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Surface Shortwave Radiation Measurements and Modeling under Intense Desert Dust Conditions †

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Abstract: Desert dust atmospheric aerosols play an important role in the Earth-atmosphere system and constitute a key agent for the Earth's climate through their radiative processes. However, dust radiative effects are still subjected to large uncertainties, due to the uncertain estimates of their optical properties. A radiative closure study, under cloudless sky, using measurements and model results of shortwave radiation at the Earth's surface was performed. All measurements were gathered under Saharan dust conditions during the ASKOS campaign at Mindelo, Cabo Verde. Radiation measurements were compared with radiative transfer simulations, using as input concurrent retrievals of dust optical properties.

Keywords: desert dust; radiative effects; shortwave and longwave radiation

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1. Introduction

Dust aerosols have a significant impact on the Earth system. Dust likely cools the climate and, due to its increase since the pre-industrial era, partially counteracts the warming caused by greenhouse gases [1]. Those estimates are, however, highly uncertain, mainly due to uncertainties in quantifying dust direct radiative effects (DREs), which can be reduced by using more accurate dust optical properties, e.g., from observations (in situ and remote sensing) [1]. For example, it has been found that coarse and super coarse dust particles warm the Earth system through their direct radiative effects, with implications for clouds and precipitation; however, they are substantially underestimated in current models [2]. Accurate representation of atmospheric conditions is also important for the determination of the dust radiative effects. Recent observations have shown that the increased water vapor in the upper Saharan Air Layer (SAL) with increased dustiness is associated with increased heating in the dry lower SAL and less negative dust direct radiative effect at TOA by 17% [3].

To reduce the uncertainties in dust aerosols' climate effects, field experiments are needed along with closure studies (e.g., [4]). In this study, clear sky shortwave (SW) ground-based measurements under intense Saharan dust conditions during the ASKOS campaign at Mindelo, Cabo Verde (CV), in summer 2022, were compared with radiative transfer model (RTM) outputs based on concurrent measured aerosol optical properties and other important atmospheric parameters. The radiative fluxes on surfaces is an essential climatic variable, and closure studies, such as the one presented herein, contribute to their accurate quantification under dusty conditions.

2. Materials and Methods

All measurements utilized in this study were gathered under Saharan dust conditions during the ASKOS campaign at Mindelo, CV. The campaign took place during summer 2022 when the dust transport above the area experiences its yearly maximum. ASKOS deployed advanced ground-based remote sensing and surface/airborne in situ instrumentation providing atmospheric parameters, including aerosols. Actinometric measurements were also performed. We focused on days with intense aerosol loads and cloudless sky conditions. Six days in the period June–September 2022 met those requirements for at least three consecutive hours, all in July 2022. For all days, the data are available for almost the same period of the day, 14:00–17:45 UTC or solar zenith angles (SZA) 6° to 55°. Table 1 summarizes the datasets utilized in the current study.

Table 1. Datasets utilized in the current study, from the ASKOS campaign at Mindelo, Cabo Verde, summer 2022.

	Parameter
Cimel/AERONET Level 1.5 products	Aerosol Optical Depth (AOD) at 500 nm Angstrom Exponent (AE) 440–675 nm Single Scattering Albedo (SSA), mean from 440–500–675–870 nm Precipitable Water Vapor (PWV)
Pyranometer (280–2800 nm)	Global Horizontal Irradiance (GHI)

The global horizontal irradiance (GHI) measurements (1 min frequency) were compared with simulations performed with the UVSPEC RTM included in the libRadtran package [5,6]. The simulations were performed using as input the concurrent AERONET retrievals (5 min frequency) of dust optical properties and PWV (Table 1). The GHI measurements were synchronized with the simulations at 5 min frequency, and GHI differences were calculated in absolute (modeled-measured) and relative terms ((modeled-measured)/measured $*$ 100%).

3. Results and Discussion

3.1. Atmospheric Conditions

AOD values ranged from 0.3 to 0.7 for the six selected days (Figure 1), with AE values below 0.3 indicating the presence of coarse particles with SSA values greater than 0.94. The second day studied (10 July 2023) was a day with a maximum AOD of 0.7, corresponding to AE value close to 0.05 and high values of PWV, up to 40 mm. This combination of atmospheric conditions resulted in very low GHI values (not shown).

3.2. Shortwave Radiative Closure at Surface

In this section, the comparison between the measured and the corresponding modeled values of GHI is presented for all days. All GHI relative differences (Figure 2a) were between -2.1 and 3.1% (-15 and 26 W/m^2), with 96% of the data within $\pm$2%. Radiative closure was confirmed for 75% of the cases, which had differences in GHI within $\pm$10 W/m^2. The modeled GHI mostly overestimated measurements with a mean GHI difference of 4.4 ± 7.8 W/m^2 (or 0.4 ± 1%), which is within measurement uncertainties. This slight overestimation may be attributed to the aerosol-related inputs. We further investigated those changes with the available aerosol and atmospheric parameters. It was found that those changes were invariant with increasing AOD (Figure 2b) and PWV (not shown). The comparison of those changes with SSA revealed that the bigger GHI differences were found for the day with the highest value of SSA, but further investigation is needed (see next paragraph).

