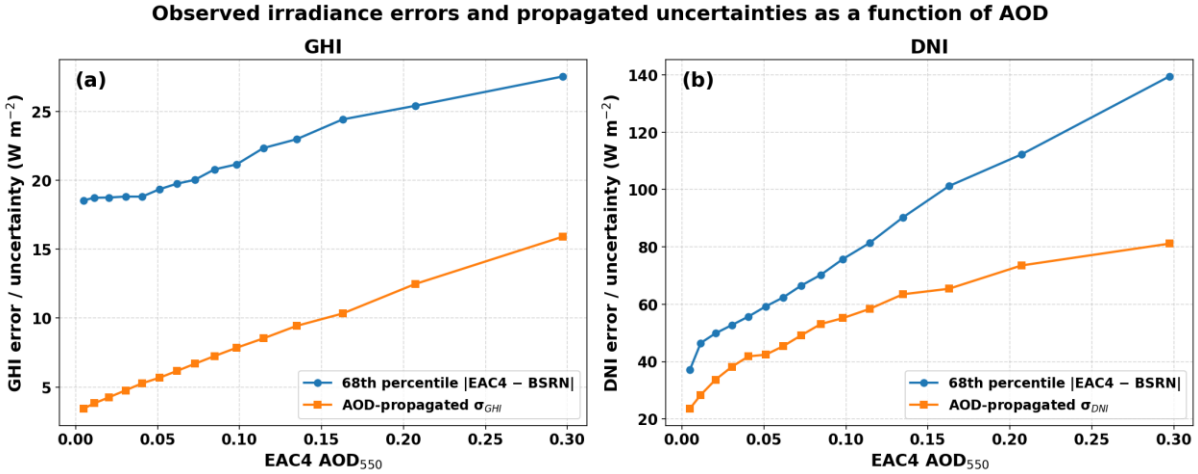

Figure R2: Observed clear-sky irradiance errors and AOD-propagated uncertainties as a function of EAC4 AOD for (a) GHI and (b) DNI. Collocations were divided into 15 equal-population bins according to EAC4 AOD. The 68th percentile of the absolute EAC4–BSRN difference and the median AOD-propagated irradiance uncertainty are shown for each bin.

We emphasize, however, that the propagated σ_F considered in this study represents only the contribution of EAC4 AOD uncertainty to the irradiance uncertainty. In contrast, the observed EAC4–BSRN differences represent the total discrepancy and also include contributions from other atmospheric and surface inputs, radiative-transfer assumptions, spatial representativeness, clear-sky identification, and measurement uncertainty. Therefore, a one-to-one correspondence between the propagated AOD-induced uncertainty and the observed EAC4–BSRN error is neither expected nor assumed. This distinction is particularly evident for GHI, for which the observed errors are larger than the AOD-induced uncertainty, whereas for DNI the AOD-induced uncertainty constitutes a

substantially larger contribution to the observed discrepancies. The corresponding comparison has been added to Sect. 3.4 and is presented in Fig. S8 of the revised Supplement (shown here as Fig. R2).

Specific comments:

L11-13 : “Despite the increasing use of atmospheric reanalysis products for solar resource assessment, the propagation of aerosol-related uncertainty into SSR calculations remains insufficiently quantified”

The logical connection introduced by “Despite” is not entirely clear. The increasing use of atmospheric reanalysis products for solar resource assessment does not, by itself, seem to contrast with the insufficient quantification of aerosol-related uncertainty in SSR calculations. Please clarify the intended link between these two statements, or consider rephrasing the sentence.

We thank the Referee for pointing this out. We agree that the original wording did not clearly express the intended contrast. The sentence has therefore been rephrased to clarify that, despite the increasing application of atmospheric reanalysis products in solar resource assessment, the quantification and propagation of aerosol-related uncertainties remain insufficiently addressed. The revised sentence now reads: “Atmospheric reanalysis products are increasingly used for solar resource assessment; however, the propagation of aerosol-related uncertainty into surface solar radiation (SSR) calculations remains insufficiently quantified.”

