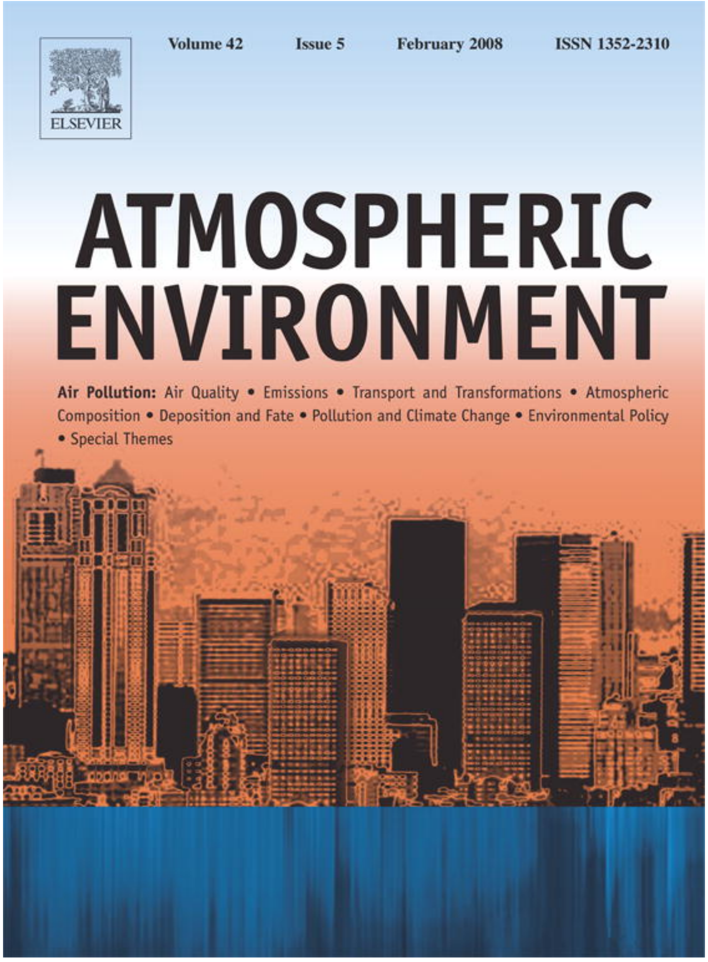
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Volcanic dust characterization by EARLINET during Etna's eruptions in 2001–2002

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Abstract

Lidar measurements were performed in the framework of the EARLINET project during the last eruptions (July–August 2001 and November 2002) of the Etna volcano. Both aerosol backscattering and extinction coefficients show the presence of remarkable aerosol layers in central and especially in southern Europe during the Etna eruptions periods. The aerosol layer altitudes ranged from 1 to 6 km. Back-trajectory, lidar ratio and backscatter related Angstrom coefficient analyses show that most of the aerosol layers originated from the Etna eruption and were made of sulfates and small absorbing volcanic ash. Thanks to the EARLINET network, the space and temporal distributions of volcanic aerosol have been studied over continental scale.

Keywords: Lidar; Mt. Etna; Lidar network; Volcanic aerosol; Aerosol transportation model

1. Introduction

Mt. Etna is one of the largest and most active continental volcanoes. It lies in Sicily (37.73°N, 15.00°E), southern Italy and its summit was at about 3310 m at the end of 2001. Mt. Etna volcano has been erupting for half a million years and its dormant periods are very rare.

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During July and August 2001 spectacular eruptions occurred at the summit craters of Mt. Etna volcano. Volcanology observations and SO_2 emission data are shown in Table 1(a). The eruptive activity started on July 13, 2001. It was accompanied by one of the most intense earthquake swarms in the last 20 years. One of the hints and gauge for the volcano eruption—SO_2 fluxes were measured by the National Institute of Geophysics and Vulcanology (INGV), Catania (Italy), using correlation spectrometer (COSPEC). The results show increasing of SO_2 fluxes to the atmosphere in the following days reaching a peak value $>20{,}000\,\mathrm{ton\,day^{-1}}$ on July 20, 2001, as shown in Fig. 1. The following reduction of SO_2 flow has been accompanied by an intense phase of the eruptive activity between July 24 and 28, 2001, characterized by heavy columns of steam, smoke and submillimetric ashes with a maximum height of the plume of about 5000 m above sea level (a.s.l.). During the whole period of the volcanic activity, July 13–August 9, 2001, about 40 million m^3 of lava and pyroclastics were emitted (Web Page of the National Institute of Geophysics and Vulcanology—Catania).

Another unusual eruption of Mt. Etna occurred from November to December 2002, described in

Table 1
Volcanology observations of Mt. Etna eruption events

Date	Volcanology observation	SO_2 emission (ton day^{-1})	SO_2/HCl
(a) *July– August 2001*			
July 12	Start seismic crisis		
July 17	Start effusive emission	2500 (background value)	0.3
	Feeble ashes emission		
July 18–19		Increasing	
July 20		20,000	2–4
July 23	Pulsed ashes emission with cloud formation	7000–8000	
July 24	Explosive activity	7000–8000	
	Plume height: 3–3.5 km		
July 25	Maximum explosive activity	16,000	
July 26	Intense explosive activity feeble degassing	8000	
July 28	Intense ashes emission	Decreasing	
	Plume height: 5 km		
July 30	Intense ashes emission		2–5
July 31	Intense ashes emission		
August 1	Intense ashes emission	6600	2–3
August 2	Intense ashes emission	5200	
August 3	Intense ashes emission	6300	
August 4	Pulsed emission	4800	
August 5	Feeble emission	2500	
Date	Volcanology observation	SO_2 emission (ton day^{-1})	
(b) *October 2001– January 2002*			
October 27	Start seismic crisis	13,000	
	Ashe plume height: 9 km		
October 28	Explosive activity	13,000	
	Intense ashes emission		
October 29	Explosive activity	20,000	
	Ashe plume height: 5 km		
October 30	Emission of large clouds of brownish ashes	20,000	
October 31	Vento da sud-ovest	16,000	
November 1–December 1	Emission of large clouds of ashes	8000–25,000	
	Ashe plume height: 3–5 km		
December 2–31	Emission significantly decreased	14,000–5000	
January 1–27		5000–13,000	
January 28	Stop of activity	2000	

