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Diurnal Sensitivity of Surface Solar Radiation to Aerosol Loading: A DISORT-Based Radiative Transfer Study

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ABSTRACT
Aerosols modify surface solar radiation primarily through extinction processes involving scattering and absorption, with impacts that depend strongly on solar geometry and aerosol optical properties. Despite widespread use of radiative transfer models, limited attention has been given to isolating the sensitivity of diurnal surface irradiance to aerosol loading under controlled parameter assumptions in aerosol rich regions such as West Africa. In this study, the Discrete Ordinate Radiative Transfer (DISORT) method is used to quantify the diurnal response of clear sky surface solar irradiance to varying aerosol optical thickness (AOT). Simulations were conducted at 10 minutes intervals from sunrise to sunset for AOT values of 0.5, 0.85, and 1.2, representing low to high aerosol loading, while single scattering albedo and backscattering fraction were held constant to isolate first-order AOT effects. Results show that increasing AOT leads to systematic attenuation of surface irradiance throughout the day, with midday reductions of approximately 15–30% relative to moderate aerosol conditions and stronger relative losses during early morning and late afternoon due to enhanced optical air mass. The study highlights the angular dependence of aerosol radiative effects and demonstrates the usefulness of idealized DISORT simulations as a baseline framework for understanding diurnal solar energy availability under heavy aerosol loading. Model assumptions and uncertainties are discussed to clarify the scope and applicability of the results.

Keywords:
Aerosols,
Solar radiation,
Radiative transfer,
DISORT,
Aerosol optical Thickness,
Direct radiative effect

INTRODUCTION

Solar radiation reaching the Earth's surface under clear sky conditions is strongly modulated by atmospheric aerosols through extinction processes involving scattering and absorption (Akinyoola *et al.*, 2024). From a radiative transfer perspective, aerosol impacts depend on aerosol optical thickness, single scattering albedo, phase function, and solar zenith angle, all of which jointly determine the angular redistribution and attenuation of incoming solar flux (Fitzpatrick *et al.*, 2004). These processes are particularly important in aerosol rich environments, where relatively small changes in aerosol loading can produce substantial variations in surface irradiance (Zhao *et al.*, 2024).

Aerosols influence climate and energy systems primarily through their direct radiative effect, whereby particles scatter solar radiation back to space or absorb it within the atmosphere, reducing the amount available at the surface (Akinyoola *et al.*, 2024). While aerosols may also act as cloud condensation nuclei, it is important to explicitly isolate the direct aerosol effect under clear sky condition so that conceptual ambiguity between aerosol radiation and aerosol cloud interactions can be avoided (Cairo *et al.*, 2024).

Despite extensive observational and modeling work, aerosol radiative forcing remains one of the largest sources of uncertainty in climate assessments (Bhatti *et al.*, 2025).

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This uncertainty arises not only from aerosol spatial and temporal variability but also from assumptions embedded within radiative transfer models, such as fixed optical properties or simplified vertical distributions (Lee *et al.*, 2023). Many previous studies emphasize regional impacts or observational correlations, yet fewer studies explicitly explore how surface solar irradiance responds to controlled variations in aerosol optical thickness within a physically transparent radiative transfer framework (Kim *et al.*, 2025).

In West Africa, frequent Saharan dust outbreaks, biomass burning, and urban pollution result in persistently high aerosol loading (Georgakopoulou *et al.*, 2024). While these conditions motivate regional studies, they also raise an important question that; to what extent can idealized, one dimensional radiative transfer simulations capture the first order sensitivity of surface irradiance to aerosol loading before introducing additional complexity such as mixed aerosol types or vertical layering (Fan *et al.*, 2025). This study addresses the above question by employing a DISORT-based radiative transfer model to systematically examine the diurnal sensitivity of surface solar radiation to aerosol optical thickness under clear sky conditions. This work introduces new aerosol parameterizations, but explicitly quantify the angular and diurnal dependence of aerosol induced attenuation using controlled parameter variation. By doing so, the study provides a physically interpretable baseline against which more complex regional aerosol scenarios can be evaluated.

