# ATMOSPHERIC OPTICAL DEPTH PROPERTIES OF THE 10 MARCH 2009 DUST STORM IN CENTRAL SAUDI ARABIA

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**Abstract**

Dust particles play a very important role in the Earth's climate system, air quality and environmental health. They affect both solar and terrestrial radiation by scattering and absorption, thus they are considered significant climate-forcing factors. Dust storms are considered natural hazards that affect daily life for short-time intervals ranging from a few hours to a few days, and they are a very frequent phenomenon in Saudi Arabia, especially in pre-monsoon season.

A severe dust storm occurred on 10 March 2009 in the northeast region of Saudi Arabia. It is considered one of the largest recorded dust events in Saudi's history. In this study, sun photometer data obtained during March, the atmospheric optical depth, and Angstrom exponent, α, over Riyadh, Saudi Arabia were investigated and presented. We evidenced exceptionally high turbidity values during the event day in comparison to the previous days. The Atmospheric Optical Depth AOD (340 nm) on the dusty day ranged between 1.642 and 0.350, with an average value of 1.102± 0.50, whereas on the previous day the AOD (340 nm) ranged between 0.353 and 0.225, with an average value of 0.290±0.04. The Angstrom exponent, α, for the wavelength range (340-440 nm) during the event day, varied between 0.130 and -0.117, with an average value of 0.012 ±0.01, whereas before the event, it varied between 0.093 and 0.386, with an average value of 0.212±0.03. Theoretical simulations using the SMART model were conducted to investigate how the turbidity conditions affected the solar irradiances during the event. That analysis suggested that the turbid conditions on the 10th significantly decreased the background global and direct-beam irradiances by about 53% and 139 %, respectively, increasing the diffuse component by 39% compared with the previous day. We also found that this storm had a great effect on several meteorological variables; there was a great drop in air temperature and visibility and an increase in both wind speed and relative humidity due to its impact.

*Keywords*: sky temperature; dust storm; AOD; March 2009; synoptic; meteorology.

## 1. Introduction

Dust is considered to be one of the major tropospheric aerosols. Dust particles affect both solar and terrestrial radiation, so they are considered significant climate-forcing factors, and an important parameter in radiation-budget studies [1, 2, 3]. Dust storms may cause a variety of problems such as reduction in visibility, which limits various activities and increases traffic accidents. Other environmental impacts include: reduced soil fertility, damage to crops, the spread of dirt, failure of telecommunications and mechanical systems, and air pollution [4]. In addition, dust aerosols have significant implications for human health [5]. A comprehensive review of dust storms and some of the latest work undertaken, and its importance for many research fields was recently reviewed by Andrew [6].

In Saudi Arabia, dust storms are considered among the most severe environmental problems. Several investigators have studied Saudi Arabia's desert dust (e.g., [7, 8]) in order to characterise the large-scale dust loading of the atmosphere over the Arabian Peninsula. However, little has been done to study the optical properties of these storms.

This paper presents a case study that focuses on the optical characteristics of atmospheric aerosols during a severe dust event occurred on 10 March 2009 in Riyadh (24.9 1° N, 46.41° E, 764 m), Saudi Arabia. This short-lived dust storm caused a widespread, heavy dust load, affected visibility, and air quality, caused a total airport shutdown, and damaged buildings, vehicles, power poles, and trees throughout the city of Riyadh[1]. This storm was massive, severe, and large enough to be seen clearly from outer space [2]. It is now considered one of the heaviest dust storms recorded in the last two decades [9]. The outbreak of this severe dust storm was marked by a cold-front passage that coincided with the propagation of a pre-existing, synoptic-scale, upper tropospheric jet stream over the central parts of Saudi Arabia. A detailed description of this synoptic development and the evolution of the disturbance are presented in a second paper.

## 2. Experimental site

The study area of Riyadh lies in the central region of the Arabian Peninsula at 24° 43 ′N; 46° 40′E, 764 m a.s.l. The central region is generally considered to be a vast eroded plateau consisting of areas of uplands, broad valleys and dry rivers. The area also contains a number of marshes. These are thought to be remnants of inland seas that existed in ancient geologic times. Riyadh is the capital of, and largest city in Saudi Arabia; a purely urbanised area, its population numbered 4,500,000 inhabitants according to the census of 2005. Surrounded by industrial areas and traffic, the region is one of the most polluted areas in the kingdom, in contrast to the remarkable natural resources like the surrounding Empty-Quarter Desert. The arid conditions prevailing at this site are responsible for a large range of seasonal temperature differences, providing cool winters and very hot summers. The area also commonly experiences low humidity, particularly in the summer. The local aerosol sources include the heavy traffic on the main roads of the city, together with the re-suspension of materials available on the ground, especially during the warm season, when the reduced rainfall and a dry terrain can increase the contribution of local mineral dust.