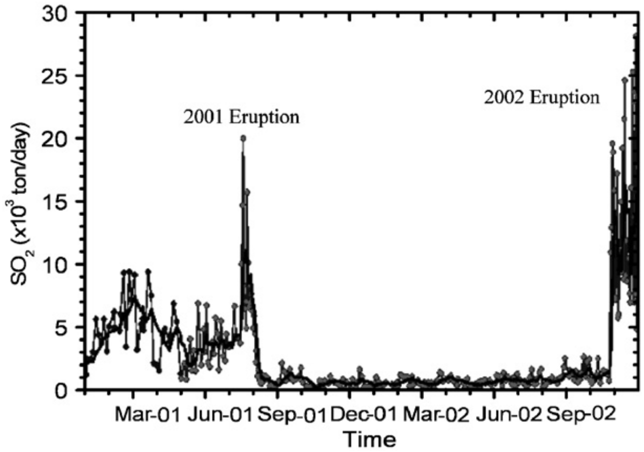

Fig. 1. Flux of SO_2 gas from the Etna eruption during the period January 2001 to December 2002 (from the web page of INGV, Catania, Italy). The thick solid line is the 6-day adjacent averaging.

Table 1(b). A huge amount of gas was released by the summit vents and by the 2750 m cone (up to 25,000 ton day^{-1}; Fig. 1). The continuing explosive activity was sustained for >1 month. The great aerosol load release in the atmosphere during these eruptions represented an extremely interesting and unique event.

The lidar technique is one of the most important remote optical methods in atmospheric aerosol studies. Of course, it is also suitable to study the aerosol from the volcano eruption. In fact, lidar has been used, for instance, to study the volcanic aerosol from Pinatubo in the stratosphere (Langford et al., 1995; Borrmann et al., 1995; Di Girolamo et al., 1996), with particular reference to their effect on global climate (Graf et al., 1993; Kerr, 1994; Labitzke and McCormick, 1992). The emission gases (SO_2, CO_2, etc.) from Mt. Etna have also been studied using lidar and in combination with other optical techniques (Edner et al., 1994; Weibring et al., 2002). The aerosol plumes have been measured in-situ by different optical methods (Watson and Oppenheimer, 2000, 2001). A complex study of Etna's volcanic plume from ground-based, in situ and space-borne was recently performed (Zerefos et al., 2006). Few studies reported lidar observations of volcanic aerosol in the troposphere (Pappalardo et al., 2004a; Villani et al., 2006). In particular, there is a lack of the systematic studies of volcanic aerosol by a continental scale lidar network.

During the period of the heavy eruptions of the Etna volcano, lidar measurements of aerosol backscattering and extinction coefficient were performed in the framework of the European Aerosol Research Lidar Network (EARLINET) (Boesenberg et al., 2001). The scientific objectives of EARLINET are to build a quantitative comprehensive statistical database of the horizontal, vertical and temporal distribution of aerosols on a continental scale. The goal is to provide aerosol data with unbiased sampling, for important selected processes and air-mass histories, together with comprehensive analyses of these data. These objectives are reached by operating a network of 22 experimental stations distributed over most of Europe, using advanced quantitative laser remote sensing to directly measure the vertical distribution of aerosols, supported by a suite of more conventional observations. The main part of the measurements is performed according to a fixed schedule (twice a week) to provide an unbiased statistically significant data set. Additional measurements are performed to target important events such as Saharan dust episodes or volcano eruptions. Back-trajectories derived from operational weather prediction models are used to characterize the history of the observed air parcels, accounting explicitly for the vertical distribution.

Both hardware setup and algorithm inter-comparisons among all lidar stations have been implemented (Matthias et al., 2004a; Pappalardo et al., 2004 b; Bockmann et al., 2004).

During the last Mt. Etna eruption periods, from end of July to beginning of August, 2001, and in November, 2002, most EARLINET lidar stations performed measurements and seven of them observed aerosol layers which were probably due to Etna eruptions. Thus, for the first time, volcanic aerosol can be studied in the troposphere on a continental scale.

More than seven lidar stations observed remarkable aerosol layers between an altitude of 2 and 6 km at different laser wavelengths in this period. Among them, the three Italian stations Naples, Potenza and Lecce are only about 350 km from Mt. Etna.

The aerosol backscattering and extinction profiles were obtained from simultaneous measurements of elastic and nitrogen Raman signals (Ansmann et al., 1992) or using the variable angle method (Sicard et al., 2002). Backscatter related Angstrom coefficients of aerosol were also obtained by multi-wavelength measurements (Sasano and Browell, 1989).

During the Etna's eruption in July and August 2001, there were also several Saharan dust events, some of which affected Europe too. As a consequence of these dust events, the formation and transformation of Etna volcanic aerosol become more complex and difficult to follow. The back-trajectory analysis has been used to study the aerosol source region and plume transport and to distinguish different special aerosol events. Lidar ratio and backscatter related Angstrom coefficient are also used to distinguish the aerosol type.

