Analysis of derived optical parameters of atmospheric particles during a biomass burning event. Comparison with fossil fuel burning

A Costa¹, S Mogo¹,²,³, V Cachorro², A de Frutos², M Medeiros¹, R Martins¹, J F López², A Marcos², N Marcos⁴, S Bizarro⁴ and F Mano⁴

¹ Departamento de Física, Universidade da Beira Interior, Covilhã, Portugal
² Grupo de Óptica Atmosférica, Universidad de Valladolid, Valladolid, España
³ Instituto Dom Luiz, Lisboa, Portugal
⁴ Baldios da Freguesia de Cortes do Meio, Covilhã, Portugal

E-mail: smogo@ubi.pt

Abstract. During the day November 26, 2014, a scheduled cleanup of the woods took place around the GOA-UVa aerosol measurement station located at the campus of the University of Beira Interior (40°16′30″N, 7°30′35″W, 704 m a.s.l.), Covilhã, Portugal. This cleanup included excessive vegetation removal during the morning, using fossil fuel-burning machinery, and burning of the vegetation during the afternoon. In situ measurements of aerosol optical properties were made and this study aims the characterization of the evolution of aerosol properties during the day. The optical parameters were monitored using a 3-wavelength nephelometer and a 3-wavelength particle soot absorption photometer. Selective sampling/exclusion of the coarse particles was done each 5 minutes. The scattering and absorption Ångström exponents as well as the single scattering albedo were derived and fully analyzed. The scattering and absorption coefficients increased dramatically during the event, reaching values as high as 720.3 Mm⁻¹ and 181.9 Mm⁻¹, respectively, for the green wavelength and PM10 size fraction. The spectral behavior of these parameters also changed wildly along the day and an inversion of the slope from positive to negative in the case of the single scattering albedo was observed.

1. Introduction

Biomass burning (BB) and fossil fuel burning (FFB) are strong sources of black carbon (BC) emissions into the atmosphere [1–4]. Despite their short lifetime, BC particles present strong effects. They are considered the strongest absorber of solar radiation in the atmosphere, interfering with the radiative balance of the planet and they are mainly fine fraction particles, inhalable by the human respiratory system and affecting human health. Studies that analyze the optical, chemical and microphysical properties of aerosols allow pave the way for understanding the contribution of these particles in radiative terms for the planet, human health and visibility [5, 6]. So, many authors direct their research to the characterization of aerosols that are released during the burning processes [1–3, 5–7]. However, due to the aggregation state of the particles (internal or external mixing), the study of all parameters associated with this type of particles becomes complex. Also, these particles, resulting from incomplete combustion processes, are

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transported long distances in the atmosphere. Thus, the effects associated are not limited to the zone where burning occurred [7].

As Portugal has extensive forest areas, biomass burning is usually associated with forest fires, however, scheduled biomass burn activities are also a resource in agriculture for clearing of vegetation. Thus, such episodes can occur regularly. Given these facts and the importance of aerosol study in episodes with these features, this paper aims to present the evolution of the optical properties of aerosols during a scheduled cleanup of the woods that includes FFB as well as BB. The data is collected by the GOA-UVa in situ measurement station, located on the campus of the University of Beira Interior (UBI). This work is the result of the collaboration between the Group of Atmospheric Optics of the University of Valladolid (GOA-UVa) and UBI.

2. Methods

2.1. Sampling location

The events analyzed in this work were registered in Covilhã, a town located in central Portugal with \( \sim 36700 \) inhabitants. Located in the proximity of the mountains (Serra da Estrela, 2000 m a.s.l.), the town towers between 450 and 800 m a.s.l. In the immediate vicinity, the mountains are enveloped by forested areas dominated by varieties of pine and chestnut trees, and the valley is dominated by agriculture in small farms. In situ measurements of aerosol properties, are continuously being collected since July 2013 in the GOA-UVa aerosol measurement station located at the campus of UBI, outside the town but 1 km straight line from the city center.