The climatology of the area experiences four dominant seasons each year: winter (December–February), pre-monsoon (March–May), monsoon (June–August), and post-monsoon (September–November). The pre-monsoon season, which the present case study refers to, is characterised by frequent dust storms and dry weather spells, when air masses carry dry and/or moist dust particles from different sources into the region.

## 3. Observational Data

[1] http://www.youtube.com/watch?v=E5KHa5hxzQM
2 http://www.eosnap.com/public/media/2009/03/duststorms/foto-full.jpg

The AOD measurements reported in this work were made with the CIMEL sun photometer (CE-318). This instrument was installed on the rooftop of the solar village (24.9 1° N, 46.41° E, 764 m) at an elevation located 15 km Northwest of the King Abdulaziz City for Science and Technology (KACST) head office. The sun photometer instrument is an automatic-tracking, sun- and sky-scanning radiometer that makes direct sun measurements with a 1.2 full field-of-view every 15 min at 340, 380, 440, 500, 675, 870, 940, and 1020 nm (nominal wavelengths). Seven of the eight bands were used to acquire AOD values, while the 940 nm wavelength was used to retrieve the total water vapour column data.

The instrumentation, data acquisition, retrieval algorithms, and calibration procedures conformed to the AERONET standards, which are described in detail in numerous studies (e.g., [10, 11]). Typically, the total uncertainty in AOD for a field instrument under cloud-free conditions is ~0.01 for $\lambda$ >440 nm, and ~0.02 for shorter wavelengths. In this study, the hourly-averaged, cloud-screened and quality assured level 1.5 products were used. The results presented in this paper will focus primarily on the AOD valuations at 340 µm. The Ångstrom parameter was also computed from AODs measured using the retrieval algorithms detailed in [11, 12] for the wavelength ranges 340-440 nm.

Standard meteorological observations such as air temperature and relative humidity were obtained from the weather station installed at the KACST main building.

## 4. Results and Discussion

### 4.1. Aerosol Optical Depth (AOD)

Aerosol Optical Depth (AOD) is one of the most important optical properties of aerosols used in the radiative transfer calculation. It is defined as the attenuation by scattering and absorption, due to aerosols, of direct solar radiation passing through the atmosphere. Understanding the spectral dependence of AOD is important for the study of atmospheric aerosols and their optical indices [13]. Additional information on aerosol properties can be obtained from analyses of the Angstrom exponent, $\alpha$, which is a measure of particle size distribution that is considered an indicator of average spectral behaviour. It can be a useful tool when used to distinguish and characterise the different aerosol types [14, 15].

The effect of the 10 March 2009 dust storm on AOD values will be investigated in this section, while the changes on the Angstrom exponent will be discussed in the following section.

For purposes of clarification, the discussion and results will include the behaviour of the variables, considered two days before and two days after the storm, and on event day, referred to herein as pre-event, post-event, and the event day, respectively.

Figure (1) shows the hourly variations of the AOD at 340 nm, and Table (1) summarises the average values of the AOD at the considered wavelength for the considered period.