L15-17 : « Prognostic AOD uncertainties are calculated using collocated EAC4 and Aerosol Robotic Network (AERONET) observations, while the resulting global mean relative AOD uncertainty is approximately 47%. »

The use of “while” is unclear here, as the two clauses do not seem to express a contrast. If the second clause is intended to report the result of the uncertainty calculation described in the first clause, “resulting in” or “yielding” might be more appropriate.

We thank the Referee for this comment. The word “while” has been replaced by “yielding” to make clear that the reported global mean relative AOD uncertainty is the result of the preceding uncertainty calculation. In addition, following the clarification provided in response to General Comment 1, the term “prognostic” has been removed. The revised sentence now reads: “AOD uncertainties are calculated using collocated EAC4 and Aerosol Robotic Network (AERONET) observations, yielding a global mean relative AOD uncertainty of approximately 47%.

L110: “automatedcloud” a space is missing

We thank the Referee for noticing this typo in our manuscript. We revised accordingly.

Fig1: you represents the surface albedo at 550nm which is not consistent with the text that mention the use of a broadband albedo (line 150).

We thank the Referee for identifying this inconsistency. The reference to broadband surface albedo in the text was inaccurate. HAMSTER provides spectrally resolved surface albedo, and in the present study the HAMSTER albedo at 550 nm was used as input to the LUT. The LUT assumes a spectrally constant surface albedo, such that the value at 550 nm is applied across the wavelength range of the radiative transfer calculations. We have revised the description in Sect. 2.3 accordingly. The label in Fig. 1 has therefore been retained, as it correctly represents the HAMSTER surface albedo value used as input to the LUT.

Specifically, the revised manuscript now reads:

“Surface albedo information was derived from the HAMSTER dataset (Roccetti et al., 2024). The HAMSTER surface albedo at 550 nm was used as input to the LUT and was assumed to be spectrally constant across the wavelength range of the radiative transfer calculations.”

L148-149: you decided to use monthly average values for TCWV and TCO, which is an important methodological choice. Knowing that these quantities are available in EAC4, can you explain the motivations and the consequences of this choice?

We thank the Referee for highlighting this methodological choice. We clarify that the TCO and TCWV inputs used in the irradiance calculations are monthly 3-hourly mean fields, i.e. separate monthly mean fields are used for each 3-hourly UTC time step (00:00, 03:00, 06:00, …, 21:00 UTC), rather than a single monthly mean field (we revised parts of the manuscript where it wasn't clear). This approach was adopted to retain the seasonal and diurnal variability of these atmospheric constituents while reducing the computational requirements of the global 2003–2024 calculations.

To quantify the consequences of this choice, we additionally performed a sensitivity analysis for 2024 using the original 3-hourly EAC4 TCO and TCWV fields. Clear-sky GHI and DNI were recalculated by replacing the monthly-3-hourly TCO and TCWV inputs with their corresponding 3-hourly values, while keeping AOD, SSA, Ångström exponent, surface albedo, and solar zenith angle unchanged. Separate calculations were performed by replacing only TCO, only TCWV, and both TCO and TCWV with their 3-hourly values, allowing their individual and combined effects to be quantified.

For the combined TCO and TCWV experiment, the annual median absolute difference between the irradiances calculated using the monthly-hourly and 3-hourly fields was 1.43 W m^{-2} for GHI and 3.31 W m^{-2} for DNI, corresponding to median relative differences of 0.50% and 0.58%, respectively. The corresponding 95th-percentile absolute differences were 15.09 W m^{-2} for GHI and 23.25 W m^{-2} for DNI, equivalent to relative differences of 3.19% and 4.20%, respectively. The sensitivity was predominantly associated with TCWV.

The spatial and seasonal variability of the combined effect is shown in Figs. R3–R4, where the monthly maps present the median absolute irradiance difference calculated independently at each grid cell from the daytime 3-hourly values within each month. The maps show that the typical effect varies geographically and seasonally but remains relatively small over large parts of the study domain, with larger median differences occurring in specific regions and periods. The spatial patterns are more pronounced for DNI than for GHI, consistent with the larger absolute differences obtained for DNI in the statistical analysis.

