environmental sciences proceedings

MDPI

Proceeding Paper

Impact of Aerosols on Surface Solar Radiation and Solar Energy in the Mediterranean Basin †

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† Presented at the 16th International Conference on Meteorology, Climatology and Atmospheric Physics—COMECAP 2023, Athens, Greece, 25–29 September 2023.

Abstract: In this study, we examine the direct effect of atmospheric aerosols on two components of downwelling surface solar irradiance, Global Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI), under clear-sky conditions and their implications for solar energy, focusing on the broader Mediterranean Basin, over an 18-year time period between 2003 and 2020. In addition to the aerosol optical depth (AOD) from satellite retrievals and model data that have been used in previous studies, the present study utilizes ground-based direct measurements of AOD and aerosol optical properties from the AErosol RObotic NETwork (AERONET) to assess the direct effect of aerosols on GHI and DNI.

Keywords: solar energy; aerosols; direct radiative effects

Citation: Kouklaki, D.; Papachristopoulou, K.; Fountoulakis, I.; Tsekeri, A.; Raptis, P.-I.; Kazadzis, S.; Eleftheratos, K. Impact of Aerosols on Surface Solar Radiation and Solar Energy in the Mediterranean Basin. *Environ. Sci. Proc.* **2023**, *26*, 56. https://doi.org/10.3390/environsciproc2023026056

Academic Editors: Konstantinos Moustris and Panagiotis Nastos

Published: 25 August 2023

1. Introduction

The approximation of the impact of atmospheric aerosols on the solar radiation field through their direct radiative effects is vital to understanding the Earth's energy balance as well as the diversity of solar resources on the Earth's surface and, therefore, the potential solar energy production.

On a global scale, the availability of solar irradiance reaching the Earth's surface is highly dependent on its attenuation by clouds, but the role of aerosols is also significant and under certain conditions can be dominant (e.g., [1,2]).

In this work, we investigate the direct impact of total aerosols on downwelling surface solar irradiance (DSSI) and more precisely, the Global Horizontal Irradiance (GHI) and Direct Normal Irradiance (DNI), under cloudless-sky conditions.

The Mediterranean Basin experiences a high concentration of different aerosol types generated from natural and anthropogenic sources. The direct radiative effect of aerosols is maximized over sources and areas affected by aerosol transport, which, in turn, can have essential implications for potential renewable energy generation and other human activities. In order to investigate these effects, various studies have used the total aerosol optical depth (AOD) from the satellite retrievals of the MODerate resolution Imaging Spectroradiometer onboard the Aqua satellite (MODIS-Aqua) and model outputs from the Copernicus Atmospheric Monitoring Service (CAMS) (e.g., [3]).

Although the accuracy of satellite-based aerosol retrievals has been improved significantly over time (e.g., [4]), ground-based measurements of aerosol optical properties are still considered more precise in many cases.

In this study, we used CAMS and MODIS datasets as well as ground-based measurements from the AErosol RObotic NETwork (AERONET) [5] to assess how deviations in aerosol optical properties impact aerosols' direct effect on DSSI.

2. Data and Methodology

This study focused on the broader Mediterranean Basin, more precisely on five AERONET stations (Table 1), for the time period between 2003 and 2020.

Table 1. The AERONET stations under study and the total period that was considered in this work for each station based on AERONET data availability.

AERONET Site	Country	Latitude	Longitude	Elevation (m)	Time Period (Years)
Burjassot	Spain	40° N	0° W	104	11
Carpentras	France	44° N	5° E	107	13
Evora	Portugal	39° N	8° W	293	11
Granada	Spain	37° N	4° W	680	13
Lecce University	Italy	40° N	18° E	30	18
OHP Observatoire [1]	France	44° N	6° E	680	11
Sede Boker	Israel	31° N	35° E	480	17

[1] Haute-Provence Observatory.

In order to calculate DSSI on an hourly basis under cloudless-sky conditions, precalculated look-up tables (LUTs) were used. These LUTs are based on simulations of surface solar spectral irradiances (global and direct) with respect to numerous atmospheric conditions affecting DSSI under cloudless conditions [3]. The simulations were performed using the libRadtran package [6] and the uvspec model. The output spectral irradiances were integrated over the whole shortwave (SW) spectrum, in the wavelength range 280–3000 nm, to obtain the total irradiances.