2. Aerosol transport models

The back-trajectories provided by the German Weather Service have been proven to be a very useful tool for the interpretation of aerosol profiles measured at a certain site. The German Weather Service calculates three-dimensional (3D) trajectories 96 h back in time from each lidar station, for six pressure levels and for two arrival times a day, 13:00 and 19:00 UT (universal time). In addition, trajectories were also calculated with the FLEXTRA model (Stohl et al., 1995), based on analyses of the European Centre for Medium-Range Weather Forecasts (ECMWF) with 1° resolution and 60 model levels. These trajectories were started from a dense vertical array of points along lidar profiles of particular interest.

Another aerosol transport model used in this paper has been developed by Euro-Mediterranean Centre on Insular Coastal Dynamics (ICoD). The ICoD mathematical modeling system forecasts/simulates various phenomena of the Earth environment. This model integrates the following natural environment components and processes: the atmosphere (hydrostatic and non-hydrostatic), ocean, aerosol/pollution processes, and atmosphere–soil interactions, etc., using state-of-the-art models. The modeling system calculates operational environmental forecasts of the Euro-Mediterranean and other regions. The modeling component for atmospheric transport of ash aerosol concentration injected into the atmosphere by the volcano has been developed. The model consists of two major components: the atmospheric model used as a driver for the concentration, and the ash aerosol model. The atmospheric model is the Eta/NCEP (National Centers for Environmental Prediction, Washington, DC) model used in the USA for routine weather predictions. The aerosol-modeling component is based on the aerosol model that was initially developed to simulate and predict the desert dust aerosol cycle in the atmosphere (DREAM model; Nickovic et al., 2001). DREAM has been modified in order to be applied to the volcano ash transport by introducing a point source of ash over a particular volcano location. It solves the Eulerian mass concentration equation describing a number of processes such as horizontal and vertical transport, particles wet and dry deposition and deposition by gravitational settling, vertical turbulent mixing, lateral diffusion and point-source concentration injection. There are four particle sizes included in calculations, ranging from 1 to $30\,\mu g\,m^{-3}$. The model produces 3D concentration fields, concentration load (vertically integrated concentration) wet and dry deposition. Due to the lack of information about the actual content of the released mineral aerosol, an arbitrary constant injection of ash concentration was used. The ash concentration is considered in the model as a chemically and radiatively passive substance.

3. Experimental setup

EARLINET aerosol lidar measurements are usually performed at two standard wavelengths, 355 nm (or 351 nm) and 532 nm. Lidar systems are Nd:YAG or XeF excimer laser based. Most of EARLINET groups use additional Raman channels at UV wavelengths, detecting the nitrogen Raman scattering at 387 nm (or 382 nm) in order to independently measure aerosol backscattering and extinction coefficients (Ansmann et al., 1992). Few groups use multi-angle measurements instead of the Raman method (Sicard et al., 2002) to get extinction.

The details of the experimental setups and geographic location of the lidar groups involved in Etna eruption aerosol measurements are shown in Table 2 (Boesenberg et al., 2001). According to the EARLINET protocols, each lidar system should establish UV 355 nm (or 351 nm) elastic backscatter and nitrogen Raman channels, but can have different technical aspects, e.g. telescope size, detectors and amplifiers, and the optical arrangement. Because of these hardware varieties, all EARLINET lidar systems were quality assured by performing direct intercomparsions of at least two systems at a time at one location (Matthias et al., 2004a). Aerosol backscatter (Bockmann et al., 2004) and aerosol extinction retrieval algorithms (Pappalardo et al., 2004b) were compared separately

Table 2
The summary of the lidar stations involved in Etna eruption measurements

Location	Athens, Greece	L'Aquila, Italy	Lecce, Italy	Minsk, Belarus	Munich, Germany	Naples, Italy	Palaiseau, France	Potenza, Italy
Coordinates	37.9716°N, 23.7875°E	42.344°N, 13.327°E, 683 m a.s.l.	40.33°N, 18.10°E a.s.l.	53.917°N, 27.383°E	48.15°N, 11.57°E, 539 m a.s.l	40.833°N, 14.183°E, 118 m a.s.l.	48.42°N, 2.16°E	40.6°N, 15.733°E, 760 m a.s.l.
Emitted wavelength (nm)	355, 532	351	351	353, 532, 694	355, 532, 1064	351	532, 1064	355, 532
Detected wavelength elastic (nm)	355, 532	351	351	353, 532, 694	355, 532, 1064	351	532	355, 532
Detected wavelength N_2 Raman (nm)	387	382	382			382		387

using synthetic lidar data. The results showed that typical error margins are in the order of 10–15%, depending on height and signal statistics. Systematic errors were mainly observed at the lowest altitudes where an incomplete overlap between the emitted laser beam and the telescope field of view can lead to an underestimation of aerosol backscatter and extinction coefficients. The low altitude systematic errors do not affect the result of this work, because the typical volcanic aerosol layers were found above 2 km.

4. Results and discussion

4.1. 2001 eruption

During the most violent eruption of Mt. Etna in 2001, from the middle of July to the beginning of August, as revealed by the SO_2 emission plotted in Fig. 1, the EARLINET lidar network performed nearly continuous measurements. Fig. 2(a–e) shows some profiles of aerosol extinction and backscattering coefficients obtained in (a) Naples (Italy), (b) Lecce (Italy), (c) Potenza (Italy), (d) Athens (Greece) and (e) Munich (Germany) on July 23–26, 2001, respectively. The corresponding lidar ratio values are also plotted. The measurements reported have been obtained from the signals averaged over 30 min. Extinction profiles are obtained in Naples, Potenza, Lecce (Italy) and Athens (Greece) by independent measurements of nitrogen Raman and elastic backscattered signals, whereas the lidar system of Munich (Germany) uses the multi-angle approach. In the case shown here Fig. 2(e), however, the aerosol cloud was quite variable in time and space, so that this technique could not provide a precise retrieval of the lidar ratio. As a consequence, the lidar ratio for continental aerosols based on Mie calculations was used. The height variation originates from the humidity dependence of this lidar ratio. On average the lidar ratio is about 55 sr.

