Monitoring of the Eyjafjalla Volcanic Plume at Four Lidar Stations over the Iberian Peninsula: 6 to 8 May 2010

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Abstract — **Lidar measurements were performed in the framework of the EARLINET and SPALINET networks during the eruption of Eyjafjalla volcano (Iceland) since 14 April 2010. The profiles of the aerosol optical properties, namely backscatter and extinction coefficients, lidar ratio and Angström exponent, show the presence of volcanic aerosol layers over all SPALINET stations since 5 May. The volcanic particles were monitored both within the planetary boundary layer and in decoupled layers up to 8 km agl over the Iberian Peninsula. This is the first time that the spatial and temporal distributions of volcanic aerosols have been studied with active remote sensing techniques over the Iberian Peninsula.**

Keywords— **lidar, Eyjafjalla eruption, remote sensing.**

I. Introduction

The Eyjafjalla volcano, situated in southern Iceland (63.63°N, 19.62°W), is an ice-covered stratovolcano composed by basaltic-andesite with a 2.5-km-wide summit caldera. Although this volcano has erupted during historical time, it has been less active than other volcanoes of Iceland's eastern volcanic zone. The last eruption before 2010 occurred during December 1821 – January 1823 (http://www.volcano.si.edu/reports/usgs/#eyjafjol).

On 14 April 2010 the Eyjafjalla volcano entered in eruption and started a strong phase of ejection of mineral ash in the atmosphere during the subsequent days. This event led to the closure of most of Europe's airspace from 15 until 20 April 2010.

The lidar technique is one of the most relevant remote sensing methods to study the atmospheric aerosol particles, and is a useful tool to monitor aerosols from volcano eruptions. In the past volcanic aerosols have been studied a long time after they have been ejected 1) in the stratosphere (i.e. Langford *et al*., 1995; Borrmann *et al*., 1995; Di Girolamo *et al*., 1996) and 2) less frequently in the troposphere [Pappalardo *et al*., 2004; Villani *et al*., 2006; Wang *et al*., 2008].

Since 15 April the Eyjafjalla volcanic plume has been followed by a set of more than 25 lidar stations, all members of the EARLINET (European Aerosol Research Lidar Network project [Bösenberg *et al*., 2001], all over Europe. The plume in North Europe was detected as high as 8 km. Its evolution in space and time has also been modelled and forecast by several models such as EURAD (EURopean Air Pollution Dispersion). EARLINET lidar stations have played and still play a double role: 1) they provide information about the presence or absence of volcanic aerosols in a given place at a given time, 2) they help to validate model forecasts. In this framework systematic studies of recently-ejected volcanic aerosol are performed over the Iberian Peninsula (IB) for the first time.

This work focuses on preliminary results of the most intense episode of the volcanic cloud monitoring over Spain and Portugal during the period 6-8 May 2010. The paper is organized as follows: Section 2 presents the experimental setup used to monitor the volcanic plume over the IB, Section 3 shows the results and discussion and, finally, some conclusions are given in Section 4.

II. Experimental setup

Three Spanish and one Portuguese lidars observed the volcanic intrusion (Figure 1):

- Centro de Geofísica de Évora (38.57ºN, 7.91ºW, 293 m asl, Évora, EVO)
- Universidad de Granada (37.16ºN, 3.58ºW, 680 m asl, Granada, GRA)

- Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (40.46ºN, 3.72ºW, Madrid, 669 m asl, MAD)
- Universitat Politècnica de Catalunya (41.39ºN, 2.11ºE, 115 m asl, Barcelona, BAR)