Overall, the sensitivity analysis indicates that the use of monthly-hourly TCO and TCWV fields has a relatively small influence on the calculated clear-sky irradiance for the majority of cases, with annual median relative differences below 1% for both GHI and DNI. Larger differences can occur in the upper tail of the distribution, as indicated by the 95th-percentile results, and the sensitivity is primarily associated with the temporal averaging of TCWV rather than TCO.

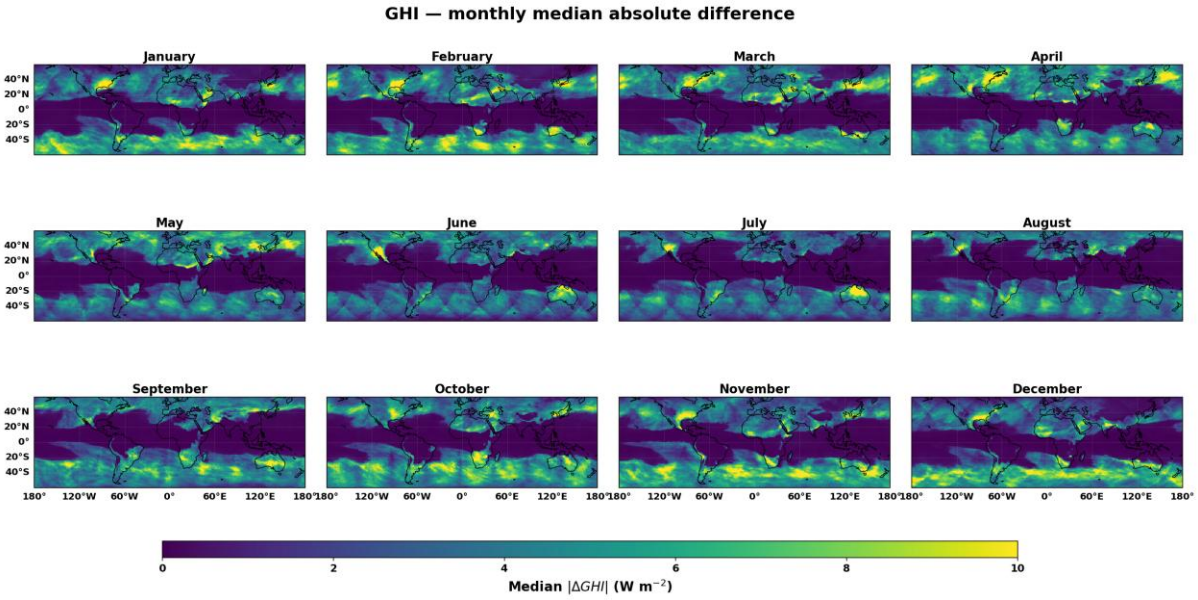

Figure R3: Monthly spatial distribution of the median absolute GHI difference resulting from the use of monthly 3-hourly mean TCO and TCWV fields instead of the corresponding original 3-hourly EAC4 values during 2024. The median is calculated independently at each grid cell from the daytime 3-hourly absolute GHI differences within each month.