To estimate hourly DHI and DNI, satellite retrievals (based on MODIS level 2 data) [7], modeled products from reanalysis (CAMS) [8] and AERONET AOD at 500 nm (interpolated to 550 nm, AOD_{550nm}, Level 2.0, Version 3.0 retrievals) were used as inputs to the LUTs.

Apart from the AOD, other aerosol optical properties and atmospheric parameters, such as the single-scattering albedo (SSA) at 550 nm and the Ångström exponent (AE) at 470–850 nm, were included in the simulations derived from Max-Planck Aerosol Climatology (MACv2) [9] in the satellite and model scenarios and from AERONET database for the ground-based measurement scenario. Other parameters, such as the precipitable water column (PWC), the total ozone column (TOC) and the surface albedo, were kept fixed at 1.5 cm, 350 DU and 0.2, accordingly. Moreover, profiles of temperature, air density and other atmospheric gases were set by their default values with respect to the standard atmospheric profile US Atmosphere [10].

The different datasets are provided in different spatial and temporal resolutions (Table 2). In terms of temporal resolution, MODIS-Aqua products are available on a daily basis, AERONET provides a continuous dataset under clear-sky conditions, MACv2 aerosol optical properties are provided on a monthly basis and finally, CAMS reanalysis products are available on a 3-hourly basis.

Table 2. Aerosol optical properties datasets and their spatio-temporal resolution.

Parameter	Source	Spatial Resolution	Temporal Resolution
AOD	MODIS CAMS AERONET	$0.1° \times 0.1°$ $0.4° \times 0.4°$ Station	1 day 3 h 10–15 min
SSA & AE	MACv2 AERONET	$1° \times 1°$ Station	1 month 10–15 min

In order to homogenize in time, the different datasets generate a full dataset in each case with 1 h resolution. Daily and monthly missing values were filled by monthly and seasonal means, respectively. In order to homogenize the three datasets in terms of spatial resolution for the study, the data were firstly re-gridded to the CAMS 0.4° × 0.4° grid and finally, the mean value was used, with respect to the selected station.

Finally, the daily global horizontal irradiation (GHI) and the direct normal irradiation (DNI) were calculated by integrating the 1 h instantaneous values and, in turn, mean annual integrals of GHI and DNI.

The relative difference of DSSI was calculated with respect to an aerosol-free atmosphere using the following formula:

$$\frac{\int \mathrm{DSSI_a} - \int \mathrm{DSSI_{af}}}{\int \mathrm{DSSI_{af}}} \times 100\ (\%) \tag{1}$$

where DSSIa stands for DSSI (GHI and DNI in $\mathrm{J/m^2}$) in the case that aerosols are present in the atmosphere, while DSSIaf stands for DSSI when an aerosol-free atmosphere is considered.

3. Results and Discussion

3.1. Aerorol Optical Depth Intercomparison

Overall mean annual absolute differences between the AOD values provided by MODIS/CAMS and AERONET are shown in Figure 1 for each station. In most cases, the AOD values provided by MODIS are in better agreement with those from AERONET than the AOD values provided by CAMS. As a general trend, CAMS overestimates AOD both compared to MODIS, except for Granada, and compared to AERONET, except for Burjassot. The most extreme difference was observed in the case of Sede Boker, where the absolute differences of both CAMS-AERONET and MODIS-AERONET reach 0.1, in contrast to Burjassot, where the differences approach zero and denote that the three databases are in good agreement.

