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).

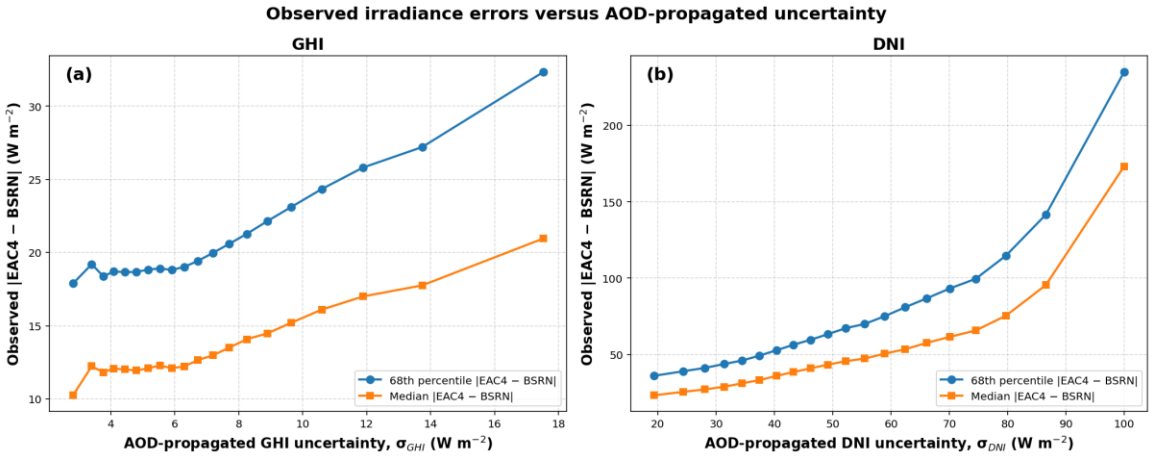


Figure R1: Relationship between the AOD-propagated irradiance uncertainty and the observed absolute EAC4–BSRN clear-sky irradiance differences for (a) GHI and (b) DNI. The 553,184 collocations were divided into 20 equal-population bins according to the propagated uncertainty. Symbols represent the median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

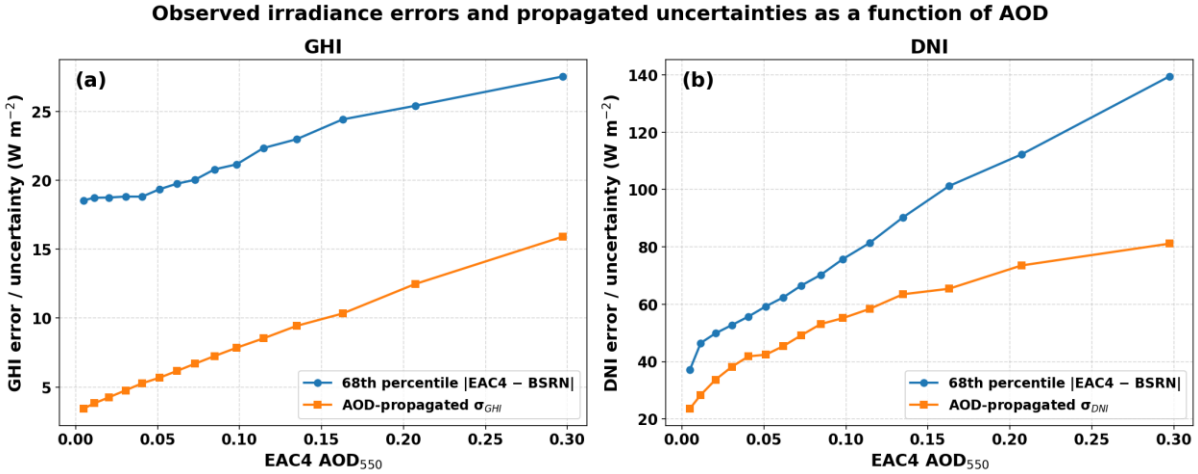


Figure R2: Observed clear-sky irradiance errors and AOD-propagated uncertainties as a function of EAC4 AOD for (a) GHI and (b) DNI. Collocations were divided into 15 equal-population bins according to EAC4 AOD. The 68th percentile of the absolute EAC4–BSRN difference and the median AOD-propagated irradiance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