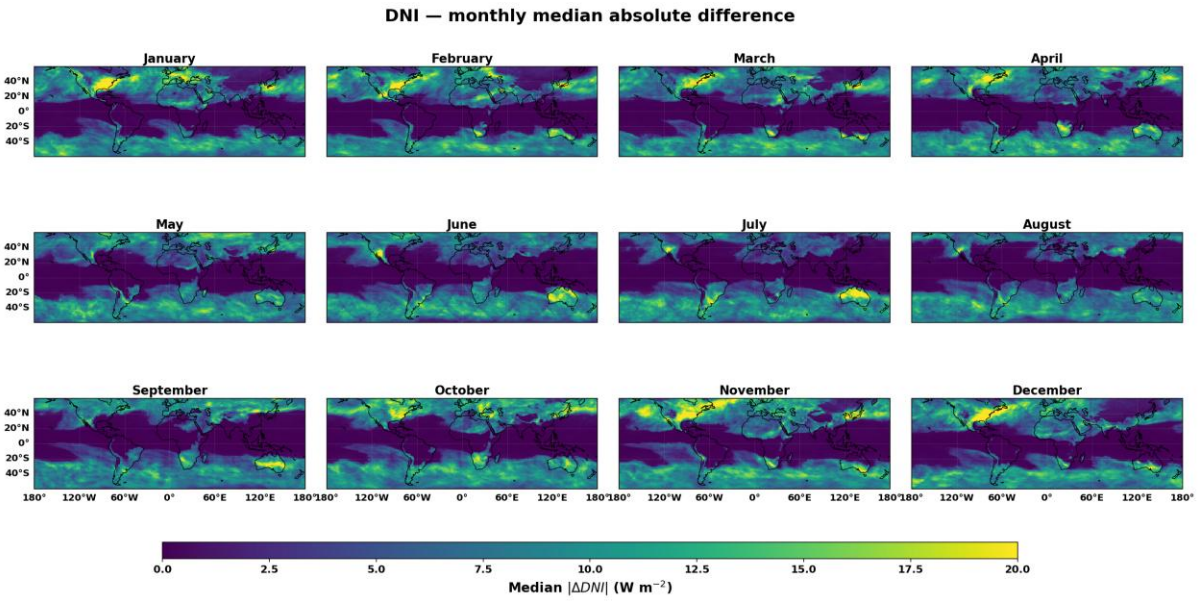

Figure R3: Same with Fig. R3 but for DNI.

Eq.4 This equation presumes that a+b AOD is less than 0.01. This is guaranteed by the value of a and the fact that AOD>0. Maybe add a sentence?

We thank the Referee for raising this point. For Eq. (4), the condition required for a real-valued uncertainty is that $a + b \cdot \mathrm{AOD}_{EAC4}$ is greater than or equal to 0.01. With the fitted values a = 0.021 and b = 0.318, and since the AOD values considered are non-negative, this condition is always satisfied. We have added a sentence after Eq. (4) to state this explicitly.

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.

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.”

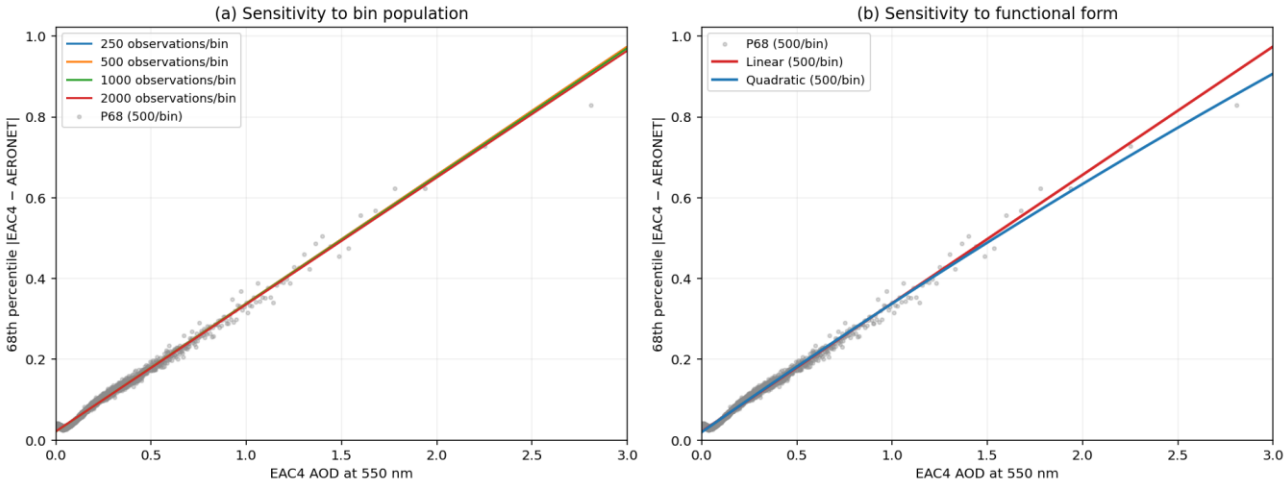

Figure R1: Sensitivity of the empirical EAC4 AOD expected-error parameterization to (a) the number of observations per AOD bin (250, 500, 1,000, and 2,000) and (b) the selected functional form (linear and quadratic), using 1,666,328 EAC4–AERONET collocated observations from 178 stations. Grey markers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