The Lagrangian particle dispersion model FLEXPART (Stohl et al., 1998, 2005) was used to simulate the dispersion of a volcanic SO_2 tracer. About 100,000 tracer particles per day were released from the location of the volcano, and daily released tracer masses were taken from Table 1. No washout was simulated. Release heights were specified according to daily volcanic activity (close to the altitude of the volcano during non-explosive phases, higher during explosive phases). Nearly continual total SO_2 tracer column distribution simulation was made. The simulation initial time was fixed on July 17, 2001. The results cover whole eruption period. All the volcano eruption aimed lidar measurements were compared with these simulation results. Fig. 2(f), as an example, shows one of simulation results at 18:00 UTC, July 23, 2001. Comparing Fig. 2(d) with (f), we can see that both the lidar measurement and simulation obtained the same aerosol source—Etna volcano eruption.

Fig. 3 shows a comparison of FLEXPART total SO_2 tracer columns with a MODIS satellite image on July 24, suggesting that FLEXPART captures the transport of the plume quite well. A set of total SO_2 tracer column plots shows that most of the emissions were transported south, into Africa. The material detected over Europe on subsequent days was actually emitted in a relatively short period

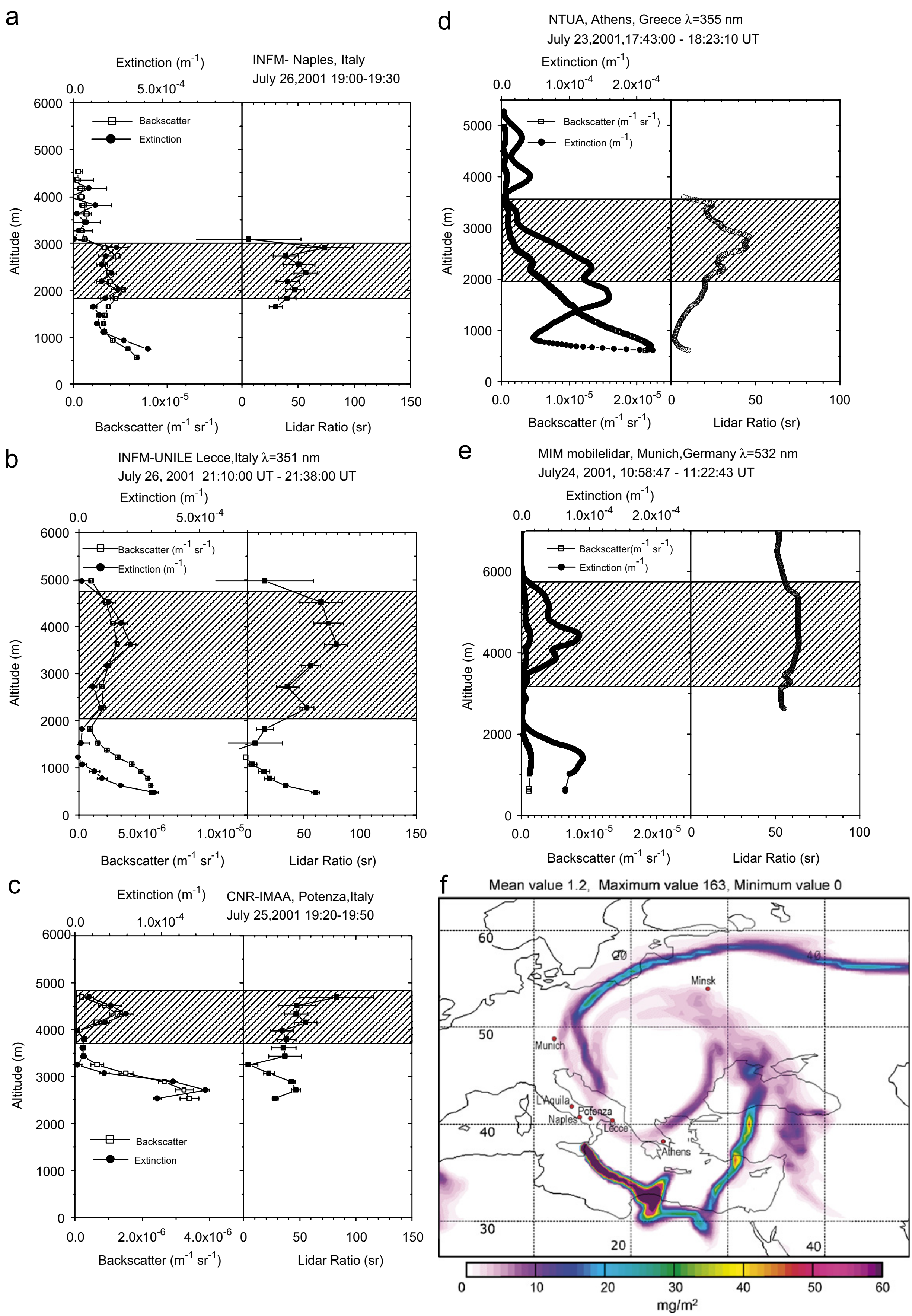

Fig. 2. Backscatter, extinction and lidar ratio of aerosol layer observed by some EARLINET lidar stations during Etna's eruption in the period July–August 2001 (a–e). The shadows indicate the possible volcanic dust layer. Simulated total SO_2 tracer columns distribution at 18:00 UTC, July 23, 2001 (f).