MATERIALS AND METHODS

Research Design

A numerical modeling approach was adopted to isolate the direct radiative effect of aerosols on surface solar radiation under clear-sky conditions. By excluding clouds and fixing selected aerosol optical properties, the simulations focus on first order sensitivities associated with aerosol loading and solar geometry (Chesnoiu *et al.*, 2024; Yoo *et al.*, 2025).

Radiative Transfer Model

Surface solar irradiance was computed by solving the radiative transfer equation using the Discrete Ordinate Radiative Transfer (DISORT) method. The model was implemented in Fortran and executed within the Plato Integrated Development Environment. DISORT was configured for plane-parallel, one-dimensional radiative transfer under broadband shortwave conditions.

Input Parameters and Assumptions

The simulations employed a solar constant of 1361 W m^{-2} and were conducted at 10 minutes intervals between 06:00 and 18:00 local time, corresponding to solar zenith angles ranging from 90° to 0° and back to 90°. Aerosol optical thickness values of 0.5, 0.85, and 1.2 were selected to represent low, moderate and high aerosol loading conditions, respectively. Single scattering albedo (SSA = 0.9) and backscattering fraction (0.04) were held constant across all simulations, implicitly representing a moderately scattering aerosol type. This assumption was made to isolate the influence of AOT and solar geometry, rather than to reproduce specific aerosol mixtures. Surface albedo was assumed to be constant and representative of typical land conditions. The atmosphere was treated as vertically homogeneous with respect to aerosol distribution, consistent with a column-integrated sensitivity analysis (Aebi *et al.*, 2020).

Model Validation

Simulated aerosol optical properties were cross-checked against observational datasets from AERONET and MODIS to ensure physical realism and consistency with observed aerosol conditions.

Uncertainty Considerations

Given the idealized nature of the simulations, the results are interpreted as first-order estimates. Variations in SSA, aerosol vertical distribution, and surface albedo are expected to modify absolute irradiance values but not the fundamental diurnal patterns identified here.

RESULTS AND DISCUSSION

The solar radiation was calculated by varying the Aerosol Optical Thickness (AOT) and keeping other parameters constant (Single Scattering Albedo = 0.9, Backscattering Fraction = 0.04, and Solar Constant = 1361 W/m²).

Diurnal Variation at Low Aerosol Loading (AOT = 0.5)

Figure 1 illustrates the diurnal variation of surface solar irradiance under low aerosol loading (AOT = 0.5). As shown in Figure 1, irradiance is very low during early morning (06:00–07:00 LT) when the solar zenith angle approaches 90°, resulting in a long atmospheric path length and enhanced aerosol scattering and absorption (Eltbaakh *et al.*, 2012; Jiang *et al.*, 2024). As the Sun rises, irradiance increases steadily, exceeding 1000 W m^{-2} by late morning. A maximum value of approximately 1217.56 W m^{-2} is recorded at solar noon when the zenith angle is minimal, consistent with radiative transfer expectations (Korpela *et al.*, 2025; Natsis *et al.*, 2024). The afternoon decline mirrors the morning increase, confirming the dominant role of solar geometry modulated by aerosol extinction. Similar diurnal behavior has been reported by Czerwińska and Krzyścin (2024) and Jiang *et al.*, (2024). Irradiance increases steadily from sunrise as the solar zenith angle decreases, reaching a maximum of approximately 1218 W m^{-2} near solar noon, before declining symmetrically toward sunset. Aerosol-induced attenuation is strongest during early morning and late afternoon, when the optical air mass is largest, enhancing extinction along the solar path.