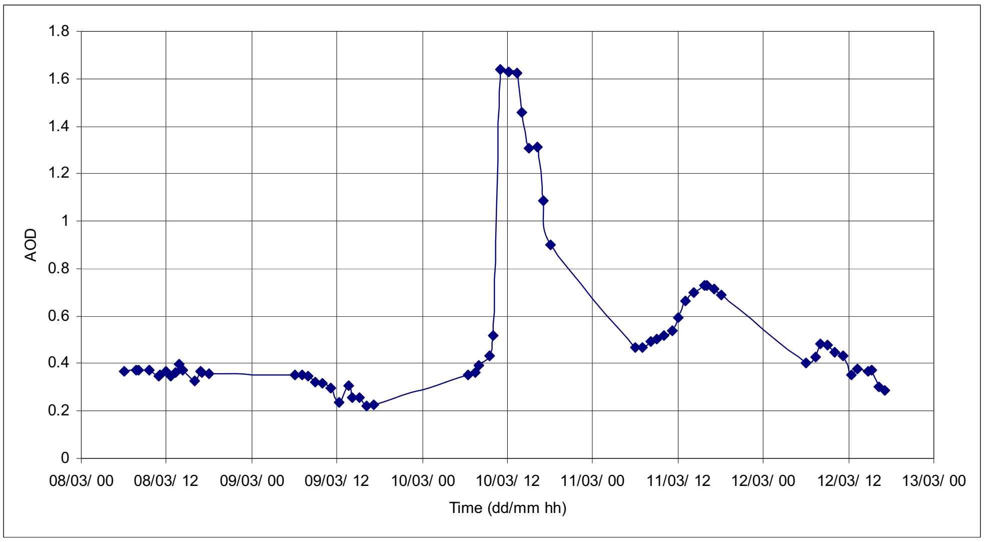


Fig 1. Day-to-day variability of AOD at 340 nm from 8th to 12th March 2009

Table 1. Summarises the average daily values of the five considered meteorological parameters for the considered period from 8-12 March, 2009.

| Day | AOD 340 µm | α 340-440 | RH % | WS (m/s) | T °C | Vis (m) |
|---|---|---|---|---|---|---|
| 8/3 | 0.363 | 0.206 | 18.52 | 10.47 | 24.00 | 9200.00 |
| 9/3 | 0.290 | 0.212 | 16.32 | 17.84 | 23.97 | 9529.17 |
| 10/3 | 1.102 | 0.012 | 26.63 | 22.65 | 20.77 | 2858.26 |
| 11/3 | 0.601 | 0.061 | 27.26 | 15.01 | 18.67 | 4369.57 |
| 12/3 | 0.394 | 0.162 | 21.31 | 12.35 | 22.33 | 5956.52 |

On 8 March, the AODs varied only slightly: these values were between 0.367 to 0.328 with a mean of 0.363±0.014. During the morning hours of 9 March, AOD was 0.353, the maximum value reached on that day. The AOD values then followed a decreasing trend till the end of the day, when the AOD was 0.225. The mean AOD values were generally lower than those for the 8th, reading 0.290±0.043. On the morning of the 10th, AOD was around 0.320, until at midday it jumped to 1.64, indicating the aerosol loading from the dust storm had influenced the study area. The AODs remained at these high values for the next three hours. They then decreased gradually to reach a value 0.902 by the end of the day, with a mean AOD value for that day of 1.101±0.50. This increase in average AODs was accompanied by a similar increase in the standard deviation, indicating a great variation in the amount of atmospheric aerosol measured during that day. This large variation can be related to the air mass that transported the aerosols affecting the study area. The AOD values during this dust storm event were very high when compared with the same values corresponding to intense dust storm events in other places around the world, including Gawangju, Korea [16], Granada Spain [17], Kwangju, South Korea [13], and Osaka Japan [18].

On the 11th, the AOD increased steadily from a morning level of 0.469, reaching a maximum of 0.731 by the end of the day, with a mean value of 0.601±0.10. On 12 March, AOD was lower in comparison with the previous day, reaching a value of 0.284. The mean AOD for that day was 0.394±0.061. Similar patterns of variation applied to the remaining wavelength bands.

Generally speaking, the AOD values for the two days preceding the dust event (8–9 March) were 0.326, which is relatively low compared with those obtained after the dust event 0.497 (11-12 March).

### 4.2 Angstrom Exponent α

The Angstrom exponents α were derived from the AOD measurements using the retrieval methods detailed in Holben et al. 1998 and Holben et al. 2001 for the wavelengths 340-440 nm.

The hourly variation of α values is shown in Fig. 2 for the five days considered, for the wavelength range 340-440 nm, and their daily averages are summarised in table 1. Apart from the 9 March data, there is a diurnal variation of α that was observed during the four days. On the 8$^{th}$ α increased from 0.172 to its highest value of 0.260 by the end of the day, with a mean value of 0.206±0.020. However, on the 9$^{th}$ α values follow a continuously increasing trend, from a minimum of 0.093 to a maximum of 0.386 by the end of the day. On that day, α was 0.212±0.09 higher than on the previous day. Around midday on the 10$^{th}$ α was 0.241, when it dropped dramatically to -0.117 at the time the dust plume arrived at the study region; α stayed below zero values until the end of the day. The mean value on the 10$^{th}$ was 0.012±0.17. On the 11$^{th}$, the variation of α was slow, when it ranged between -0.03 in the morning and 0.103 at the end of the day. On the 12$^{th}$, the α trend resumed its daily variation when it increased from 0.120 to 0.228 by the end of the day. The means for the 11$^{th}$ and 12$^{th}$ were 0.061± 0.040 and 0.162±0.036, respectively.