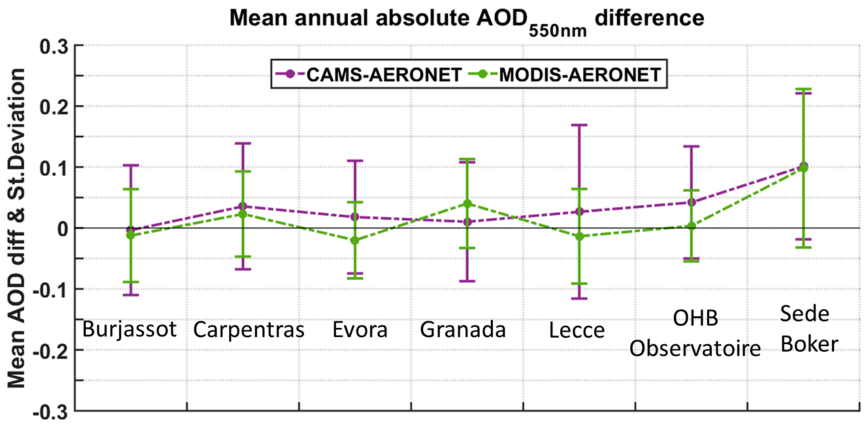


Figure 1. Mean annual differences in AOD between CAMS-AERONET and MODIS-AERONET datasets and their standard deviations for each station.

According to all three datasets, Sede Boker experienced the highest mean AOD during the entire period, reaching almost 0.2, followed by Lecce. Concerning the lowest AOD values, AERONET indicates that it was measured in OHB Observatory, while according to CAMS and MODIS, it was measured in Evora. Finally, SSA varied from 0.88 (Granada) to 0.93 (Lecce) based on AERONET and 0.93 (Lecce and Sede Boker) to 0.95 (Evora) when referring to the MACv2 dataset (Table 3).

Table 3. Mean AOD and SSA values retrieved from AERONET, CAMS and MODIS datasets for each station for the entire period under study.

AERONET Station	AERONET		CAMS		MODIS	
	AOD	SSA_{AER} [1]	AOD	SSA_{MACv2} [2]	AOD	SSA_{MACv2}
Burjassot	0.14	0.91	0.13	0.94	0.13	0.94
Carpentras	0.12	0.89	0.15	0.94	0.14	0.94
Evora	0.10	0.90	0.12	0.95	0.08	0.95
Granada	0.13	0.88	0.14	0.94	0.17	0.94
Lecce University	0.16	0.93	0.19	0.93	0.15	0.93
OHB Observatoire	0.09	0.91	0.13	0.94	0.09	0.94
Sede Boker	0.18	0.91	0.28	0.93	0.28	0.93

[1] AERONET-derived SSA, [2] MACv2-derived SSA.

3.2. Aerosol Direct Radiative Effect

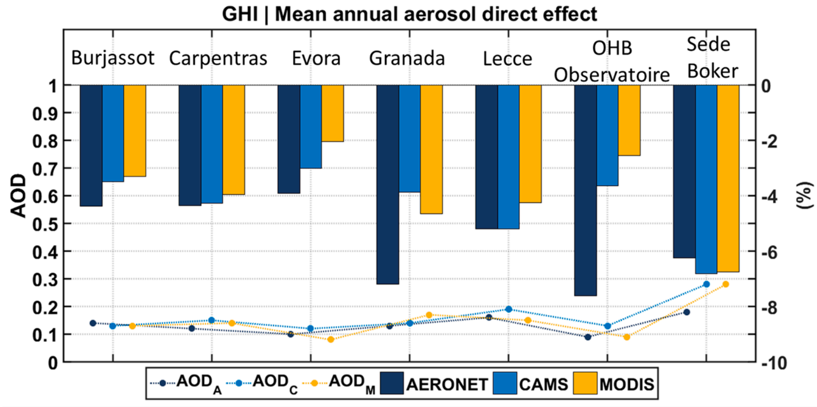
We assessed the effect of aerosol optical properties on GHI and DNI based on retrievals of aerosol optical properties from the three different datasets (Figure 2). The GHI and DNI reaching the surface are reduced with respect to an aerosol-free atmosphere, explaining the negative values of their effect. Additionally, the results of the performed sensitivity analysis indicate that aerosols' direct effects are more pronounced in the case of DNI compared to GHI.

The highest deviations in GHI were observed in the case of the Granada and OHB Observatory stations, and more specifically, on the effect of AERONET AOD, which can be explained by the low SSA measurements (Table 3), while in the case of the Lecce University station, the differences between the effect of AERONET and CAMS AOD seem to be in very good agreement.