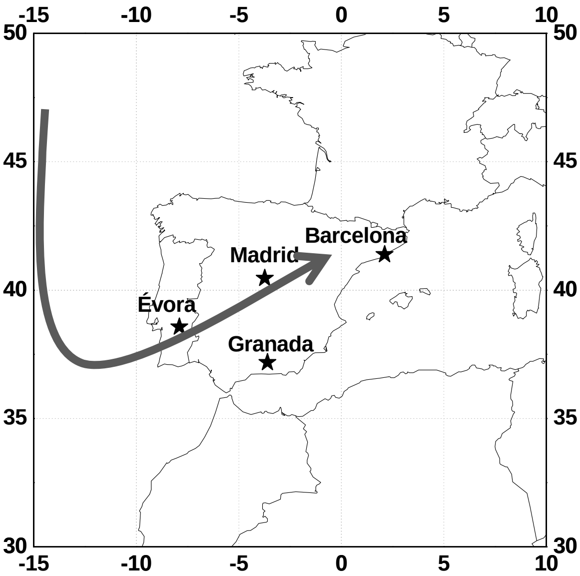

Fig. 1 Geographical distribution of the lidar stations involved in SPALINET that monitored the volcanic plume

All those stations are members of SPALINET (the Spanish and Portuguese Aerosol LIdar NETwork, www.lidar.es/spalinet/en). The measurement systems are Raman lidars and are able to provide independent aerosol backscatter and extinction coefficients profiles at night time by means of the so-called Raman method [Ansmann *et al*., 1992], and also backscatter profiles using the Klett-Fernald-Sasano method [Fernald *et al*., 1972; Fernald, 1984; Klett, 1981, 1985; Sasano and Nakane, 1984; Sasano *et al*., 1985] at both day and night time. A description of MAD, GRA and BAR systems can be seen in Sicard *et al*., (2009). The Évora station was included in SPALINET recently and the description of EVO system can be found in Guerrero-Rascado *et al.* (2010).

Due to the synoptical situation over the Atlantic Ocean the volcanic cloud did not arrive over the IB before early May. It first hit the South-Southwest of the Peninsula and then moved northeastward. EVO and GRA stations first detected the volcanic aerosol plume on 5 May, MAD station on 6 May and BAR station 2 days later. Figure 2 presents the report of the four lidar stations during the first half of May 2010. Most of the not performed measurements were caused by rain and/or low clouds.

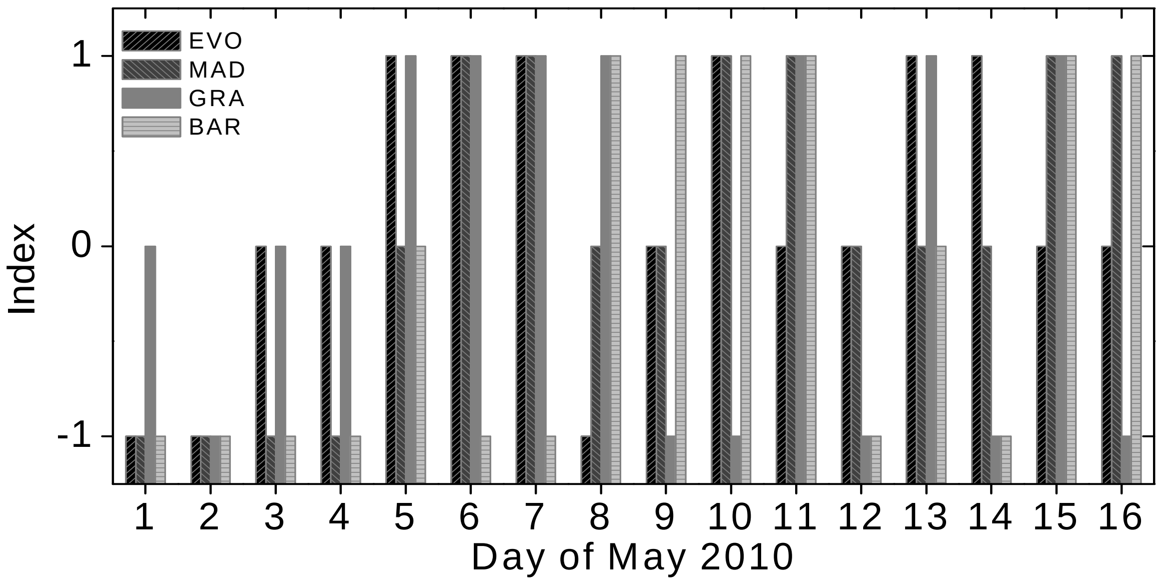

Fig. 2 Report of the lidar measurements performed by the four lidar stations during the first half of May 2010. Index: (1) volcanic aerosols were detected, (0) no volcanic aerosols was detected, and (-1) no measurement was performed

