Analysis of atmospheric vertical profiles in the presence of desert dust aerosols

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Abstract. The present work aims at studying a very recent episode of desert dust transport that affected Iberia in mid May 2015. The dust aerosols were detected over Évora, where a varied set of instrumentation for aerosol measurements is installed, including: a CIMEL sunphotometer integrated in AERONET, a Raman Lidar and a TEOM monitor, as well as ceilometer and a microwave radiometer (profiler). The aerosol occurrence, detected using the columnar, vertically-resolved and in situ measurements, was characterized by a fairly high aerosol optical thickness that reached a value of 1.0 at 440 nm and showed mass concentration peaks at the surface of the order of 100 μg/m³. Subsequently, the tropospheric vertical profiles of humidity and temperature obtained with the passive microwave (MW) radiometer are analysed in order to distinguish possible modifications that can be connected with the transport of desert dust. Modelling results are also examined and the total, SW and LW radiative forcings are investigated, taking into account the different vertical profiles obtained during the desert dust occurrence. It is found that the differences in the atmospheric profiles mostly affect the LW radiative forcing, with an underestimation of about 30% when the actual vertical profile is not considered.

1. Introduction
Solar radiation is the main source of energy for the Earth-atmosphere system. It is well known that any change in the atmospheric composition would significantly affect the radiative budget and, as a result, the global temperature of the Earth. Important components of this system are atmospheric aerosols, interacting directly and indirectly with solar and terrestrial radiation. Desert dust aerosols from North Africa are frequently transported towards the Iberian Peninsula, driven by propituous synoptic conditions [1-3]. These episodes are most frequent during summertime [4-6], when air masses from Northern Africa are favored to reach higher latitudes. However there are still many uncertainties and accurate reliable measurements and analyses are demanded to reduce those uncertainties [7]. This sorts Iberia as a privileged location to study desert dust aerosols and the interaction of these particles with radiation and clouds. In order to quantify the effects of atmospheric aerosols on solar and terrestrial radiation, the concept of aerosol radiative forcing (ARF) is generally used. This variable indicates the magnitude of change in the radiative balance at a given level due to changes in aerosol physical/optical properties.

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The aim of this work is to study an intense episode of desert dust transport that affected Évora site, Portugal, in mid May 2015. The vertical distribution of atmospheric variables as temperature and water vapor, obtained from a microwave radiometer profiler, is investigated in order to identify features that may be associated with the desert dust event. SW and LW radiative forcings are examined as well, taking into account the different vertical profiles obtained during the desert dust occurrence.

The work is organized as follows: after the introduction, a brief description of the site, instrumentation used and a characterization of the desert dust transport are presented in section 2; the method is described in section 3 followed by the results and discussion in section 4. Finally, conclusions are summarized in section 5.

2. Site, instrumentation and characterization of the desert dust transport

Simultaneous measurements of several atmospheric quantities are taken in Évora, at the Atmospheric Physics Observatory of the University of Évora (Institute of Earth Sciences - ICT) (38°34’ N, 7°54’ W, 293 m a.s.l). Mass concentration measurements at the surface are measured with a TEOM (Tapered Element Oscillating Microbalance) Series1400a monitor, installed in the site since January 2006, provided with a PM$_{10}$ sampling head to remove particles with an aerodynamic diameter larger than 10 µm. The aerosol optical thickness (AOT) is measured with a CIMEL CE-318 sunphotometer, which is integrated in AERONET [8]. Figures 1 and 2 show the hourly mass concentration measurements and the AOT at 440 nm, respectively, between 10 and 16 May 2015. It can be noted that high values of mass concentration and AOT were measured on 12 and 13 May, which gradually decreased during the 14 May. These high values were accompanied by a strong decrease of the Angstrom exponent (AE) in the same days (also represented in the right hand axis of Figure 2) that gradually increased during the 14 May. The high values of mass concentration at the surface, together with high AOT and low AE values are consistent with the presence of desert dust in the region.

![Figure 1. Hourly mass concentration measurements at the surface taken with a TEOM in Évora between 10 and 17 May 2015.](image1)

![Figure 2. AERONET AOT at 440 nm (left hand axis) and Angstrom exponent between 440 and 870 nm (right hand axis), between 10 and 17 May 2015, over Évora.](image2)

The active remote sensing measurements, obtained with a Raman lidar system and a ceilometer (Vaisala CL31), are shown respectively in Figures 3 and 4 and illustrate the vertical distribution of aerosols (dust).
Figure 3. Range corrected signal at 532 nm, measured with the Évora Raman lidar system in the evening of 13 May 2015.

