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Proceeding Paper

Direct Radiative Effects of Dust Events over Limassol, Cyprus in 2024 Using Ground-Based Measurements and Modelling [†]

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Abstract

Dust plays a significant role in the atmospheric radiative balance by altering both shortwave and longwave radiation fluxes. While deserts are the primary sources of dust emissions, atmospheric circulation can transport dust over long distances, impacting air quality and climate in remote regions. These transport episodes, commonly known as dust events, vary in intensity and effects. Despite extensive research, uncertainties persist regarding their precise radiative impacts. This study examines the direct radiative effects of dust events in 2024 (a year marked by heightened dust activity) over Limassol, Cyprus. A comprehensive approach is employed, integrating radiative transfer modelling, ground-based solar radiation measurements, and dust optical property analysis. The LibRadtran radiative transfer package is used to simulate atmospheric radiative transfer under dust-laden conditions, incorporating key dust optical properties such as Aerosol Optical Depth, Single Scattering Albedo, and the Asymmetry Parameter retrieved from the Limassol's AERONET station. Observations from solar radiation station at the ERATOSTHENES Centre of Excellence serve as validation for the model. This study quantifies the radiative impact of dust by evaluating changes in surface irradiance, providing valuable insights into the role of dust in atmospheric energy balance.

Keywords: radiative effects; dust; Cyprus 2024

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1. Introduction

Atmospheric aerosols, particularly desert dust, significantly affect the Earth's radiation budget by modifying both incoming solar and outgoing terrestrial radiation [1,2]. Dust particles directly interact with solar radiation through scattering and absorption processes that depend heavily on the aerosols' optical and microphysical properties such as aerosol optical depth (AOD), single scattering albedo (SSA), and asymmetry parameter. These properties vary not only with dust composition but also with atmospheric conditions, leading to uncertainties in the quantification of their radiative impacts [3,4]. In addition to their climatic effects, dust aerosols can reduce solar energy availability and influence surface temperatures [5]. The need for accurate assessment of their direct radiative effect is particularly relevant in the context of solar energy production, especially in regions such as Cyprus with high solar potential and frequent dust exposure [3,6].

This study investigates the direct aerosol radiative effect of dust events in 2024 over Limassol, Cyprus—a year characterized by notably elevated dust activity. Using the LibRadtran radiative transfer model, simulations are performed under dust-laden atmospheric conditions using input from the AERONET station in Limassol. Observed global solar irradiance from the Eratosthenes Centre of Excellence's radiation station serves as ground-based validation. The monitoring infrastructure in Limassol includes as part of the Aerosol Remote Sensing Observational platform of the CARO National Facility a CIMEL sun photometer (part of the AERONET network), and a PollyXT lidar system for vertical profiling of aerosols, and high-quality pyranometers for solar radiation measurements [7,8]. This work quantifies changes in surface irradiance and estimates radiative forcing efficiencies during dust episodes, contributing to a more precise understanding of how dust impacts regional radiative transfer processes. The results offer insight into the role of aerosol optical properties in shaping surface radiation and support efforts to improve solar energy forecasting in dust-affected environments [9–11].

2. Data and Methodology

This study utilizes a combination of ground-based, satellite, and model-generated datasets to assess the direct radiative effect of dust over Limassol, Cyprus. The primary aerosol optical properties were retrieved from a Cimel CE 348NE Sun Photometer (Cimel, Paris, France), part of the AERONET network, located at the Cyprus University of Technology. In this study we utilized level 1.5 cloud-screened data, including aerosol optical depth (AOD), single scattering albedo (SSA), asymmetry parameter (ASY), Ångström exponent, and precipitable water column (PWC) [12]. These parameters were used as core inputs for the radiative transfer model simulations.