2.2. Instrumentation and data processing

For transporting aerosols from the atmosphere to the instruments, an inlet protected with a rain cap is used. The cut-off diameter of the inlet nozzle and sample transport line is approximately 10 \( \mu \)m and the airflow through the sampling line is divided into several separate flows and directed toward individual instruments. The collecting system includes a valve for selective sampling/exclusion of the coarse particles, which was done each 5 minutes in such a way that during 5 minutes only the fine fraction (PM1) reaches the instruments and the following 5 minutes the complete PM10 fraction reaches the instruments.

The scattering coefficients, \( \sigma_s \), were measured at three wavelengths (450, 550 and 700 nm) using an integrating nephelometer (model 3563, TSI). The instrument is described in detail by [8] and [9]. The averaging time was set to 5 min. The zero signal was measured once per hour. The data was corrected for truncation errors according to [9].

The light absorption coefficients, \( \sigma_a \), were measured at three wavelengths (470, 522 and 660 nm) using a particle soot absorption photometer (PSAP, Radiance Research). The instrument is described in detail by [10] and [11]. The averaging time used for the PSAP was 60 s, and the filter was replaced whenever the amount of transmitted light reached 70% of the initial intensity. The data was corrected for the loading of particles on the filter, the amount of light scattered by the particles, the flow rate and the spot size according to [10] and [11].

The corrected aerosol scattering coefficients were extrapolated to the working wavelengths of the PSAP using the Ångström exponents.

The aerosol single-scattering albedo (SSA), \( \omega_0 \), is obtained as the ratio between the aerosol light scattering and the extinction:

\[
\omega_0 = \frac{\sigma_s}{\sigma_s + \sigma_a}.
\]

To investigate the wavelength dependence of the optical parameters, we calculated the scattering/absorption/SSA Ångström exponent. This parameter is commonly used for the analysis of the variations of the spectral shape of the optical parameters and is defined as the negative slope of the logarithm of the optical parameter as a function of the wavelength. It
is given by:

$$\sigma_x = K\lambda^{-\alpha_x},$$

(2)

where \(x\) may represent the scattering coefficient, the absorption coefficient or the single scattering albedo. Using only one pair of wavelengths, the Ångström exponent can be obtained from the following simplified formula:

$$\alpha_x(\lambda_1, \lambda_2) = \frac{-\log(\sigma_x(\lambda_2)/\sigma_x(\lambda_1))}{\log(\lambda_2/\lambda_1)}.$$  

(3)

Data is available for the day November 26, 2014 and the statistical data for all instruments were calculated based on 5-min averages.

3. Results and discussion

Figure 1(a) shows the evolution of the absorption and scattering coefficients, as well as single scattering albedo throughout the day. Figure 1(b) shows the evolution of the Ångström exponents. The analysis of the data series was divided into three stages: during the biomass burning episode, fossil fuel burning episode and rest of day. The statistical measures such as mean, standard deviation, maximum and minimum values are presented in table 1.