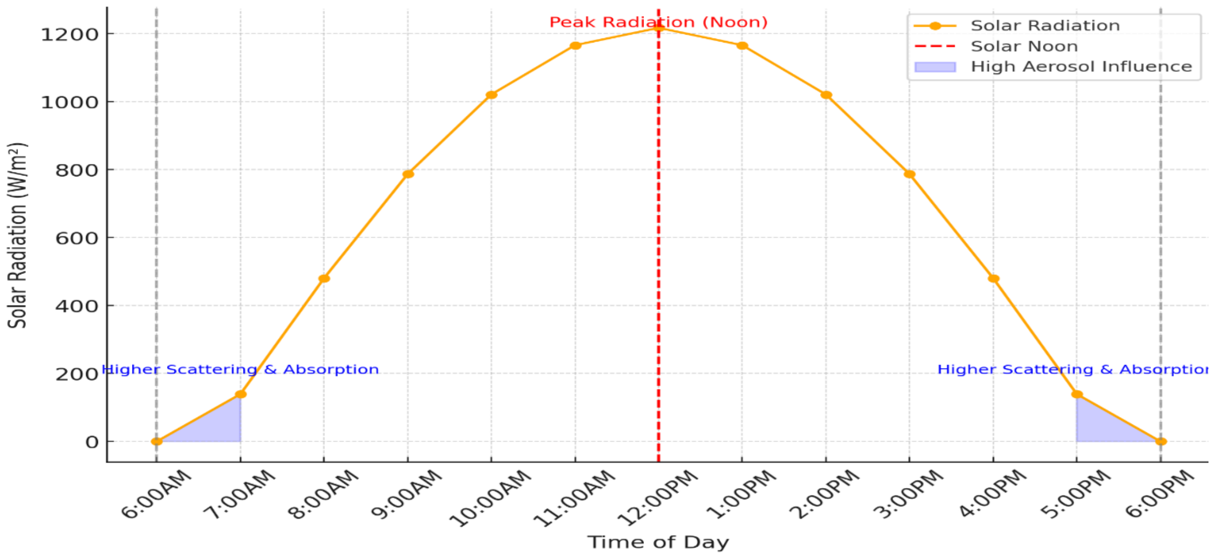

Figure1: Diurnal variation of surface solar irradiance under low aerosol loading

Diurnal Variation at Moderate Aerosol Loading (AOT = 0.85)

Figure 2 presents the diurnal variation of surface solar irradiance for a moderate aerosol loading (AOT = 0.85). Compared with Figure 1, irradiance values are systematically reduced across all times of the day. The noon peak decreases to approximately 1039.19 W m⁻², corresponding to about a 15% reduction relative to AOT = 0.5. This attenuation reflects enhanced aerosol scattering and absorption under increased column loading, consistent with previous DISORT-based and observational studies (Aebi *et al.*, 2020; Melhem *et al.*, 2025; Chakraborty & Das, 2025). Despite the reduced magnitude, the symmetry of the curve about solar noon is preserved, emphasizing that aerosol loading primarily modulates irradiance amplitude rather than diurnal structure.85, the diurnal shape of the irradiance curve remains similar, but absolute values are systematically reduced. Midday irradiance decreases to approximately 1039 W m⁻², representing a reduction of about 15% relative to the low aerosol case. This reduction reflects enhanced scattering and absorption as aerosol optical depth increases, while the persistence of diurnal symmetry highlights the dominant role of solar geometry.