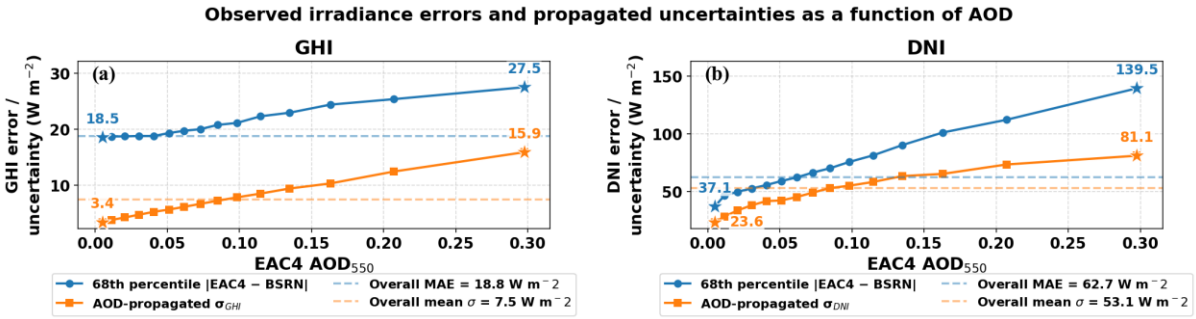

Figure R2: Observed clear-sky irradiance errors and AOD-propagated uncertainties as a function of EAC4 AOD_{550} for (a) GHI and (b) DNI. Collocations were divided into 15 equal-population bins according to EAC4 AOD_{550}. The 68th percentile of the absolute EAC4–BSRN difference (blue) and the median 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.

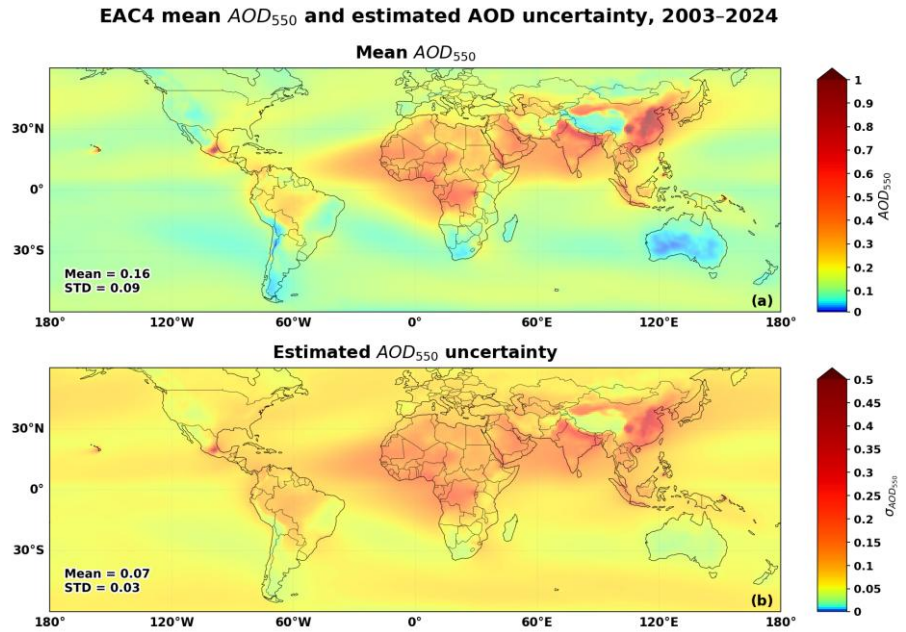

Figure R3: Same with Fig. 3 but with different colorbars for the absolute AOD and its uncertainty as proposed by the Referee.