Aerosol Direct Radiative Effects of a Transatlantic Biomass Burning Plume over Granada, Spain

J.L. Guerrero-Rascado[1], F.J. Olmo[2,3], F. Molero[4], F. Navas-Guzmán[2,3], M.J. Costa[1], A.M. Silva[1], M. Pujadas[4], M. Sicard[5] and L. Alados-Arboledas[2,3]

[1] Évora Geophysics Centre (CGE), University of Évora, Rua Romão Ramalho 59, 7000, Évora, Portugal
[2] Andalusian Center for Environmental Research (CEAMA), University of Granada – Autonomous Goverment of Andalusia, Av. del Mediterráneo s/n, 18071, Granada, Spain
[3] Department of Applied Physics, University of Granada, Fuentenueva s/n, 18071, Granada, Spain
[4] Centro de Investigaciones Energéticas, Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain
[5] Department of Signal Theory and Comunications, Remote Sensing Lab., Universitat Politécnica de Catalunya/Institut d'Estudis Espacials de Catalunya, Barcelona, Spain

Abstract — **This work presents the assessment of the aerosol direct radiative effects for a special episode of transatlantic transport of a biomass burning plume, performed over Granada, south-eastern Iberian Peninsula, on 20th August 2007. The knowledge of aerosol radiative impact requires an accurate determination of their optical and microphysical properties, which are obtained here using ground-based remote sensing instrumentation by means of a combination of lidar and sun-photometer. Our data highlight the presence of a multilayered structure with a well-defined planetary boundary layer and biomass-particles in elevated layers, extending up to 9 km asl, at the south-eastern part of the Iberian Peninsula. The aerosol direct shortwave radiative effects, evaluated from simulations with SBDART code, show that the biomass burning plume increases the heating rate up to 0.5 K/day in spite of the small contribution of these particles to the total aerosol optical depth (10-20%). In addition, our results indicate that the biomass burning plume strengths the negative radiative forcing about -5 down to -8 W/m^2 at the surface, between noon and evening. At the TOA, radiative forcing appeared slightly positive but very close to zero at noon, and negative in the evening with a decrease of 1.5 W/m^2 caused by the presence of the biomass burning plume.**

Keywords— **Biomass burning, heating rate, lidar, radiative forcing.**

I. Introduction

The aerosol particles scatter and absorb solar radiation influencing the Earth's radiation budget. Among other effects, they can reduce the solar radiative flux at the surface, can limit surface evaporation and surface heat fluxes, and also modify the radiative properties and lifetime of clouds [Raut and Chazette, 2008]. Quantifying and decreasing the uncertainty in aerosol effects on climate is crucial to understand climate change and also to improve the predictions of future climate change for assumed emission scenarios. For climate models, the aerosol direct shortwave radiative forcing at the surface and at the top-of-the atmosphere (TOA) is especially relevant. It is defined as the changes in the respective net fluxes due to scattering and absorption processes of shortwave (solar) radiation by aerosol particles in cloud-free conditions.

The emissions from fires affect significantly the atmospheric composition both at regional and global scales. During the combustion a wide range of chemically active gases are released and the fires are an important source of aerosols which have strong radiative effects [Forster *et al.*, 2007]. The emitted trace gases and aerosols that escape the planetary boundary layer and reach higher altitudes have long lifetimes and can suffer long-range transport, with the potential to affect climate far from the fire sources. Thus, fires plume have been detected over continental, intercontinental and even hemisphere scale [Val Martin *et al*., 2010].

This study focuses on the effect of biomass burning particles over Granada (Spain) after a long-range transport from North America. On 20th August 2007 a plume of particles was detected in the free troposphere up to 9 km asl. The paper is organized as follows. Section 2 presents the active and passive instrumentation used in this work. Section 3 described the methodology applied to the remote sensing data and the code to derive the radiative properties. Section 4 shows the results and discussion and, finally, the main conclusions are given in section 5.

II. Instrumentation and Methodology

The instrumentation used in this work is operated at the Andalusian Center for Environmental Research (CEAMA) located in Granada (Spain, 37.16ºN, 3.6ºW, 680 m asl (above sea level)). The station is included in SPALINET (Spanish and Portuguese Aerosol LIdar NETwork), EARLINET (European Aerosol Research LIdar NETwork) and AERONET (AErosol RObotic NETwork).