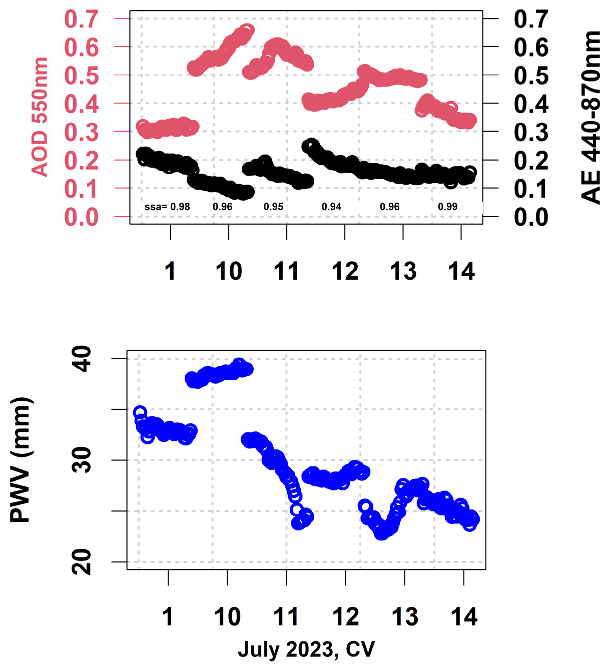
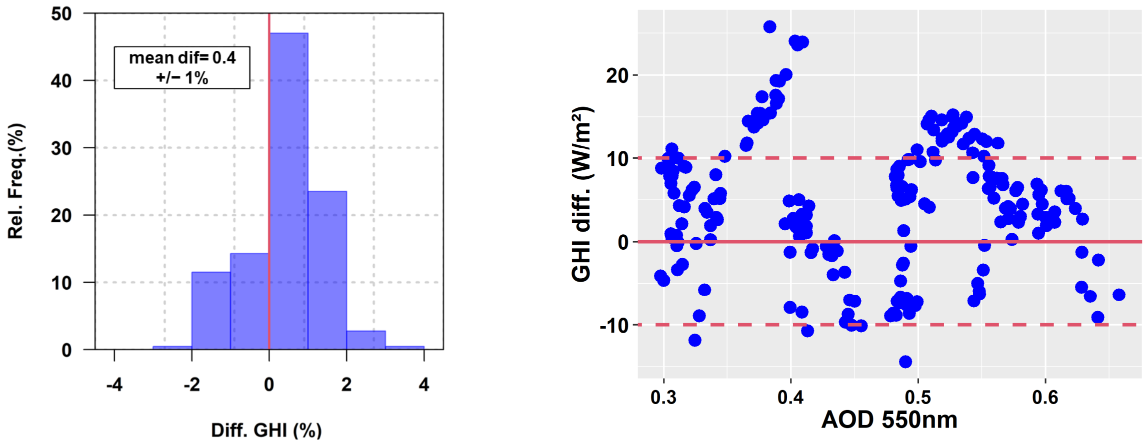


Figure 1. AERONET measurements of AOD at 550 nm, AE 440–870 nm, and PWV (in mm) from CV station, July 2022.



(**a**) (**b**)

Figure 2. (**a**) Relative frequency of the GHI relative differences (%); (**b**) GHI differences versus AOD 550 nm.

Table 2 presents the mean values and standard deviation of the absolute and relative GHI differences per day, along with the aerosol and water vapor input parameters to the RTM. The greatest value of GHI overestimation was found for a day with a relatively low mean AOD (0.37), which was a day with an SSA value close to 1 and relatively low PWV (25.3 mm). AERONET SSA retrievals are quality-assured for cases with AOD > 0.4, thus, the SSA value for the specific case may be associated with high uncertainty.

Table 2. Mean values and standard deviation of AOD at 550 nm, AE 440–870 nm, SSA and PWV (in mm), July 2022 ASKOS campaign at Cabo Verde and GHI absolute and relative differences.

Day	AOD	AE	SSA	PWV (mm)	SZA (°) Range	GHI Diff. (W/m^2)	GHI Diff. %
01 July	0.31 ± 0.01	0.19 ± 0.01	0.98	32.9 ± 0.4	8.7–50.9	3.5 ± 6.0	0.4 ± 0.7
10 July	0.58 ± 0.04	0.11 ± 0.02	0.96	38.5 ± 0.4	6.5–53.1	6.6 ± 6.4	0.7 ± 0.8
11 July	0.56 ± 0.03	0.15 ± 0.02	0.95	29.1 ± 2.7	6.3–54.0	5.2 ± 6.3	0.6 ± 0.8
12 July	0.42 ± 0.02	0.20 ± 0.03	0.94	28.4 ± 0.4	7.0–54.3	−1.3 ± 4.9	−0.3 ± 0.7
13 July	0.49 ± 0.01	0.15 ± 0.01	0.96	25.1 ± 1.7	6.3–54.2	1.1 ± 7.6	0 ± 1.0
14 July	0.37 ± 0.02	0.15 ± 0.01	0.99	25.3 ± 0.8	6.1–45.0	12.4 ± 7.8	1.4 ± 0.8

4. Summary and Outlook

A radiative closure study under clear sky conditions was performed using measurements and RTM model outputs of surface SW radiation under intense Sahara dust conditions in July 2022, during the ASKOS campaign at Cabo Verde. According to our results, radiative closure of surface GHI (i.e., differences between modeled values and measurements within ± 10 W/m^2) was attained for 75% of the cases (96% of cases within ±2%), using as inputs concurrent retrievals of dust optical properties and PWV. SSA was found to be the parameter related to the higher deviations, although further investigation is needed to reach safer conclusions. Other parameters related to mineralogy, shape, and size should be considered for the radiative closure to be confirmed under certain conditions. The preliminary results of this study along with the future work aim to contribute to knowledge gaps on dust radiative effects using unique—in terms of location and quality—experimental campaign data.

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Data Availability Statement: ASKOS data are available in the ESA's EVDC portal https://evdc.esa.int/ (accessed on 22 August 2023).

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

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