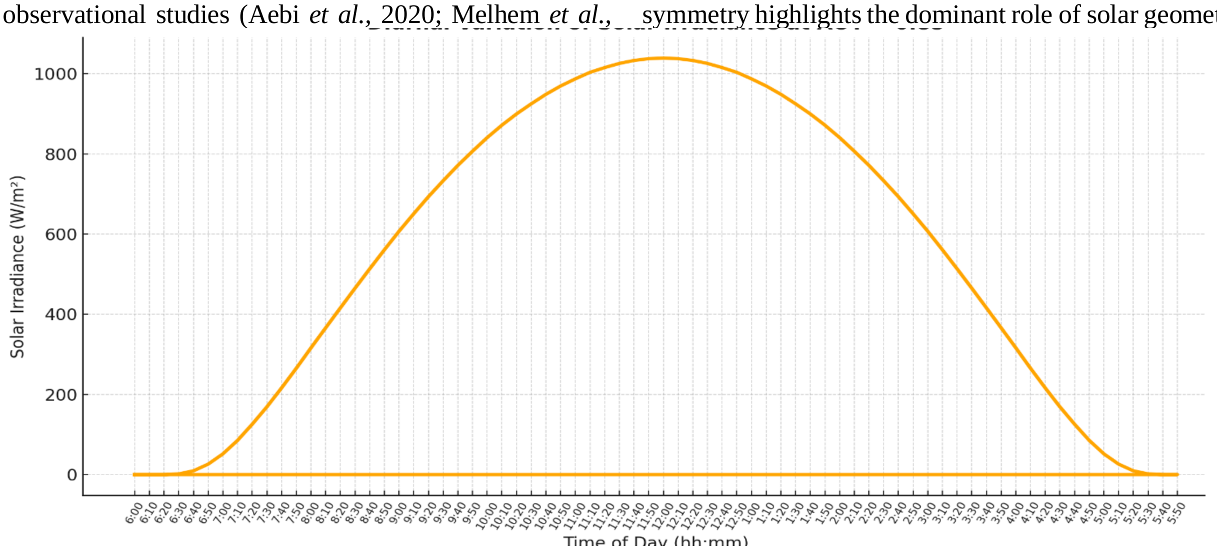

Figure 2: Diurnal variation of surface solar irradiance for a moderate aerosol loading (AOT = 0.85)

Diurnal Variation at High Aerosol Loading (AOT = 1.2)

Figure 3 shows the diurnal variation of surface solar irradiance under very high aerosol loading (AOT = 1.2). Strong aerosol extinction significantly suppresses irradiance throughout the day. The maximum noon value drops to approximately 859.98 W m^{-2}, representing a reduction of nearly 30% relative to the low aerosol case and about 17% relative to AOT = 0.85. Morning and evening irradiance values are particularly diminished due to the combined effects of large solar zenith angles and high aerosol optical depth. These findings agree well with recent studies by Chauhan *et al.,* (2024), Ashgezari and Bidhendi (2025), and Igbawua *et al.,* (2025), which reported strong attenuation of surface radiation under heavy aerosol conditions. The noon maximum is reduced to approximately 860 W m^{-2}, corresponding to an additional reduction of about 17% relative to AOT = 0.85 and nearly 30% relative to AOT = 0.5. Early morning and late afternoon irradiance values are particularly diminished, emphasizing the nonlinear interaction between aerosol loading and optical air mass.

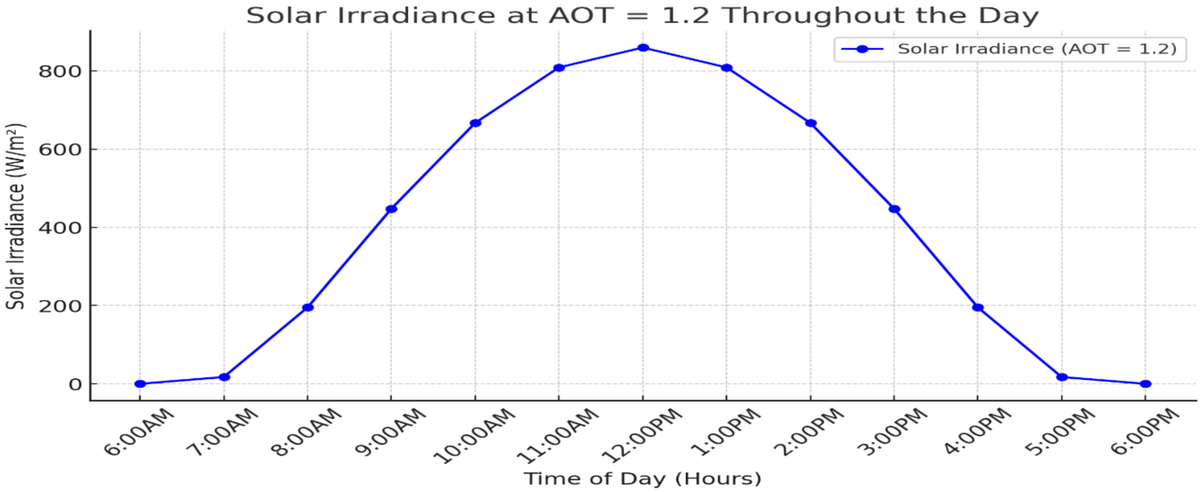

Figure 3: Diurnal variation of surface solar irradiance for a high aerosol loading (AOT = 1.2)