Solar irradiance measurements were obtained from an EKO (Osaka, Japan) MS-80 pyranometer. To identify cloud-free conditions, sky imagery from the co-located ASI-16 All Sky Imager (EKO, Osaka, Japan). Vertical profiles of aerosol layers were provided by the PollyXT multiwavelength-Raman lidar from TROPOS (Leipzig, Germany), which is operated at the Cyprus Atmospheric Remote Sensing Observatory National Facility (CARO NF) of the Eratosthenes Centre of Excellence at Limassol (34.677° N, 33.0375° E).

For model validation and dust event detection, MODIS imagery from the Terra and Aqua satellites was acquired via NASA EOSDIS LANCE and GIBS/Worldview platforms [13]. Additionally, total column ozone data was sourced from the Ozone Monitoring Instrument (OMI), which provides daily gridded global ozone estimates [14]. To determine the geographic origin of dust events, the HYSPLIT model was used in backward mode, initialized at altitudes defined by the lidar-observed aerosol layers [15].

We implemented a multi-step approach integrating data filtering, dust case identification, source attribution, and radiative modeling. Cloud-free periods were first selected using imagery from the EKO (Osaka, Japan) all-sky camera, after which AERONET Level 1.5 data were temporally matched. To classify aerosol types and identify dust events, we applied the aerosol typing scheme by Dubovik et al. (2002) [16], which uses thresholds in AOD and Ångström exponent to distinguish dust from other aerosol types. This classification was further verified using PollyXT lidar profiles to ensure the presence of elevated aerosol layers consistent with long-range dust transport. MODIS imagery confirmed the spatial distribution of the dust plumes, and HYSPLIT backward trajectories (initialized at lidar-observed altitudes) were used to determine whether the dust originated from the Sahara, the Middle East, or represented a mixed source.

Radiative simulations were performed using the libRadtran UVSPEC model (version 2.0.5) with the DISORT solver (six streams) and the REPTRAN fine-resolution absorption parameterization [17,18]. Inputs included AERONET-derived AOD, SSA, ASY, and water vapor, total column ozone from OMI, and a fixed surface albedo of 0.2. Simulations were run for both dusty and aerosol-free conditions. The model outputs were validated against solar horizontal irradiance measurements from the MS-80 pyranometer from EKO, (Osaka, Japan) at the surface.

3. Results and Discussion

Three major dust events were identified in Limassol during 2024, occurring at the end of March (Event 1), end of April (Event 2), and end of May (Event 3). These cases were selected based on their high aerosol optical depth (AOD) values, distinct vertical structure from lidar observations, and strong attenuation in ground-based solar radiation measurements. The optical parameters, including daily mean AOD and its standard deviation, as well as the daily mean Angstrom exponent and its respective standard deviation, are given in Table 1. But not all the days that are presented in Table 1 are dust-affected.

Figure 1 shows satellite imagery from MODIS confirming widespread dust plumes over Cyprus during all three events.

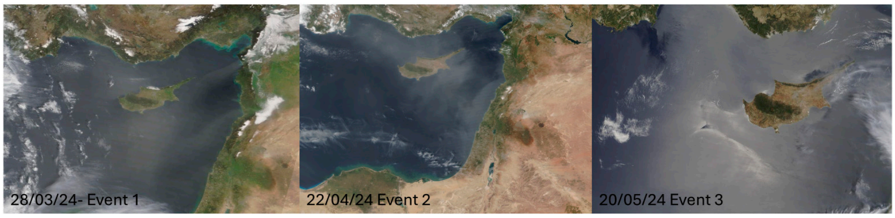

Figure 1. Modis Images from the three events over Cyprus (GIBS/Worldview).

Figure 2 presents profiles of the volume depolarization ratio (VDR) from the PollyXT lidar system during the period of 15/05/2024–25/05/2024 (Event 3). Pronounced dust layers (VDR > 0.15) are evident, extending up to approximately 4 km above ground level. Notably, between 20/05/2024 and 23/05/2024, dust penetrated the lowest atmospheric levels, reaching the surface and affecting air quality. The HYSPLIT trajectories shown in Figure 3 traced their origins to the Sahara. These intense events provided ideal conditions for quantifying the direct radiative impact of dust under clear-sky conditions.