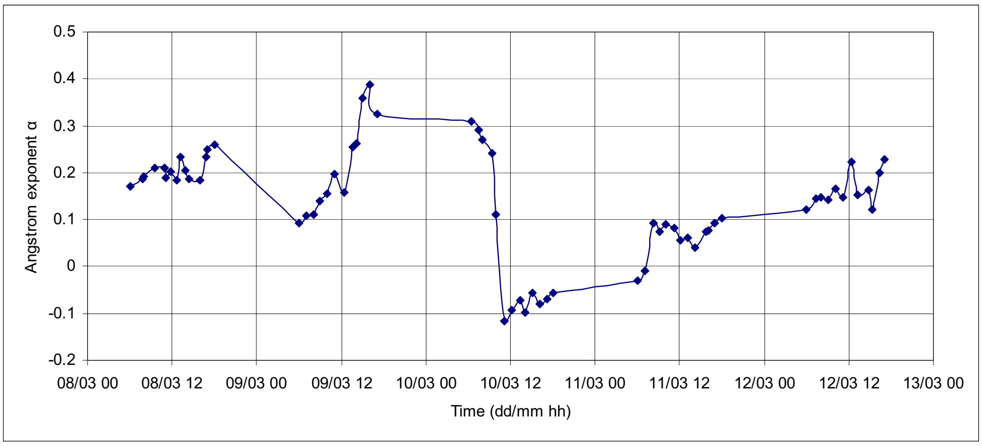


Fig. 2. Day-to-day variability of Angstrom component α for the wavelength range 340-440 nm from March 8-12, 2009.

It should be noted that the mean α value for the two days preceding the dust event (8–9 March) was 0.209, which is high compared with the 0.110 obtained afterwards (10-11 March). Also, with the exception of the event day, α had its mean maximum values on 9 March and minimum values on 11 March.

Also, the variations of α during the five days considered are bi-modal with the largest mode and smaller mode. This suggests the prevalence of two types of aerosols during this period. The largest mode is related to the prevalence of fine particles from urban-industrial sources, while the smaller mode is linked to the presence of coarse particles such as desert dust particles.

Finally, for the purpose of completeness, the impact of this severe storm on some of the meteorological parameters will be briefly discussed. These parameters are relative humidity (RH), air temperature (T), visibility (Vis), and wind speed (WS). Figure (3) shows the variations of these parameters for the relevant five days, and their daily mean values are summarised in the last four columns of table (1). The figures show that there were dramatic and immediate changes on these parameters, caused by the arrival of the dust plume. WS reached a maximum of 28 m/s, while T dropped by about 6 $^{o}$C, to reach a value of 22 $^{o}$C at 14:00 on the 10th. Relative humidity on the other hand, increased until it reached a maximum of 44 % at 1:00 on the 11th .This is due to the moisture brought into the region by the storm. Visibility (Vis) dropped from 10 km to about zero and remained at this value for the three hours following the event. The mean values of T and Vis post-event were lower than pre-event. On the other hand, RH was higher post-vent in comparison with pre-event data.