A multiwavelength Raman lidar is used for vertically resolved measurements of the particle optical properties to characterize the biomass burning plume discussed in this work. The Raman lidar system is configured in a monostatic biaxial alignment pointing vertically to the zenith. The light source is a pulsed Nd:YAG laser with fundamental wavelength at 1064 nm, additional emissions at 532 and 355 nm are obtained by using second and third harmonic generators. The receiving system consists of a receiving telescope, 40 cm diameter. The collected radiation is split into seven channels allowing the detection of elastic signals at 1064, 355 and 532 nm (in parallel and perpendicular components) and three Raman channels at 387 and 607 nm (nitrogen Raman-shifted signal from 355 and 532 nm, respectively) and 408 nm (water vapour Raman-shifted signal from 355 nm).

From the lidar signals aerosol backscatter profiles have been retrieved, both day and night time, using Klett-Fernald-Sasano's algorithm [Fernald *et al*., 1972; Fernald, 1984; Klett, 1981 and 1985; Sasano and Nakane, 1984; Sasano *et al*., 1985]. The errors associated to the overlap function do not affect the results of this work, because the present study focus on layers above 2 km.

The column integrated characterization of the atmospheric aerosol is done by means of an automatic sun tracking photometer Cimel CE-318-4. It is a sun-photometer which makes direct sun measurements with a 1.2º full field of view at 340, 380, 440, 675, 870, 940, and 1020 nm, taking about 8 s to scan all wavelengths using a filter wheel. The instrument also includes protocols for the measurements of sky radiance values in a reduced number of wavelength using almucantar and principal plane geometries. A whole description can be seen in Holben *et al*. (1998).

Solar extinction measurements are used to derive the aerosol optical depth at each wavelength except at 940 nm which is used to retrieve the total column water vapour. A cloud screening filtering is applied to the data [Smirnov *et al*., 2000]. Aerosol spectral dependence is also derived from the Angstrom law.

The sky radiance measurements, performed at the almucantar and principal planes at 440, 675, 870, and 1020 nm in conjunction with solar direct irradiance measurements at these same wavelengths, were used to retrieve the volume size distribution, the single scattering albedo, and the asymmetry parameter, at these four wavelengths based on a non-spherical inversion method [Olmo *et al*., 2006].

Two kinds of calibrations are required for the Cimel instrument. Thus Langley calibrations are performed at a high mountain site in the close range of Sierra Nevada (2200 m a.s.l) at least twice a year [Alcantara-Ruiz *et al*., 2004]. The sub-system that measures the radiances is calibrated at the laboratory using an integrating sphere [Alados-Arboledas *et al.*, 2004].

The aerosol direct shortwave radiative forcing has been investigated by means of the SBDART code (http://arm.mrcsb.com/sbdart/) during this event of long-range transport from North America. SBDART is a tool that computes plane-parallel radiative transfer both within the atmosphere and at the surface, including all important processes that affect the radiation [Ricchiazzi *et al*., 1998]. This code provides radiative transfer computations for aerosol particles using as input the spectral aerosol optical depth, the spectral single scattering albedo, and the spectral asymmetry parameter (derived from radiometric measurements). Other inputs required by the code include the solar zenith angle, total ozone columnar content (retrieved from TOMS, http://toms.gsfc.nasa.gov/), and the selection of an atmospheric model to prescribe the gaseous composition of the atmosphere (summer mid-latitude atmosphere in our case). Several simulations have been computed considering different vertical distributions of aerosols in order to evaluate the aerosols radiative impact for the whole column and also for the isolated biomass burning plume.

III. Results and discussion

In summer 2007, several strong episodes with high loads (in terms of optical depth) of aerosol particles occurred over the Iberian Peninsula. In particular, on 20th August 2007 an unexpected plume of particles was detected in the free troposphere. The backward trajectories analysis based on HYSPLIT [Draxler and Rolph, 2003] (Figure 1) and FLEXTRA [Stolh *et al*., 1998, 2005] models reveal as main source region the East coast of North-America, where many forest fires were active during the first part of August 2007, as detected by MODIS sensor (http://firefly.geog.umd.edu/firemap/).