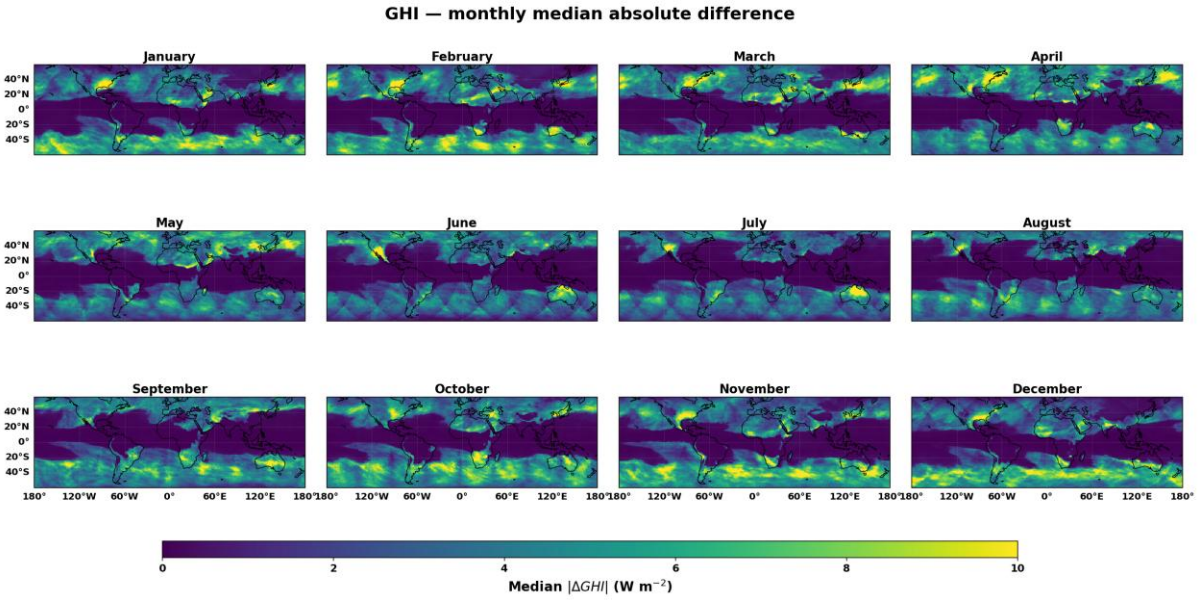


Figure R3: Monthly spatial distribution of the median absolute GHI difference resulting from the use of monthly 3-hourly mean TCO and TCWV fields instead of the corresponding original 3-hourly EAC4 values during 2024. The median is calculated independently at each grid cell from the daytime 3-hourly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

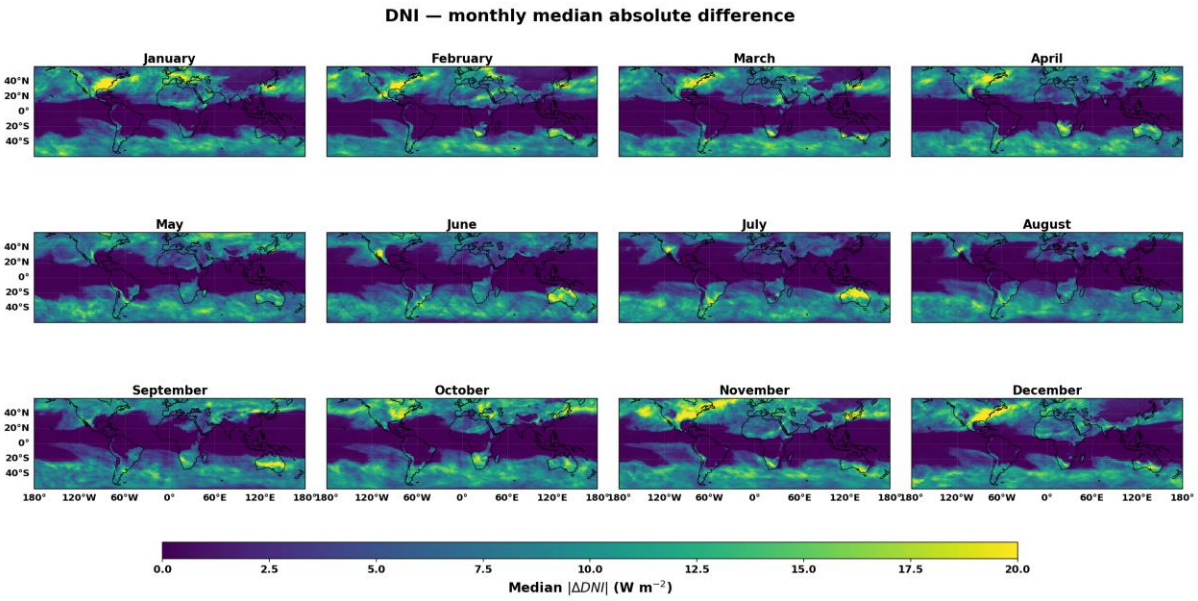


Figure R3: Same with Fig. R3 but for DNI.

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.