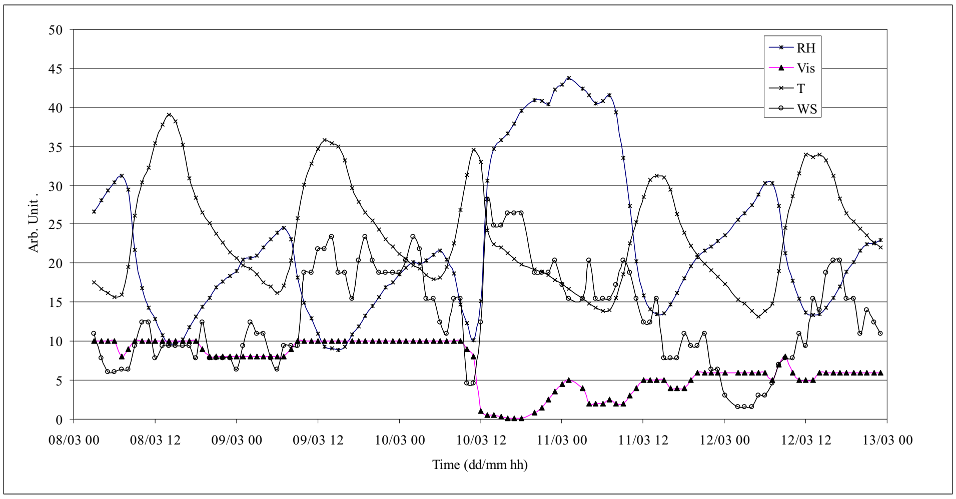


Fig. 3. Day-to-day variability of the four meteorological parameters (see text) from 8-12 March 2009.

## 4.4 Attenuation of solar radiation by aerosols -- SMART Modelling

When solar radiation passes through the atmosphere, it is attenuated by the physical processes of scattering (by air molecules and aerosols) and absorption (mainly by O3, H2O, O2, CO2, NO2, and absorbed aerosol particles). Absorption takes place in spectral ranges that differ for each atmospheric gas, while scattering exists across the whole spectrum with its wavelength dependence due to the specific characteristics of the scattered particles. The effects of different aerosol loads on both the spectral and broadband solar radiation components have been investigated extensively, both experimentally and theoretically, by several researchers (e.g. [19, 20]).

The aim of this section is to investigate how the turbidity conditions caused by the 10 March dust storm affected the solar irradiance components. For this purpose the radiative transfer model was used, known as SMARTS version 2.9.2 [21, 22]. For the present study, the 9$^{th}$ of March had the lowest AOD values among the five days we assumed to be low turbidity days. Therefore, attenuation of the global irradiances component caused by the dust storm at Riyadh on the 10th and 11th were compared with that on 9th. From the SMARTS model the global, diffuse, and direct-beam irradiances were obtained in the spectral band 280 nm – 1100 nm (panels a, b, c, respectively, in Fig. 4). These irradiances were obtained at the same zenith angle (air mass 1.5) and for standard ozone and water-vapour amounts, whereas an urban aerosol model was chosen as the most representative of the atmospheric conditions at Riyadh. This analysis includes three cases: i) indicative of background conditions with low aerosols (AOD = 0.290); ii) for AOD 500 = 1.106 as the daily mean on 10  March; and iii) for an AOD  of 0.601 as the daily mean on 11  March. For the non-dusty day, the spectral distribution of the three components was similar to that of clear skies [23]. However, the effect of high aerosol loads on the spectral distribution of the solar irradiances for the 10th and the 11th differs significantly from one wavelength to another. While the diffuse irradiance showed great increases at higher wavelengths due to higher aerosol values, the direct and global irradiances were greater for shorter wavelengths than for the longer wavelengths.

The study of integrated solar radiation components across the whole spectrum (280 – 1100 nm broadband) suggests that the turbid conditions decreased the global irradiance significantly, by 53% and 17% for 10 and 11 March, respectively. The direct irradiances decreased more intensely by 139% and 46% on the 10th and 11th, respectively, compared to cleaner conditions on the 9th of March, whereas the turbid atmosphere had an impact on the diffuse component, by increasing it by 39% and 15% on 10 and 11 March, respectively.