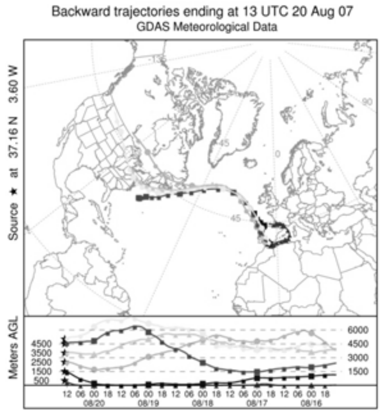


Fig. 1 Backtrajectories ending over Granada on 20th August 2007

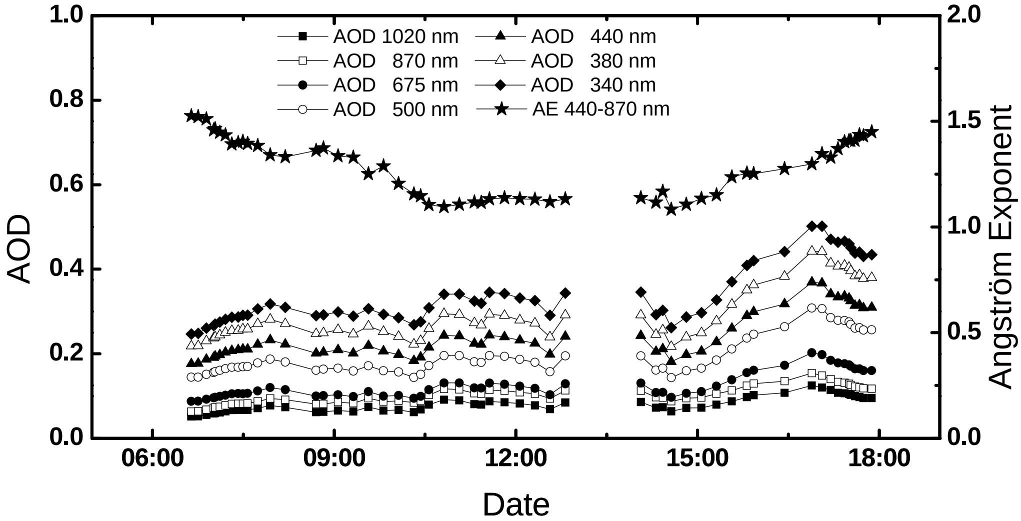
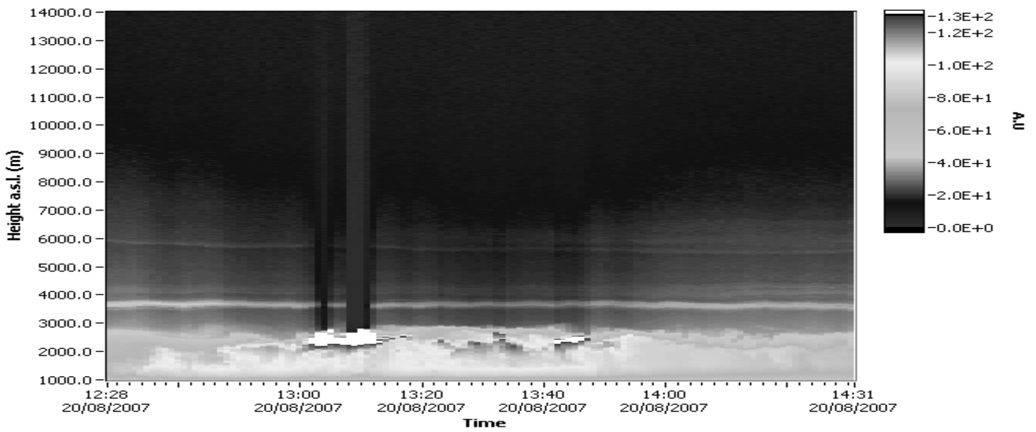


Fig. 2 Instantaneous values of aerosol optical depths and Angström exponents derived from Cimel on 20th August 2007