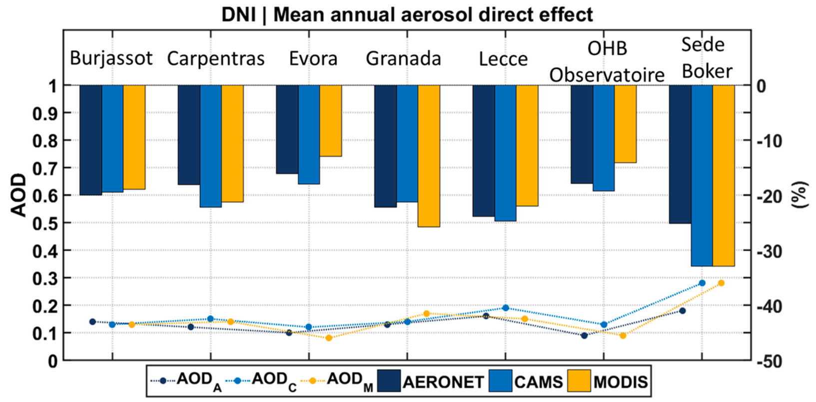
For the Carpentras station, the effect on GHI appears to be higher in the case of AERONET, which can be explained by the effect of the SSA component on the diffuse parameter, and therefore, on GHI (Table 3).

However, a lower aerosol load according to AERONET retrievals (Figure 1) explains the lower effect on the DNI by approximately 4% according to CAMS and 3% according to MODIS (Figure 2). The respective results of the intercomparison for the Burjassot station are in line with the slightly overestimated AOD values both in the cases of GHI and DNI. Finally, the very good agreement in AOD derived from CAMS and MODIS is reflected in the respective effect on DNI for Sede Boker.

The discussed findings are in line with those of previous studies focusing on the same region [3]. Comparing the results of relative DSSI differences for different stations and aerosol datasets, the main differences in DNI are due to AOD-related differences, while for GHI, apart from AOD, other optical properties (SSA, AE) and the site-dependent contribution of direct irradiance (site latitude–range of solar elevations) can play a significant role.



(**a**)



(**b**)

Figure 2. The mean AOD (left *y*-axis) and the relative difference in DSSI with respect to an aerosol-free atmosphere (right *y*-axis) for each station and database for (**a**) GHI and (**b**) DNI.

4. Conclusions

The present study aimed to provide a better estimation of the role of aerosols in surface solar radiation under clear-sky conditions and the respective deviations of the aerosols' direct effects on DSSI according to three AOD datasets (satellite, CAMS, ground-based) for seven AERONET stations around the Mediterranean Basin. According to our results, CAMS AOD is mostly overestimated compared to ground-based measurements, while MODIS AOD is in better agreement with AERONET AOD measurements. The results signify that the effect of AOD is more significant in the case of DNI, contributing to deviations from an aerosol-free atmosphere that vary from 12% for the Evora station to almost 32% for the Sede Boker station, whereas in the case of GHI, the relative differences do not exceed 8%. More considerable differences were observed in the case of Granada and the OHP Observatory; however, the AOD mean annual values indicate that the deviations in GHI are mainly caused by differences in other optical properties such as the SSA.

Author Contributions: Conceptualization, D.K., S.K. and K.P.; methodology, D.K., K.P. and S.K.; software, D.K. and K.P.; validation, D.K., K.P. and S.K.; formal analysis, D.K. and K.P.; investigation, D.K. and K.P.; resources, D.K., K.P. and I.F.; data curation, D.K., K.P. and P.-I.R.; writing—original draft preparation, D.K.; writing—review and editing, all authors; visualization, D.K.; supervision, S.K. and K.P.; project administration, K.E., S.K. and A.T.; funding acquisition, K.E., S.K. and A.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research was financially supported by the PANGEA4CalVal project (Grant Agreement 101079201) funded by the European Union and the Hellenic Foundation for Research and Innovation (H.F.R.I.) under the "First Call for H.F.R.I. Research Projects to support Faculty members and Researchers and the procurement of high-cost research equipment grant" (Atmospheric parameters affecting Spectral solar IRradiance and solar Energy (ASPIRE), project number 300).

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: All data presented in this study can be made available upon request from the authors.

Conflicts of Interest: The authors declare no conflict of interest.

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