The lidar range corrected signal at 532 nm (Figure 3) shows a widespread aerosol layer extending from the lower levels up to about 4-5 km, with a lower signal for increasing height, which corresponds to lower aerosol concentrations. The stronger signal above the dust layer, between 7 and 8 km, corresponds to cirrus clouds. The orange vertical stripes depicted in Figure 4 indicate the time span with lidar measurements (Figure 3), although the weaker ceilometer laser does not allow having much information above 2 km, a diminution of the signal may be distinguished; on the other hand, the typical lidar overlap prevents this instrument to measure at very low altitudes (first few hundreds of meters), where the ceilometer is a good option. The red features in the first levels above the surface (Figure 4) are related with technical issues of the instrument. A good choice is the combination of both in order to gather as much vertical information as possible. The ceilometer backscattering profiles allow for distinguishing an aerosol layer on 12 May that separates from the boundary layer around noon and is visible during the next day and until the morning of 14 May, which probably corresponds to the dust aerosols.

Figure 4. Ceilometer (CL31) backscattering profiles in Évora, between 12 and 14 May 2015. The orange vertical stripes indicate the time span with Lidar measurements (Figure 3).

The measurements presented before hinting at the desert dust intrusion, are corroborated by the back trajectory analysis presented in Figure 5, corresponding to the 120-h back trajectories arriving at Évora at 500, 2000 and 4000 m between 11 and 14 May 2015 obtained from HYSPLIT model (Hybrid Single-Particle Lagrangian Integrated Trajectory) version 4 [9-10]. The back trajectories show that on 11 May the circulation is from west at middle-levels (North Atlantic Ocean), but from 12 to 14 May the higher trajectories are originated in North Western African (NWA) regions, maybe transporting desert dust into Iberia. At the surface it seems there may have been also some intrusion (13 May), although it is not so evident.
In agreement with the back trajectory analysis, the transport of dust from NWA regions toward Iberian Peninsula was favored by the synoptic environment during the period (charts not shown here). The dust was transported by the southwesterly flow at middle levels established due to the presence of a ridge extending from North Africa to Central Europe (11 May). The development of a relatively deep high pressure center was observed near the Strait of Gibraltar during 12 and 13 May, bringing NWA inland air into the southwest flow. At the surface, the development of a cyclone near the Azores was observed during 11 and 12 May. The cyclone developed along a semi-stationary frontal zone on 11 May associated to a low pressure system centered approximately at 55°N and 20°W. After the dissipation of the system on 13 May, the Azores anticyclone retook its normal position, well configured at the surface during 14 May, and the general westerly flow over Portugal was restored, thus ending the southwesterly transport of dust from NWA.

Figure 5. 120-h back trajectories arriving at Évora at 500, 2000 and 4000 m during the period 11-14 May 2015.

The atmospheric vertical profiles of temperature and humidity used in this work are obtained with the RPG-HATPRO humidity and temperature profiling passive microwave radiometer (MWR) [11], installed in Évora since September 2014. The MWR also measures liquid water path (LWP), integrated water vapor (IWV), wet and dry delay and stability indices. It has two bands, 22-31 GHz (7 channel filter bank humidity profiler and LWP radiometer) and 51-58 GHz (7 channel filter bank...
temperature profiler) and presents zenith and azimuth scanning capabilities. Attached to the MWR there are also a meteorological station and an infrared radiometer providing cloud base detection.

3. Method
The analysis of the atmospheric vertical profiles of temperature and humidity (absolute and relative) obtained with the MWR is done through the inspection of these profiles in the days before, during and after the desert dust transport occurrence. The profiles are intercompared and checked against a widely used climatological atmospheric profile [12].