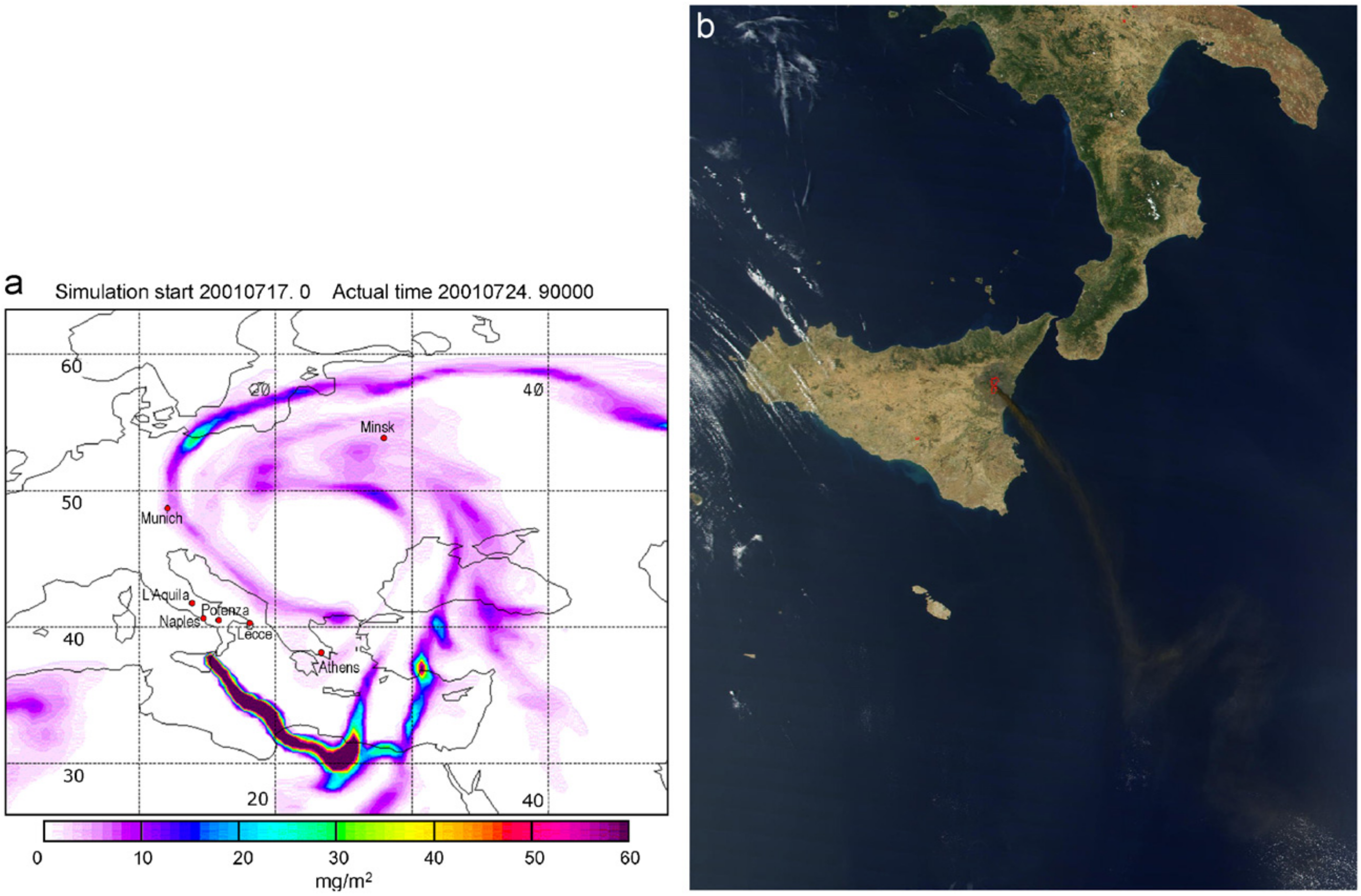

Fig. 3. Comparison of FLEXPART total SO_2 tracer columns (a) with a MODIS satellite image on July 24, 2001 (b).

from the second half of July 19 and the first half of July 20. This was, however, the phase with the largest SO_2 emissions, following the opening of a new volcanic event in the evening of July 19. A filament of this plume looped around an upper-level flow that was cut off on July 21 and remained stationary for the next 5 days with a center over south-eastern Europe. In the simulation, the filament indeed travelled first over Greece on July 23, southern Germany on July 24 and finally over Italy on July 25–26, in agreement with the observations. The model, however, suggests little plume material to be present over Europe during the first days of August, except for a minor part of the plume that was first transported south over Africa from where it travelled northward to Spain on August 1 and then eastward. Thus, the aerosol enhancements on July 30 and beginning of August observed at the Italian stations cannot be confirmed to originate from the Etna eruption.

In order to study quantitatively the transport of the aerosol layer, the integrated backscatter coefficients of different lidar stations are shown in Fig. 4.