Comparative Aerosol Impact

Figure 4 compares surface solar irradiance for AOT values of 0.5, 0.85, and 1.2. All curves exhibit a similar diurnal pattern governed by solar geometry, with maximum irradiance near solar noon and minima at sunrise and sunset. However, increasing AOT results in progressively lower irradiance at all times of day. As evident in Figure 4, relative attenuation is smallest near noon and largest during early morning and late afternoon, when optical air mass is greatest. Comparable diurnal attenuation patterns have been reported by Natsis *et al.,* (2024), Czerwińska and Krzyścin (2024), Korpela *et al.,* (2025), and Chauhan *et al.,* (2024). This comparative analysis highlights the importance of aerosol loading in reducing diurnal solar energy availability, particularly during periods of low solar elevation.

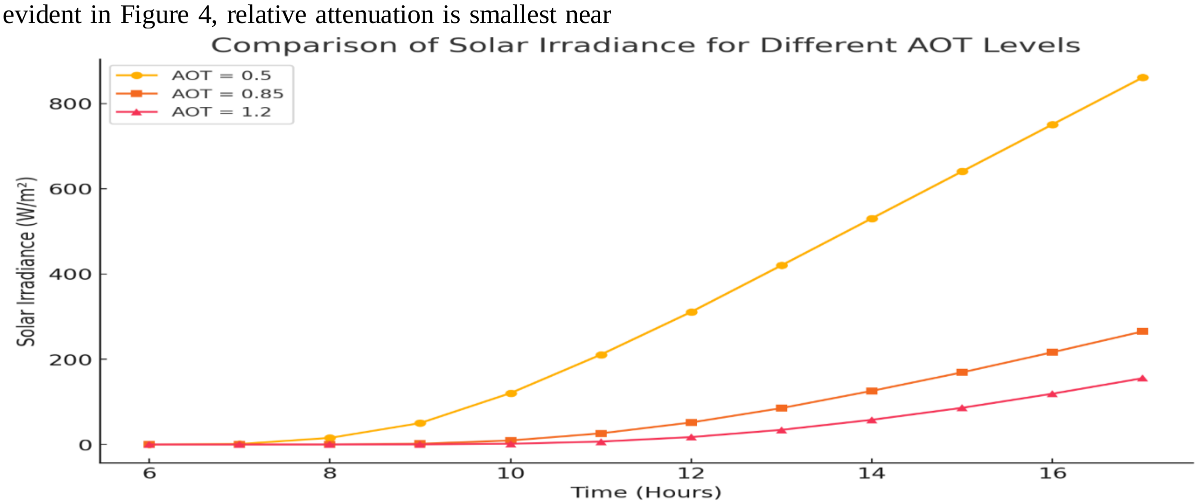

Figure 4: Comparison of solar irradiance for different AOT levels

CONCLUSION

This study employed a DISORT-based radiative transfer model to quantify the diurnal sensitivity of clear sky surface solar radiation to aerosol optical thickness. The results demonstrate that increasing aerosol loading leads to substantial and systematic reductions in surface irradiance, with relative losses amplified at large solar zenith angles. Under very high aerosol conditions, midday irradiance can be reduced by nearly 30% compared to moderate aerosol loading, highlighting potential implications for solar energy availability.

The findings represent first-order estimates derived under idealized assumptions, including fixed aerosol optical properties and vertically homogeneous aerosol distribution. As such, they provide a physically interpretable baseline rather than a complete characterization of real atmospheric variability. Future work should extend this framework by incorporating aerosol type variability, vertical structure, spectral resolution, and direct comparison with collocated ground based irradiance measurements. Framing aerosol impacts in terms of expected percentage energy losses offers a practical pathway for linking radiative transfer modeling to solar energy and climate applications.

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