As mentioned above, the aerosol effects on solar and terrestrial radiation are usually quantified through the so called aerosol radiative forcing (ARF), calculated in this work at the surface level. The ARF is defined here (similarly to AERONET) as the difference between the downward global solar irradiance at the surface in the presence of aerosols, $I_d$, and the same quantity in background/baseline conditions, $I_d^0$, (Eq. 1), assuming that, in background/baseline conditions, the aerosol optical thickness is null, as:

$$ARF = I_d - I_d^0$$  \hspace{1cm} (1)

The hourly mean values of ARF, and subsequently daily values of ARF, were calculated as well. For this, the daily averaged forcing is calculated by integrating the hourly data during the whole day (24 h):

$$DARF_{\text{libRadtran}} = \sum_{24} \frac{ARF_{\text{hourly}}}{24}$$  \hspace{1cm} (2)

The shortwave and longwave irradiances are simulated with the libRadtran radiative transfer model [12]. Version 1.7 of the libRadtran is used in this study with inputs of aerosol optical properties, columnar ozone, precipitable water vapor column and surface albedo. Aerosol properties and precipitable water vapor were obtained from AERONET measurements. Total ozone column was provided by the Ozone Monitoring Instrument (OMI). The surface albedo data have been obtained from the Surface and Atmospheric Radiation Budget (SARB) working group, part of NASA Langley Research Center's Clouds and the Earth's Radiant Energy System (CERES) mission. Other variables taken into account in setting up the model are the following: extraterrestrial irradiance values (obtained from [13]) and the radiative transfer equation solver (the discrete ordinate method [14], DISORT2 calculated with 16 streams, was used). The vertical profiles considered are those obtained from the MWR measurements and a climatological profile is also considered for comparison purposes.

4. Results and discussion
Figure 6 shows the atmospheric profiles obtained from the MWR measurements at 12:00 UTC, between 11 and 14 May 2015. Clearly there is a distinction for all variables, between the profiles obtained on 12-13 May (desert dust event) and the rest of the days. The temperature profiles on 12 and 13 May show higher values in the lower troposphere (up to about 4 km), whereas in the higher levels there is little difference between all MWR temperature profiles. The midlatitude summer (mls) temperature profile presents considerable differences with respect to the MWR temperature profiles, overestimating the temperature values above 5 km with respect to all MWR profiles and underestimating it below 3 km, especially with respect to 12 and 13 May MWR profiles. The absolute humidity on 12 and 13 May present lower values for lower altitudes, with a minimum at about 1 km, then the values increase becoming coincident with the rest of the days at 2 km, and from this altitude until 6 km the absolute humidity is higher than for the rest of the days. Concerning the mls absolute humidity profile, the values are practically coincident with those from the MWR obtained for 11, 14
and 15 May, only slightly higher between 1 and 3 km of altitude. The relative humidity shows differences as well, with the MWR profiles for 12 and 13 May reaching a minimum (less than 10%) at 1 km and then steadily increasing until about 4 km and from this height on becoming roughly constant. This behavior differs from the other 3 days (11, 14 and 15 May), when the decrease at lower levels is not so abrupt, neither the increase at higher levels.

![Figure 6](image)

**Figure 6.** Atmospheric vertical profiles obtained from MWR measurements from 11 to 15 May 2015 at 12:00 UTC and mls profile contained in libRadtran database: a) temperature; b) absolute humidity; c) relative humidity.

The different behavior of temperature and humidity obtained for 12 and 13 May with respect to the other days is most probably related with the different circulation (coming from North Africa) that affected the south of Portugal during these days, when warmer air masses with a different vertical moisture distribution with respect to those reaching the site before and after, coming from west through the Atlantic (Figure 5), transported the desert dust particles. This low level warm air is rather dry below 2 km and above this altitude atmospheric moisture exceeds that of the other days analyzed. This could be connected with the differences in the low and mid-level trajectories, with the first more continental and the second over the Atlantic Ocean (see Figure 5).