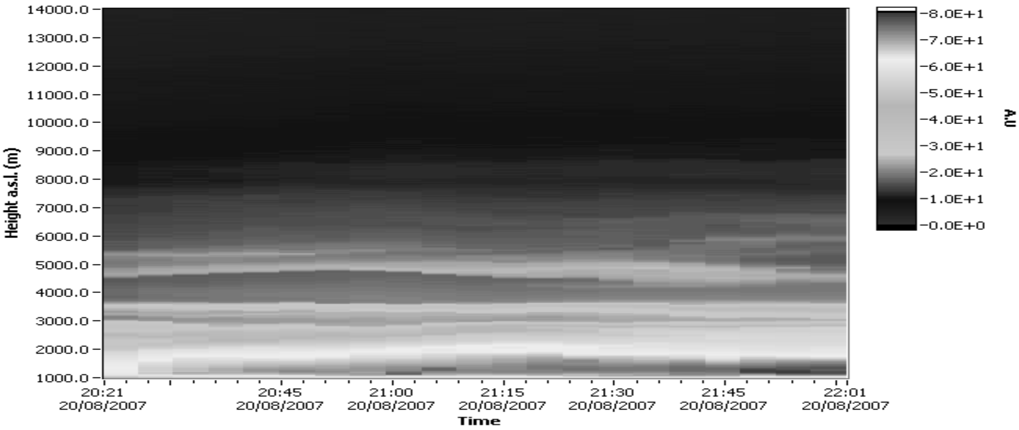


Fig. 3 Temporal evolution of range corrected signal at 532 nm derived from lidar on 20th August 2007

Over Granada, the Cimel CE-318-4 allows for monitoring the diurnal variability for the aerosol optical properties along the whole 20th August, except around 13:00 UTC when some clouds are present. As can be seen in Figure 1, the sun-photometer indicates atmospheric conditions with low-medium aerosol loads. During the morning the aerosol optical depth is rather constant, in terms of aerosol optical depth, and an increase of the aerosol load (aerosol optical depth at 440 nm up to 0.37) is observed in the afternoon and evening from 15:00 UTC. The Angström exponents (440-870 nm) range between 1.1 and 1.5 during this day.

Lidar measurements were performed at selected times. Figure 3 shows the evolution of the range corrected lidar signal at 532 nm, i.e. the raw lidar signal multiply by the square distance, for two periods of measurements. In spite of the presence of clouds around 13:00 UTC preventing direct sun-photometer measurements, only a brief low cloud was seen by the lidar field of view during the measurements. The lidar measurements highlight the presence of a multilayered structure over Granada with a well-defined planetary boundary layer and aerosol particles in elevated layers extending up to 7 and 9 km asl at noon and evening, respectively. Lidar computations reveals that particles above the planetary boundary layer contribute about 10-20% to the aerosol optical depth, with backscatter-related Angström exponents around 2-3 for different spectral ranges. The combination of the backward trajectories analysis and MODIS information together with these large Angström exponents allows for stating that the aerosols over the planetary boundary layer correspond to biomass burning particles originated during fires in North America that arrive to our station after a transatlantic transport.

The radiative transfer calculations were performed at noon and evening considering two different scenarios: (i) actual (measured) aerosol vertical profiles including both planetary boundary layer PBL (regional/local aerosols) and biomass burning plume BB (long-range transported), and (ii) simulated aerosol vertical profiles including only the planetary boundary layer contribution. The radiative forcings of aerosols depend on the solar zenith angle. Thus, to compare the different scenarios a fixed zenital angle of 30º was used.

The Table 1 presents the direct shortwave radiative forcing at surface, TOA and atmosphere on 20th August at noon and evening for the different scenarios. At the TOA, the radiative forcing is generally negative, indicating a potential cooling of the system, but can be also slightly positive. In our computations, the radiative forcing appeared slightly positive but very close to zero at noon, and negative in the evening with a decrease of 1.5 W/m^2 caused by the biomass burning plume. Previous studies reported similar values. For example, Johnson *et al.* (2008) found a TOA radiative forcing of -9.8 W/m^2 from FAAM aircraft measurements averaged over the DABEX experiment. Raut and Chazette (2008) found a mean value of -1.4 W/m^2, although positive values up to 0.4 W/m^2 were also obtained. The absolute values were lower than in previous studies and were partly attributed to relative high absorption properties in the biomass burning layer, preventing a part of the upwelling diffuse flux from returning to space.

At the surface the results indicate that the differences between noon and evening are low (below 5%) for the same scenario, and the biomass burning plume enhances the negative radiative forcing ~5-8 W/m^2 between noon and evening. This cooling effect detected at the surface is not negligible, especially taking into account the small contribution of these biomass burning particles to the total aerosol optical depth (10-20%). From the calculated radiative forcings at surface and TOA, the radiative forcing at the atmosphere can be derived. All scenarios show large positive atmospheric forcing, with values between +32.6 and +49.3 W/m^2, indicating a potential warming of the system. Moreover, the radiative forcing of the atmosphere increased ~5-7 W/m^2 as a consequence of the advected biomass burning particles, indicating an increase of the absorption of solar radiation in the atmosphere due to these particles.

Table 1 Direct shortwave radiative forcing at Surface, TOA and Atmosphere on 20th August 2007.