| Table 1. Evaluation of the overall ranges and arithmetic mean values of the absorption/scattering coefficients and SSA as well as the respective Ångström exponents in PM1 and PM10 fractions. FFB: fossil fuel burning. BB: biomass burning. B, G, R: blue, green and red wavelengths. Statistical values are presented for all the day, excluding the time of the events. For the BB and FFB events, only the peak value is presented. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| PM10 | rest of the day | FFB | BB | BB | BB | rest of the day | FFB | BB | rest of the day | FFB | BB | rest of the day |
| StD | max | min | mean | peak | peak | peak | mean | min | max | mean | min | max |
| 11.3 | 56.2 | 8.1 | 22.9 | 66.6 | 879.4 | B | B | 712.3 | 74.1 | 21.6 | 8.3 | 45.8 | 10.4 |
| 9.4 | 48.1 | 6.2 | 18.3 | 52.6 | 720.3 | G | G | 605.5 | 58.8 | 17.0 | 6.2 | 35.8 | 8.4 |
| 7.4 | 38.2 | 4.0 | 12.9 | 35.6 | 516.3 | R | R | 463.6 | 40.8 | 11.7 | 3.9 | 29.1 | 6.1 |
| 6.7 | 31.3 | 2.6 | 10.1 | 58.2 | 212.9 | B | B | 681.0 | 63.2 | 10.1 | 3.4 | 40.9 | 7.0 |
| 5.4 | 22.6 | 2.4 | 8.2 | 48.8 | 181.9 | G | G | 490.4 | 52.4 | 8.0 | 2.7 | 31.7 | 5.4 |
| 4.1 | 17.8 | 2.1 | 6.6 | 39.1 | 145.1 | R | R | 309.3 | 41.9 | 6.0 | 2.0 | 22.6 | 4.0 |
| 0.1 | 0.8 | 0.5 | 0.7 | 0.3 | 0.1 | B | B | 0.1 | 0.3 | 0.7 | 0.4 | 0.9 | 0.1 |
| 0.1 | 0.8 | 0.4 | 0.7 | 0.3 | 0.1 | G | G | 0.2 | 0.3 | 0.7 | 0.5 | 0.9 | 0.1 |
| 0.1 | 0.8 | 0.4 | 0.7 | 0.3 | 0.1 | R | R | 0.2 | 0.2 | 0.7 | 0.5 | 0.9 | 0.1 |
| 0.1 | 2.2 | 1.6 | 1.9 | 1.9 | 2.5 | B-G | B-G | 2.5 | 2.0 | 1.9 | 0.8 | 2.3 | 0.3 |
| 0.3 | 2.4 | 0.5 | 1.8 | 1.9 | 2.5 | B-R | B-R | 2.5 | 2.0 | 1.9 | 0.7 | 2.5 | 0.3 |
| 0.2 | 2.5 | 1.4 | 1.9 | 2.0 | 2.6 | G-R | G-R | 2.5 | 2.0 | 1.9 | 0.7 | 2.5 | 0.3 |
| 0.3 | 2.8 | 1.2 | 1.8 | 1.7 | 2.7 | B-G | B-G | 3.0 | 1.7 | 1.8 | 1.2 | 3.2 | 0.4 |
| 0.2 | 2.5 | 1.1 | 1.6 | 1.5 | 2.5 | B-R | B-R | 2.8 | 1.5 | 1.6 | 1.2 | 2.7 | 0.3 |
| 0.2 | 2.3 | 1.1 | 1.4 | 1.4 | 2.5 | G-R | G-R | 2.7 | 1.3 | 1.4 | 1.1 | 2.4 | 0.2 |
| 0.1 | 0.3 | 0.1 | 0.04 | 0.03 | 0.9 | B-G | B-G | 0.9 | 0.1 | 0.03 | 0.5 | 0.3 | 0.1 |
| 0.1 | 0.4 | 0.3 | 0.1 | 0.1 | 0.9 | B-R | B-R | 0.7 | 0.2 | 0.1 | 0.4 | 0.4 | 0.1 |
| 0.1 | 0.4 | 0.3 | 0.2 | 0.1 | 0.7 | G-R | G-R | 0.6 | 0.2 | 0.2 | 0.3 | 0.4 | 0.1 |

The period of the BB episode is easily identified by the pronounced peak in figure 1(a). The FFB episode can also be detected mainly by increase of the absorption values in the morning. We will present values for one wavelength (green) for easiness on reading. The \(\sigma_s\) values registered
Figure 1. Temporal evolution of optical parameters during the day. FFB: fossil fuel burning. BB: biomass burning.