III. RESULTS AND DISCUSSION

During the first days of the intrusion (5-6 May) several volcanic layers were detected by all stations (except Barcelona) with a vertical distribution between ground level and 8 km agl. The plume was characterized in terms of minimum and maximum of the detection height, optical properties, and mass concentration profiles. Table 1 shows the daily minimum and maximum heights where the volcanic aerosols were detected at all stations. It shows that, while the plume is transported northeastward over the IB, it clearly sinks from the free troposphere into the planetary boundary layer (PBL) over some stations.

Table 1 Minimum and maximum heights (in km) where volcanic aerosols were detected during 6-8 May 2010.

Lidar	6 May	7 May	8 May
EVO	2-7.5	1.5-6	-
GRA	3-5	2.5-5.5	PBL 2.5-3.5
MAD	4-5	3-4	-
BAR	-	-	PBL 2-3

Figure 3 shows some examples of profiles for aerosol backscatter, extinction, Angström exponent and lidar ratio. For EVO and MAD stations, nocturnal measurements are presented using the Raman method. For GRA and BAR stations, diurnal profiles are shown and a fixed lidar ratio of 50 sr was used in the Klett-Fernald-Sasano method. This value is in agreement with that obtained by independent measurements in the other two stations. The inverted profiles have been obtained from signals averaged over 1 hour when possible and from which clouds were removed.

Lidar ratio (the ratio between aerosol extinction and backscatter coefficient) is an important optical parameter in aerosol characterization, because its value is typical for a certain aerosol type. It depends on many aerosol properties such as chemical composition, size distribution of the particles, and particle shape. The lidar ratios detected were ~40 sr at 532 m and ~45 sr at 355 nm over EVO station. Almost simultaneously, a lidar ratio ~50 sr was obtained at MAD station. These values are in agreement with those observed over many European sites in April 2010 after the volcano eruption and communicated in EARLINET daily reports (http://www.earlinet.org/index.php?id=235). During the eruption of the Etna volcano in 2002, similar values were monitored in Italy. Values ranging between 41 and 66 sr with a mean value of 53 sr at 355 nm were reported by Villani *et al*. (2006) and also ~ 55 sr (at the same wavelength) by Pappalardo *et al*. (2004). These authors concluded that the observed volcanic aerosol layer contained sulphate particles with a low soot content. Since soot is highly absorbing and results in very high lidar ratios (above 70 sr) and the lidar ratios observed over the IB (below 50 sr) it is probably that the soot plays a minor role for this volcanic eruption. Furthermore preliminary analysis suggests that the concentration of sulphate particles was low.

From the backscatter profiles and assuming the Angström law, we estimate the so-called backscatter-related Angström exponent. The estimation of this parameter provides some qualitative information about the kind of observed aerosols [Pappalardo *et al*., 2004]. In the spectral range 355-532 nm a value of ~0.5 was estimated at EVO and GRA station. The values in the spectral range 532-1064 nm were slightly larger at all sites: ~1.2 at EVO, ~1.0 at GRA and <1 at BAR. For comparison, note that they agree with the estimations performed over other European sites in April 2010 and communicated in EARLINET daily reports whose preliminary results indicated values ranging between 0.5 and 1.6 in the spectral range 355-532 nm. Nevertheless, what we found is completely different from the measurements made during the Etna eruptions in 2002. Pappalardo *et al*. (2004), Villani *et al*. (2006), and Wang *et al*. (2008) reported Angström exponents of ~2.4, ~2.2 and ~ 2.7, respectively, concluding that the volcanic layer was mainly composed by young submicrometric particles and absence of large ash particles. Two hypotheses can thus explain our results: 1) the material erupted from the Eyjafjalla volcano is different from that erupted from Etna volcano in 2002, and 2) the volcanic aerosols suffered transformation processes during the transport from Iceland (~ 3000 km away from the IB). To further investigate those hypotheses, a more detailed work considering the whole period and additional instrumentation is needed.