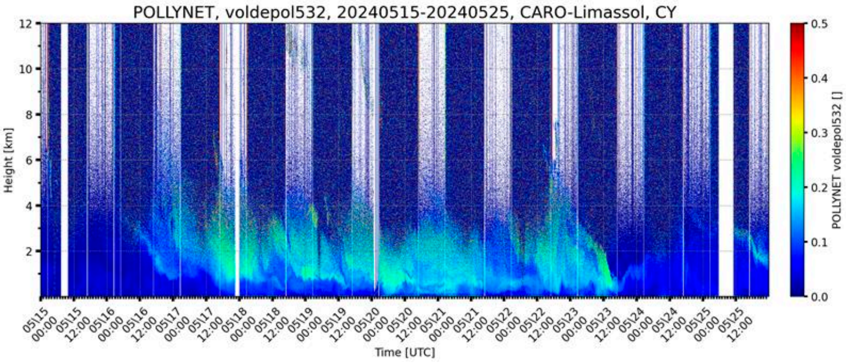

Figure 2. PollyXT lidar volume linear depolarization ratio at 532 nm over Limassol, Cyprus, from 15 to 25 May 2024 (event 3).

Table 1. Mean daily optical properties for the 3 major dust events in Limassol during 2024. Highlighted are the days exhibiting the most intense radiative effects (see Section 3.2 for details).

Event 1	**AOD_500nm**		**440–870_Angstrom_Exponent**	
	mean	**std**	**mean**	**std**
Date				
2024-03-26	0.415	0.054	0.254	0.061
2024-03-27	0.294	0.036	0.231	0.013
2024-03-28	0.448	0.066	0.191	0.021
2024-03-29	0.486	0.030	0.236	0.052
2024-03-30	0.372	0.029	0.350	0.082
2024-03-31	0.280	0.007	0.382	0.018
2024-04-01	0.269	0.014	0.425	0.056
2024-04-02	0.241	0.029	0.498	0.038
2024-04-03	0.172	0.026	0.584	0.148
2024-04-04	0.271	0.115	0.282	0.079

Event 2	**AOD_500nm**		**440–870_Angstrom_Exponent**	
	mean	**std**	**mean**	**std**
Date				
2024-04-17	0.134	0.032	0.845	0.114
2024-04-18	0.351	0.097	0.246	0.064
2024-04-19	0.214	0.063	0.543	0.132
2024-04-20				
2024-04-21				
2024-04-22	0.611	0.159	0.186	0.024
2024-04-23	0.379	0.017	0.204	0.017
2024-04-24	0.531	0.021	0.207	0.013
2024-04-25				
2024-04-26				
2024-04-27				
2024-04-28	0.277	0.022	0.339	0.024

Event 3	**AOD_500nm**		**440–870_Angstrom_Exponent**	
	mean	**std**	**mean**	**std**
Date				
2024-05-15	0.142	0.036	1.315	0.110
2024-05-16	0.150	0.024	1.172	0.173
2024-05-17	0.400	0.051	0.311	0.041
2024-05-18	0.372	0.049	0.248	0.047
2024-05-19	0.464	0.049	0.289	0.048
2024-05-20	0.413	0.022	0.314	0.069
2024-05-21	0.399	0.016	0.400	0.057
2024-05-22				
2024-05-23	0.276	0.103	0.273	0.068
2024-05-24	0.166	0.015	0.776	0.075
2024-05-25	0.205	0.044	0.927	0.127