Case	Surface	TOA	Atmosphere
Noon PBL	-41.6	+2.7	+44.3
Noon PBL+BB	-46.4	+3.0	+49.3
Evening PBL	-39.4	-6.9	+32.6
Evening PBL+BB	-47.8	-8.4	+39.4

The atmospheric heating rate is not homogenous in the vertical column due to the variable aerosol vertical distribution. Figure 4 shows the vertical profile of heating rate for the different scenarios considering in this work, showing that the biomass burning plume increases the heating rate up to 0.5 K/day in spite of the small contribution of these particles to the total aerosol optical depth. Our results are lower than the ones obtained in previous works. Raut and Chazette (2008) found heating rates, associated with the aerosols, up to 2.2 K/day in the biomass burning layer, despite a moderate aerosol optical depth in the layer (about 0.3). Keil and Haywood (2003) reported a value of 2.05 K/day for biomass burning particles with aerosol optical depth around 0.25 at 550 nm, and León *et al*. (2002) found values of 2.2 K/day during INDOEX, with conditions of aerosol optical depth around 0.6 at 532 nm. We consider that the values obtained in this work agree with the previous works despite the fact that, in our case, the aerosol loads are rather smaller (aerosol optical depth of 0.37 at 440 nm for the whole atmosphere, with the biomass burning layer representing only a fraction of 10-20%.

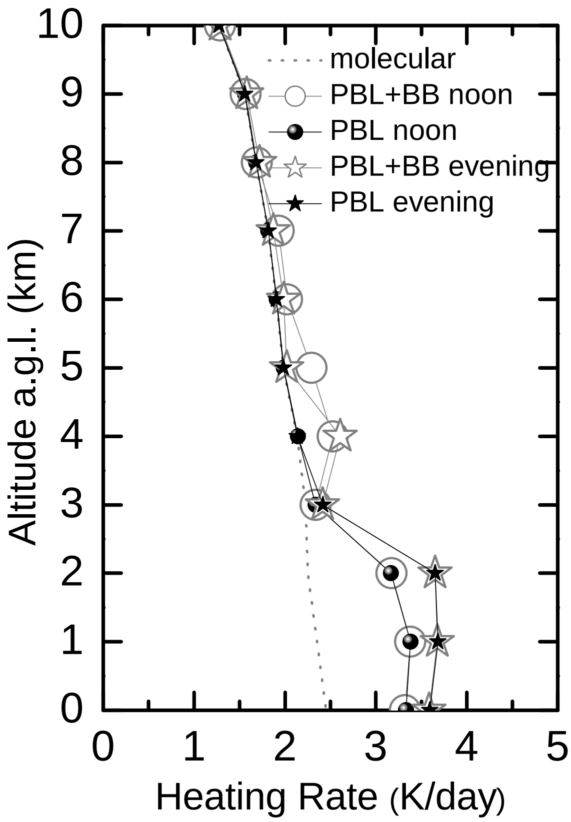


Fig. 4 Profiles of heating rate (K/day) for several conditions on 20th August 2007

IV. Conclusions

The episodes of large aerosol loads in the free troposphere are frequent over Granada. Most of them correspond to transport from Saharan desert, but some are episodes of transatlantic transport of biomass burning particles from North America. These last ones, in spite of being almost undetected in terms of column integrated optical properties, can modify the local radiative properties of the atmosphere over the station in which the particles are advected.

In this work, an event of transatlantic advected biomass burning, detected over Granada on 20th August 2007, has been analyzed in order to illustrate its potential radiative effects. Our results demonstrate that, even under conditions of low aerosol loads (about 10-20% of the aerosol optical depth), the transatlantic biomass burning layers can affect the local radiative properties, substantially. Thus at the TOA, the radiative forcing appeared negative in the evening with a decrease of 1.5 W/m^2 caused by the biomass burning plume, and at the surface the biomass burning plume strengths the negative radiative forcing around 5-8 W/m^2

between noon and evening. This cooling effect detected at the surface is not negligible, especially taking into account the small biomass burning particles loads. Concerning the atmosphere, the advected biomass burning particles enhanced the absorption of solar radiation in the atmosphere and thus the atmospheric forcing increased ~5-7 W/m^2. As a consequence, the vertical profile of heating rate increased up to 0.5 K/day, due to the presence of the biomass burning plume, in spite of the small contribution of these particles to the total aerosol optical depth.

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