One of the most critical aerosol parameters during such kind of warning hazards for aviation is the aerosol mass concentration. For example, the U.S. army considers mass loading of volcanic aerosols above 50 mg/m^3 as a potential hazard. The UK Civil Aviation Authority (CAA) establishes a threshold of 1 mg/m^3 to avoid dangers of the aircrafts and engines. Over The Netherlands a limit has been proposed of 1 mg/m^3. From the lidar profiles, it is possible to derive the mass concentration profiles by means of a conversion factor. Concretely, the lidar extinction profiles can be converted into mass concentration profiles using the so-called specific extinction coefficient. As a preliminary estimation, a value of 0.64 m^2/g at 550 nm, given by OPAC database (Optical Properties of Aerosol and Clouds) software [Hess *et al.*, 1998], has been applied to our 532-nm profiles. Figure 4 shows the vertical profiles of mass concentration, in µg/m^3, over the four lidar stations at selected days. The maximum detected values for the volcanic layers were 106, 269, 77 and 39 µg/m^3 at the EVO, GRA, MAD, and BAR stations, respectively. Therefore all values remain below the thresholds aforementioned. Here again we observed that the volcanic aerosols concentration decreases when the plume is transported northeastward.

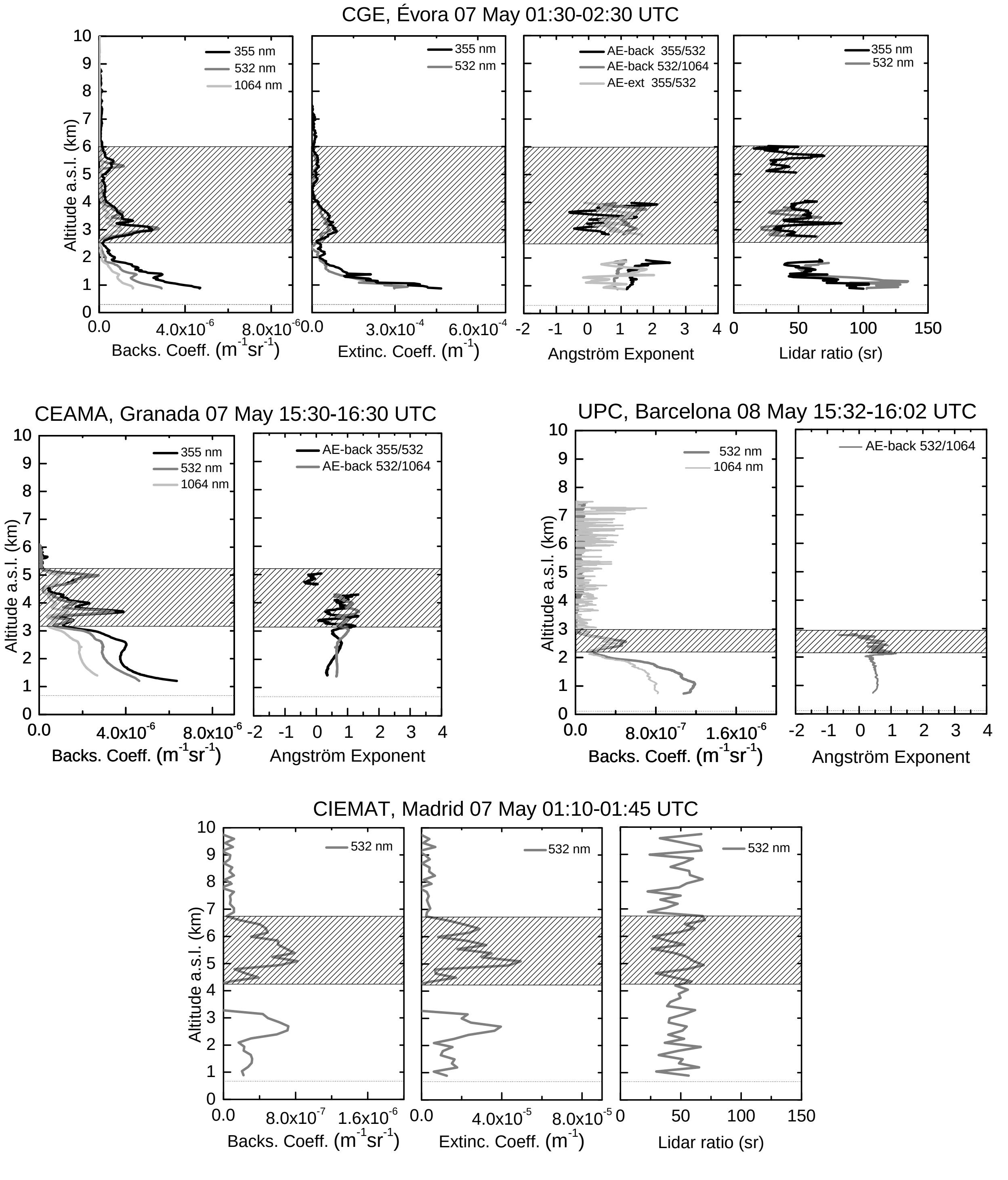

Fig. 3 Vertical profiles of aerosol optical properties at four lidar station at selected days. The shadows indicate the possible volcanic aerosol layer

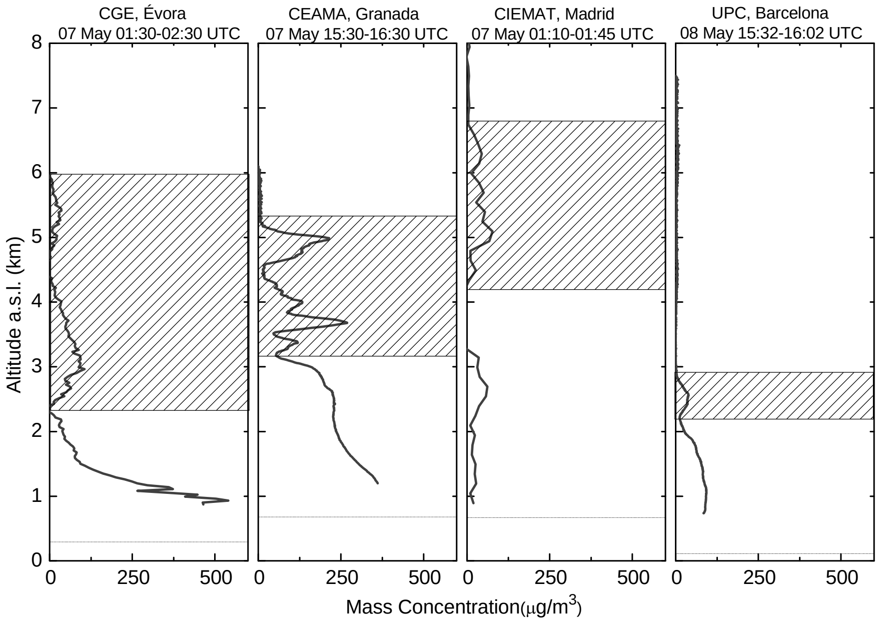

Fig. 4 Vertical profiles of mass concentration (μg/m^3) at the four lidar station at selected days. The shadows indicate the possible volcanic aerosol layer and the horizontal dotted line indicate the ground level

IV. Conclusions

After the eruption of the Eyjafjalla volcano in Iceland on 14 April 2010 an intensive monitoring activity of the atmosphere from different lidar remote sensing networks started. Because of the synoptical situation the volcanic cloud did not arrive over the IB before the beginning of May. In this work, preliminary results about different vertically resolved volcanic aerosol properties have been presented. The first estimations of the lidar ratio (~ 40-50 sr) observed over the IB are consistent with mineral particles with a very low amount of sulphates. The backscatter-related Angström exponent ranged between ~0.5 and ~1.2 at all SPALINET stations depending on the used spectral range. Both estimations agree with the estimations performed over other European sites in April 2010 in the framework of the EARLINET project. Differences respect to the most recent Etna eruptions in 2001-2002 have been detected and might be related to different sizes and type of the observed volcanic particles. Further investigation is needed to confirm this hypothesis. Finally, an estimation of the vertical profiles of mass concentration has been calculated from the lidar extinction profiles. The values obtained do not exceed the thresholds established by the different authorities.

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