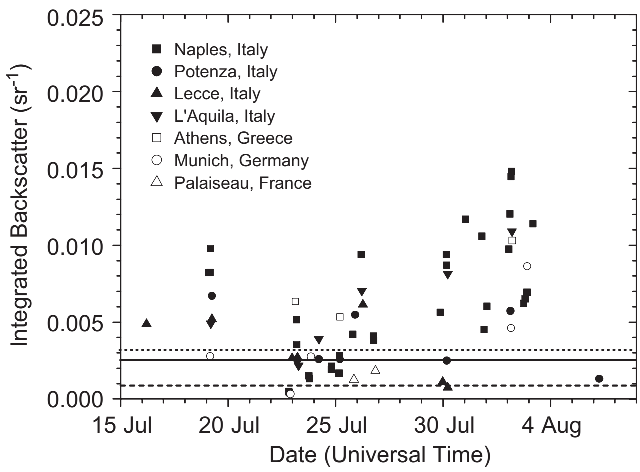

Fig. 4. Integrated backscattering coefficient ($\lambda = 351$ or 355 nm) for several lidar stations concerning Etna's 2001 eruption; solid, dotted and dashed lines present the integrated backscattering coefficient background which are averaged above PBL during year 2001 for Naples, Lecce and Potenza (Italy), respectively.

The integrations are made for the identified aerosol layers, which are usually above the planetary boundary layer (PBL). For comparison, the integrated aerosol backscatter coefficients above the PBL and averaged over whole year 2001 are also shown for the Italian sites. It was obtained by integrating the backscattering coefficient from the top of the PBL up to 7 km and averaging over all regular measurements in clear sky conditions. The trajectory analyses show that there was a Saharan dust event on July 19, 2001, in southern Italy. The results of three nearest Italian lidar stations, Naples, Potenza and Lecce show that except for this Saharan dust event the integrated backscatter coefficients increase from the end of July and reach their maximum on August 2. Then they decrease and disappear to background values after August 9. This pattern agrees well with the volcanology and visual observations of Mt. Etna's eruption (INGV Website and Table 1) except for a few days delay. In fact, the maximum of eruptive activities was on July 25 (Fig. 1 and INGV Website). This means that it is took >1 week to transport volcanic aerosol from Mt. Etna to the southern European lidar sites, even though they are only about 300 km away from the volcano.

The EARLINET network makes use of 4-day back-trajectories, provided by the German Weather Service, for aerosol source range analyses. Although they are reliable and efficient for the study of some special events, e.g. Saharan dust transport over Southern Europe (Ansmann et al., 2003), in this case they do not allow discriminating the aerosol source region because they are too short. Instead, 10-day back-trajectories from FLEXTRA model are shown for Naples, Italy, on July 27, July 28 and July 31, 2001, in Fig. 5 as an example. Back-trajectory plots show clearly that in this period the air-mass circled around a high-pressure system. Therefore, the aerosol layers observed in this period in Naples, Lecce and Potenza, Italy, originated from Etna's eruption but traveled a long distance before

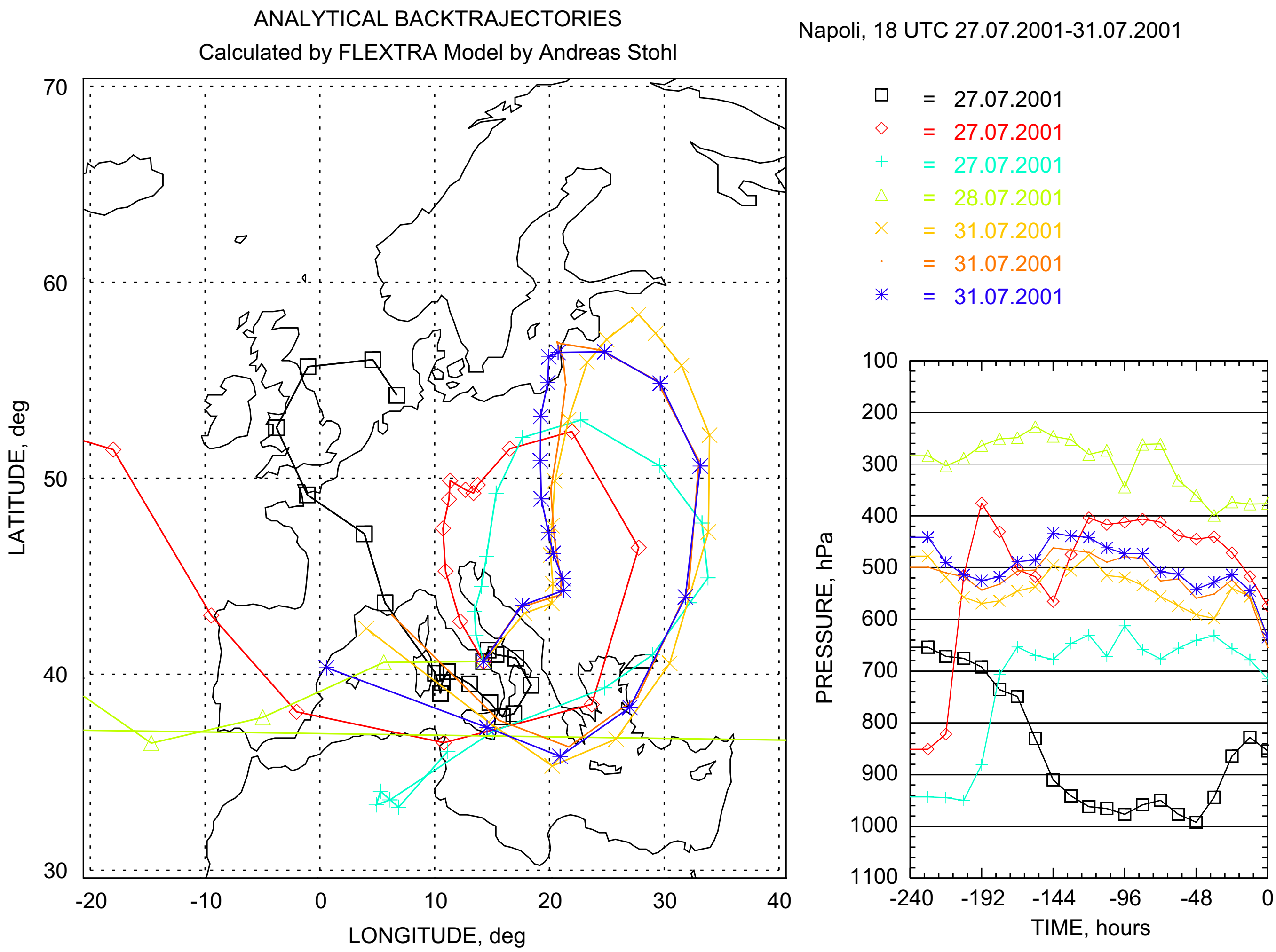

Fig. 5. Ten-day back-trajectories from the Naples, Italy, lidar station in the period of Etna's 2001 eruption, calculated with the FLEXTRA model.