during the day without including the BB and the FFB events ranged from 6.2 to 48.1 Mm\(^{-1}\) (average 18.3 and standard deviation of 9.4 Mm\(^{-1}\)) on PM10. For the fine fraction, PM1, the \(\sigma_s\) ranged from 6.2 to 35.8 Mm\(^{-1}\) (average 17.0 and standard deviation of 8.4 Mm\(^{-1}\)). The \(\sigma_a\) values registered during the day without the events ranged from 2.4 to 22.6 Mm\(^{-1}\) (average 8.2 and standard deviation of 5.4 Mm\(^{-1}\)) on PM10. For PM1 the \(\sigma_s\) ranged from 2.7 to 31.7 Mm\(^{-1}\) (average 8.0 and standard deviation of 5.4 Mm\(^{-1}\)). The average \(\omega_0\) values observed in the period out of events was 0.7 (standard deviation of 0.1) for both fractions, PM10 and PM1. During the BB event the \(\sigma_s\) reached values of 720.3 and 605.5 Mm\(^{-1}\), the \(\sigma_a\) reached values of 181.9 and 490.4 Mm\(^{-1}\), the \(\omega_0\) decreased to values as low as 0.1 and 0.2, respectively for PM10 and PM1 fractions. During the FFB event the \(\sigma_s\) reached values of 52.6 and 58.8 Mm\(^{-1}\), the \(\sigma_a\) reached values of 48.8 and 52.4 Mm\(^{-1}\), respectively for PM10 and PM1 rations. The \(\omega_0\) decreased to values as low as 0.3.

During the BB event, for the pair of wavelengths B-R, \(\alpha_s\) assumed extreme values (0.5 to 2.5) showing the presence of small and large particles throughout the burning event, figure 2(a). The \(\alpha_a\) values were spread in the range 1.2 to 2.8 showing the presence of different chemical species during the event, figure 2(b). \(\alpha_{\omega_0}\) assumed negative values, which means an increase of the SSA along the spectrum, figure 2(c). Figure 2(d) shows a large range of values, however, the most extreme values can also be considered a characteristic of the BB.

During the FFB event, for the same pair of wavelengths B-R, \(\alpha_s\) assumed values in the range 1.7 to 1.9 showing only slight variation in the size of particles during the event, figure 2(a). The \(\alpha_a\) showed values very concentrated in the range 1.1 to 1.5 as a characteristic of the burning particles, figure 2(b). \(\alpha_{\omega_0}\) remained always positive showing a decrease of SSA with
Figure 2. (a), (b), (c) Optical parameters as a function of the respective Ångström exponents. (d) Absorption versus scattering Ångström exponents.

the wavelength, figure 2(c). Figure 2(d) shows a very concentrated range of values that can be considered characteristic of FFB events.

The wavelength dependence of absorption is another way to understand the relative importance of biomass and fossil fuel contribution to BC. Figure 3 compares the normalized light absorption as a function of wavelength for the two events, showing higher spectral dependence during BB and softer dependence during FFB. This result agrees with the observations of other authors studying similar events [3].

4. Final comments
We studied the optical evolution of aerosols resulting from a biomass burning and a fossil fuel combustion events that occurred the same day. The study was conducted in central Portugal, in a region dominated by forest and agriculture in small farms. The primary optical measurements made were light absorption by particle soot absorption photometry and light scattering by nephelometry. Very high values were observed for the scattering and the absorption coefficients, which lead to low SSA values. The scattering and absorption Ångström exponents showed similar behavior, with higher values for the pair blue-green and smaller values for the pair green-red. During the biomass burning event, the Ångström exponent of the SSA assumed negative values, showing an increase of SSA along the spectrum. The fundamental insight gained from this
field study is the distribution of the scattering and absorption Ångström exponents during both events. While the biomass burning event is characterized by the most extreme values registered, the fossil fuel combustion event is characterized by a very concentrated range of values. Also, during biomass burning events, the spectral shape of the absorption coefficient drops quicker than in average conditions out of event. During fossil fuel combustion events, the spectral shape of the absorption coefficient drops more slowly than in average conditions out of event.

Given the fact that a large number of scheduled biomass burn activities are done as a resource in agriculture for clearing vegetation, in Portugal and other countries, it is desirable to evolve methodologies that systematically study these events, both quantitatively and qualitatively. Further the findings from our work establish the need to focus on assessing the effects of black carbon emitted from biomass burning and fossil fuel combustion to the radiative forcing, the human health, etc, in order to evaluate its potential impacts.

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