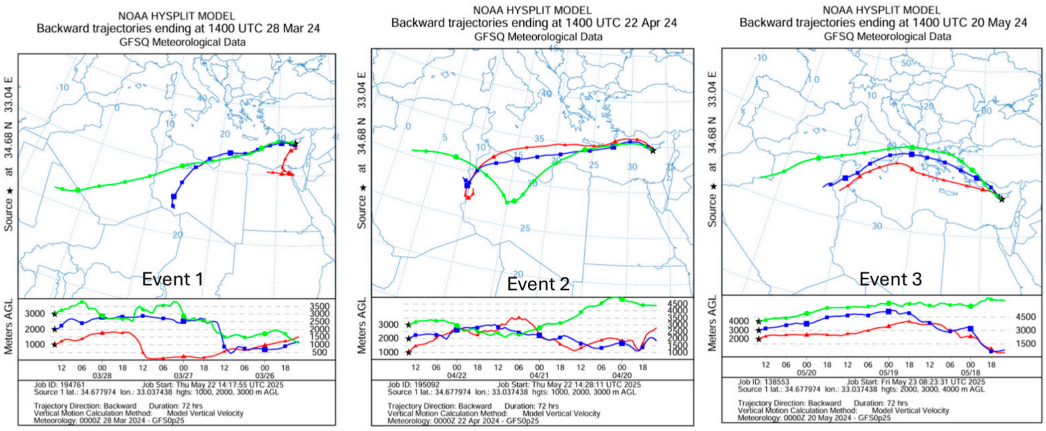

Figure 3. 72 h backward trajectories calculated with the Hybrid Single Particle Lagrangian Integration Trajectory (HYSPLIT) NOAA model [15] and Reanalysis meteorological data for the 3 events indicating dust originated from Sahara, with red, green and blue are the different heights of the backward trajectories.

3.1. Model Evaluation

To evaluate the accuracy of the radiative transfer simulations, modeled global horizontal irradiance (GHI) values were compared against in situ measurements from the EKO MS-80 pyranometer under dust-affected conditions. Figure 4 shows the correlation between modeled and measured GHI for all identified dust cases in 2024. The model performed exceptionally well, with a coefficient of determination R^2 = 0.98, indicating strong agreement between the two datasets. The root mean square error (RMSE) was 27.68 W/m^2, and the mean bias error (MBE) was −5.47 W/m^2, suggesting a slight underestimation of modeled GHI. The color scale in the scatter plot illustrates the percent difference between measured and modeled values, with most points clustered around the 1:1 line and percent differences generally within ±10%.

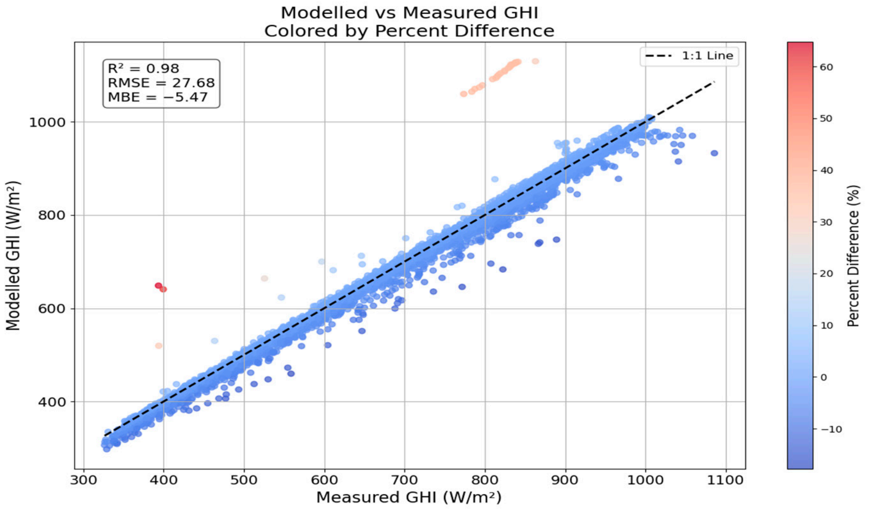

Figure 4. Comparison between modeled and measured global horizontal irradiance (GHI) during identified dust events in 2024 over Limassol.