being detected at the Italian stations. Similar results are obtained for July 23, 2001, for Athens, Greece, and for July 23, 2001, for Minsk, Belarus. At the same time, these back-trajectories can explain why the lidar measurement aerosol load peak has several days delay with respect to the volcanology observation even though Naples and Lecce are only 300 km from Mt. Etna.

In the period of the Etna eruption, there were few minor Saharan dust events. The lidar ratio, backscatter related Angstrom coefficient and back-trajectories analyses are used to identify the aerosol type and source region.

Table 3 shows the Raman lidar measurement results of aerosol layer height, integrated backscatter and lidar ratio obtained during the Etna eruption in Naples, Potenza and Lecce. For comparison, the results of some days of Saharan dust, mist and clear sky condition are listed also.

Lidar ratio analysis showed a significant change of the values obtained during the Etna eruption (~50 sr) compared to the ones on previous and successive days in Naples and Lecce (~40 sr). The observed lidar ratio values are higher than the typical ones of Saharan dust transport events (~35 sr), also. Statistical analysis of 1-year lidar measurement in Naples shows that the median and the most possible lidar ratio is about 30–40 sr (Matthias et al., 2004b) for above the top of the PBL and in clear sky conditions. Similar results were obtained in Potenza, Athens (Greece), Minsk (Belarus) and L'Aquila (Italy).

Measurements of the backscattering coefficient at two different wavelengths allow evaluating the backscatter related Angstrom coefficient, related to the size and chemical composition of the aerosol type (Sasano and Browell, 1989). The backscatter-related Angstrom coefficient is defined as

$$\delta = -\frac{\ln(\beta_{\lambda_1}/\beta_{\lambda_2})}{\ln(\lambda_1/\lambda_2)}. \quad (1)$$

Some EARLINET members, the groups of Athens (Greece), Munich (Germany) and Potenza (Italy), have more than one wavelength backscattering channel. It is possible to study aerosol type

Table 3
Summary of the some lidar measurement result for Etna's 2001 eruption

Date and time (UT)	Aerosol layer height (km)	Integrated backscatter at 355 nm ($\times 10^{-3}$ sr^{-1})	Lidar ratio (sr)	Remark
Naples				
July 19, 2001, 19:00–19:30	1.5–6	9.77	33±4	Saharan dust
July 23, 2001, 18:40–19:10	1.5–4	5.15	47±5	Etna
July 25, 2001, 18:50–19:20	1.5–3.5	2.81	57±8	Etna
July 26, 2001, 19:00–19:30	1.8–3.0	5.40	47±4	Etna
July 30, 2001, 18:45–19:15	1.5–4	8.70	50±4	Etna
August 02, 2001, 19:00–19:30	1.5–3.5	14.8	46±4	Etna
August 03, 2001, 18:45–19:15	1.5–5.5	11.4	50±4	Etna
August 20, 2001, 18:40–19:10	1.5–3.5	4.50	39±9	Mist
August 23, 2001, 18:50–19:20	1.5–3.5	6.90	34±5	Clear sky
Lecce				
July 16, 2001, 19:30–20:00	3–6	4.88	52	Etna
July 19, 2001, 20:30–21:00	2–7	5.19	64	Etna
July 26, 2001, 21:00–21:30	2–5.5	6.13	58	Etna
July 30, 2001, 19:30:20:00	3–5	0.73	35	Saharan dust

Date and time (UT)	Aerosol layer height (km)	Integrated backscatter at 355 nm ($\times 10^{-3}$ sr^{-1})	Angstrom coefficient	Lidar ratio (sr)	Remark
Potenza					
July 19, 2001, 20:30–21:00	2.5–6.5	6.63	0.9	43	
July 23, 2001, 20:00–20:30	2.5–3.5	0.807	1.6		
July 24, 2001, 19:55–20:25	3.3–5.1	0.996	1.9	54	Etna
July 25, 2001, 19:20–19:50	3.8–4.8	0.547	2.8	53	Etna
July 26, 2001, 12:25–12:35	2.9–5.4	2.83	0.9		Etna
July 30, 2001, 19:05–19:35	2.2–5.5	1.96	2.6	63	Etna
August 2, 2001, 18:05–18:35	2.3–3.5	4.20	2.8		
August 6, 2001, 21:00–21:30	2.2–3	0.386	2.1		

and dimension by measuring backscatter related Angstrom coefficient and lidar ratio. Table 3 gives the measurement result of Potenza (Italy) at two wavelengths, $\lambda_1 = 355\,\text{nm}$ and $\lambda_2 = 532\,\text{nm}$. Aerosol backscatter coefficient at 532 nm is retrieved by using an iterative approach (Di Girolamo et al., 1999) with an assumption on lidar ratio profile; the typical values of lidar ratio used are taken from literature with the support of 5 years of Lidar ratio direct measurements at 355 nm performed at Potenza site (Mona et al., 2006).Combining the lidar measurement and back-trajectory analyses, we can distinguish different aerosol types (listed in the last column in Table 3). A few cases are ambiguous.