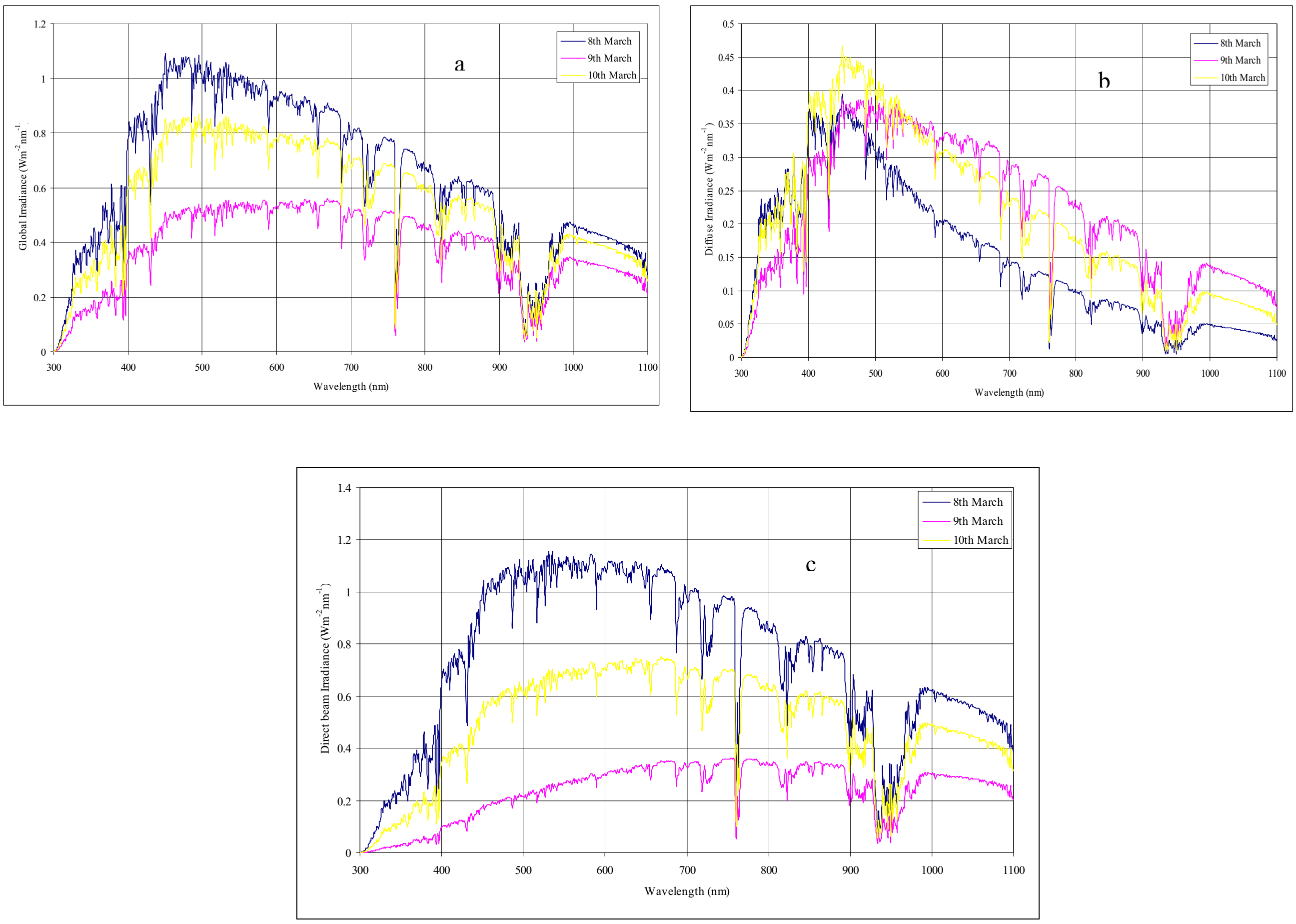

Fig. 4. Estimated spectral irradiances from SMARTS model, (a) global, (b) diffuse, (c) direct-beam for three turbidity conditions; i) non turbid clear conditions AOD = 0.290 (9 March ), ii) for AOD = 1.102 (10 March), and iii) for AOD = 0.601 (11 March).

## 5. Conclusion:

On 10 March 2009, a severe, massive dust storm event struck Riyadh and lasted several hours. The impact of this storm on aerosol optical depth (AOD) and the Angstrom exponent α , were analysed, and the results were discussed. The analysis shows significant changes in the parameters considered, as well as the meteorological parameters due to this event.

The AOD at λ = 340 nm increased by 207 % immediately after the storm. In comparison with the 9th, the daily mean values of AOD were higher by 279 % and 106% for the 10th and the 11th, respectively, due to increased aerosol loads.

At the time of the arrival of the dust plume, the Angstrom exponents for different wavelength ranges plunged to negative values. The mean α value on that day was 0.012±0.17, which is about 90% lower than the average values on the 9th, and 63 % lower than on the 11th, and α values on the event day and on the following days were lower than those before the dust storm.

Theoretical simulations showed that due to the dust storm there was also a remarkable decrease, by 53% and 139 % respectively, in the broad band-global and direct irradiances reaching the ground, in comparison with the previous non-dusty day, whereas diffuse solar irradiance components increased by 39%.

In short, the effects of this storm on several meteorological parameters were presented. We found a great drop on air temperature and visibility and an increase on both wind speed and relative humidity due to the impact of the storm.


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