3.2. Daily Radiative Attenuation During Dust Events

The daily evolution of shortwave radiation attenuation was analyzed for each of the three most intense dust events in 2024. Figure 5 shows the attenuation expressed as the difference between the measured shortwave irradiance and the model output under aerosol-free conditions. The shaded area represents ±1 standard deviation. Negative values indicate reduction in surface irradiance due to the presence of dust aerosols. All three events exhibited sustained and significant reductions in surface solar irradiance, with peak attenuation occurring on March 28, April 22, and May 19, respectively. These days coincide with elevated AOD values and strong aerosol layer signatures from lidar, confirming the presence of dense dust. Attenuation values exceeded –100 W/m^2 at their peak, highlighting the considerable impact of dust on surface energy input. The variability across days, as shown by the standard deviation bands, reflects fluctuations in dust load and atmospheric stability. These results reinforce the importance of accounting for dust-related attenuation in radiative transfer modeling and solar energy assessments over Cyprus.

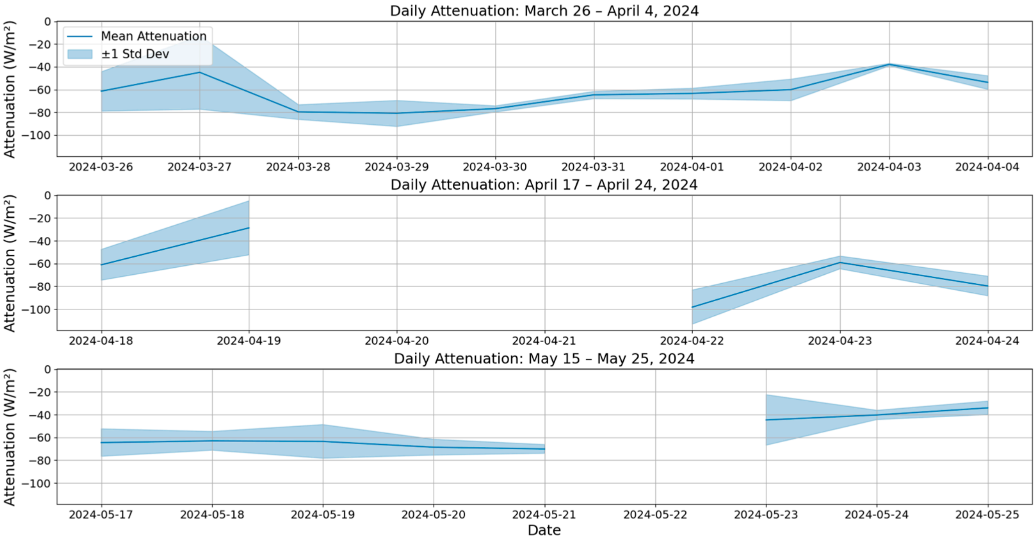

Figure 5. Daily mean shortwave (SW) radiation attenuation during the three major dust events in 2024 over Limassol.

4. Conclusions

This study evaluated the direct radiative effects of intense dust events over Limassol, Cyprus, during 2024 using a combination of solar ground-based measurements, lidar profiling, satellite observations, and radiative transfer modeling. Three major dust episodes—on March 28, April 22, and May 19—were identified and analyzed in detail. The libRadtran model, driven by AERONET optical properties and validated with high-precision pyranometer data, demonstrated high agreement with observed global horizontal irradiance (R^2 = 0.98, RMSE = 27.68 W/m^2). Daily shortwave attenuation during these events exceeded –100 W/m^2, underscoring the substantial impact of mineral dust on surface solar radiation. These findings highlight the importance of incorporating accurate aerosol optical properties and vertical profiling (via lidar) in radiative effect assessments. Future work will extend this analysis over longer time periods, aiming to further refine the radiative forcing estimates and support improved solar energy forecasting and climate modeling in the Eastern Mediterranean.

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