**Table 1.** Daily mean SW and LW clear-sky downwelling irradiance at the surface for different vertical profiles of temperature and absolute humidity (mls: mls profile; MWR: profiles obtained from MWR measurements; MWR T: temperature profile obtained from MWR measurements and mls humidity profile; MWR H: mls temperature profile and humidity profile obtained from MWR measurements).

| Vertical profile considered | SW downwelling irradiance at the surface (W/m²) | LW downwelling irradiance at the surface (W/m²) |
|----------------------------|-----------------------------------------------|-----------------------------------------------|
|                            | 11 May | 12 May | 13 May | 14 May | 11 May | 12 May | 13 May | 14 May |
| mls                        | 666.26 | 614.35 | 595.05 | 647.30 | 299.74 | 307.94 | 310.65 | 302.24 |
| MWR                        | 666.34 | 616.07 | 596.75 | 647.88 | 306.59 | 313.65 | 321.78 | 290.60 |
| MWR T                      | 666.16 | 614.36 | 595.09 | 647.16 | 306.78 | 318.72 | 326.70 | 293.56 |
| MWR H                      | 666.41 | 616.08 | 596.75 | 648.03 | 299.60 | 302.91 | 305.84 | 299.06 |

The daily mean SW and LW clear-sky downwelling irradiances at the surface were calculated from 11 to 14 May, considering different vertical profiles of temperature and absolute humidity. The results are summarized in Table 1, where simulations are identified as: mls for simulations using the mls profile; MWR: simulations using the profiles obtained from MWR measurements; MWR T: simulations considering the temperature profiles obtained from MWR measurements and the mls
humidity profile; MWR H: simulations using a mls temperature profile and the humidity profiles obtained from MWR measurements. In the case of SW radiation, there is very little change in the four types of simulation, although on 12 and 13 May a slightly higher change is observed. Accordingly, results suggest that, to some extent, the atmospheric moisture plays a more important role since MWR H simulations are nearer MWR values than MWR T. Nevertheless, results show that the atmospheric profile does not play a central role in the clear-sky SW irradiance at the surface. As for LW irradiance, the differences obtained in the four simulations for each day demonstrate the importance of using the actual atmospheric profile. In addition, it can be also concluded for the results in Table 1 that in this case, the temperature profile seems to have greater importance since the results of MWR T are nearest to MWR (considered here the actual irradiance values).

**Table 2.** Daily mean SW, LW and total aerosol radiative forcing from 11 to 14 May 2015, considering two types of atmospheric vertical profiles: climatological and microwave measurements.

| Date       | Aerosol radiative forcing (W/m²) |   SW |   LW | Total |
|------------|---------------------------------|------|------|-------|
|            | mls atmospheric vertical profiles | MWR atmospheric vertical profiles | mls atmospheric vertical profiles | MWR atmospheric vertical profiles | mls atmospheric vertical profiles | MWR atmospheric vertical profiles |
| 2015-05-11 | -6.04                           | -5.97 | +0.14 | +0.20 | -5.9 | -5.77 |
| 2015-05-12 | -34.57                          | -33.60 | +3.77 | +5.31 | -30.80 | -28.29 |
| 2015-05-13 | -45.30                          | -44.33 | +4.64 | +6.89 | -40.66 | -37.44 |
| 2015-05-14 | -15.05                          | -14.71 | +1.24 | +1.65 | -13.81 | -13.06 |

The daily mean SW, LW and total (SW plus LW) ARF values calculated from 11 and 14 May 2015 are presented in Table 2. The SW ARF presents the lowest values on 12 and 13 May, when the AOT values were higher (Figure 2). As expected due to the results in Table 1, the use of mls or MWR profiles does not change significantly the ARF obtained (change of about 2% on the 13 May), with a slight tendency of mls case to underestimate the SW ARF with respect to the MWR case. Nonetheless, the same cannot be concluded for the LW ARF, where meaningful underestimations are found due to the use of mls profile, reaching roughly 33% on the 13 May. These results reflect on the total ARF, causing an underestimation when the actual vertical profile is not considered.

**5. Conclusions**

The work is focused on the transport of Saharan desert dust that occurred in mid May 2015 and affected the south of Portugal. The episode is characterized using *in situ*, as well as passive and active remote sensing measurements. The tropospheric vertical profiles of humidity and temperature obtained with the passive microwave radiometer show that during the dust transport the atmospheric temperature is systematically higher than in the other days and the humidity is lower in the low atmosphere, becoming higher than the reference days for the higher tropospheric levels. The differences found are probably related with the different circulation that affected the south of Portugal during these days, bringing warm air from North Western Africa, with a different vertical moisture distribution with respect to those reaching the site before and after. The analysis of SW and LW dowelling irradiance and ARF at the surface level show that the differences in the atmospheric profiles mostly affect the LW, with an underestimation of about 30% in the ARF when the actual vertical profile is not considered.
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