The relatively high mean values of the lidar ratio, ~57 sr, and the backscatter related Angstrom coefficient, ~2.7, averaged over the observed volcanic aerosol layers, are consistent with aerosol made of sulfates and small absorbing particles such as volcanic ash (Sasano and Browell, 1989; Evans, 1988).

4.2. 2002 eruption

After the violent flank eruption of July–August 2001, Mt. Etna was rather calm for >10 months, except for usual fumes from the four summit craters and minor ash emissions. More violent eruptions began again in November 2002 and lasted for >1 month.

Like in the previous Etna eruption, unusual aerosol loads were observed by the EARLINET network. Three aerosol backscatter coefficient profiles, averaged lidar ratio and backscatter related Angstrom coefficient are shown in Fig. 6(a–c) as examples. The corresponding DREAM model results are shown in Fig. 6, also. This model began to run regularly for the EARLINET network from 2002.

In Fig. 6(a), the case of November 2, 2002, Potenza, Italy, we can see that a special aerosol layer was present from 3.5 to 5 km with a lidar ratio of about 50 sr and a backscatter related Angstrom coefficient of 2.5. The relatively high values of the lidar ratio and backscatter related Angstrom coefficient suggest that it is the same type of volcanic aerosol as Etna 2001 eruption. Similar results are shown in Fig. 6(b,c), for the cases of November 1 and November 25, 2002, in Naples, Italy.

The DREAM model by ICoD confirmed this result despite some deviation in altitude for the first

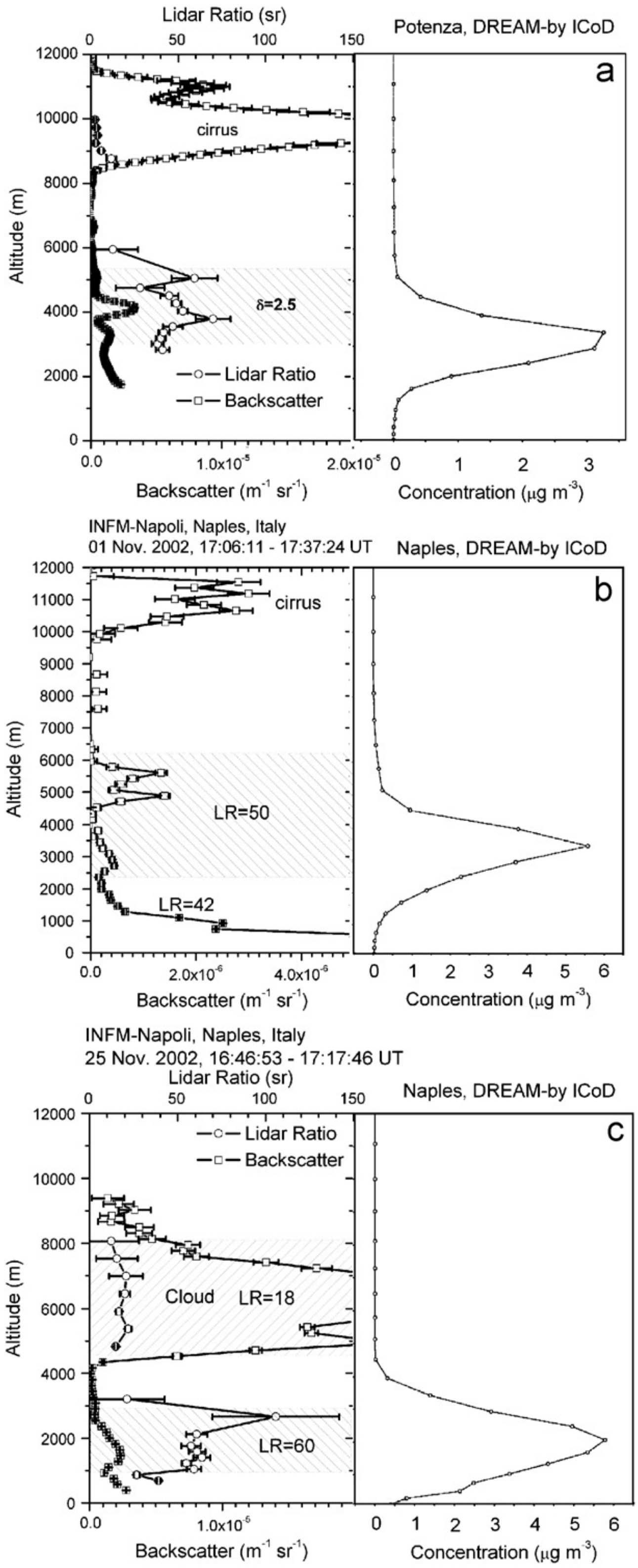

Fig. 6. Backscatter and lidar ratio of aerosol layer observed by Potenza on November 2, 2002 (a) and Naples on November 1, 2002 (b) and on November 25, 2002 (c). Forecast aerosol profiles by ICoD are also shown for comparing. The shadows indicate the possible volcanic dust layer or cloud.

two cases. Deviations could result from the following two reasons. First, the model is designed to simulate the ash aerosol concentration dependent on gravitational settlement; therefore, it does not represent transport of gases such as SO_2. Thus, the maximum ash concentrations get slightly lower elevations than observed. A second possible source of errors could originate from the fact that the shown model results are done in a routine model exercise during the Etna 2002 event with a constant arbitrary ash influx. In spite of these limitations, the model results may be considered to well indicate the general evolution of the ash cloud.

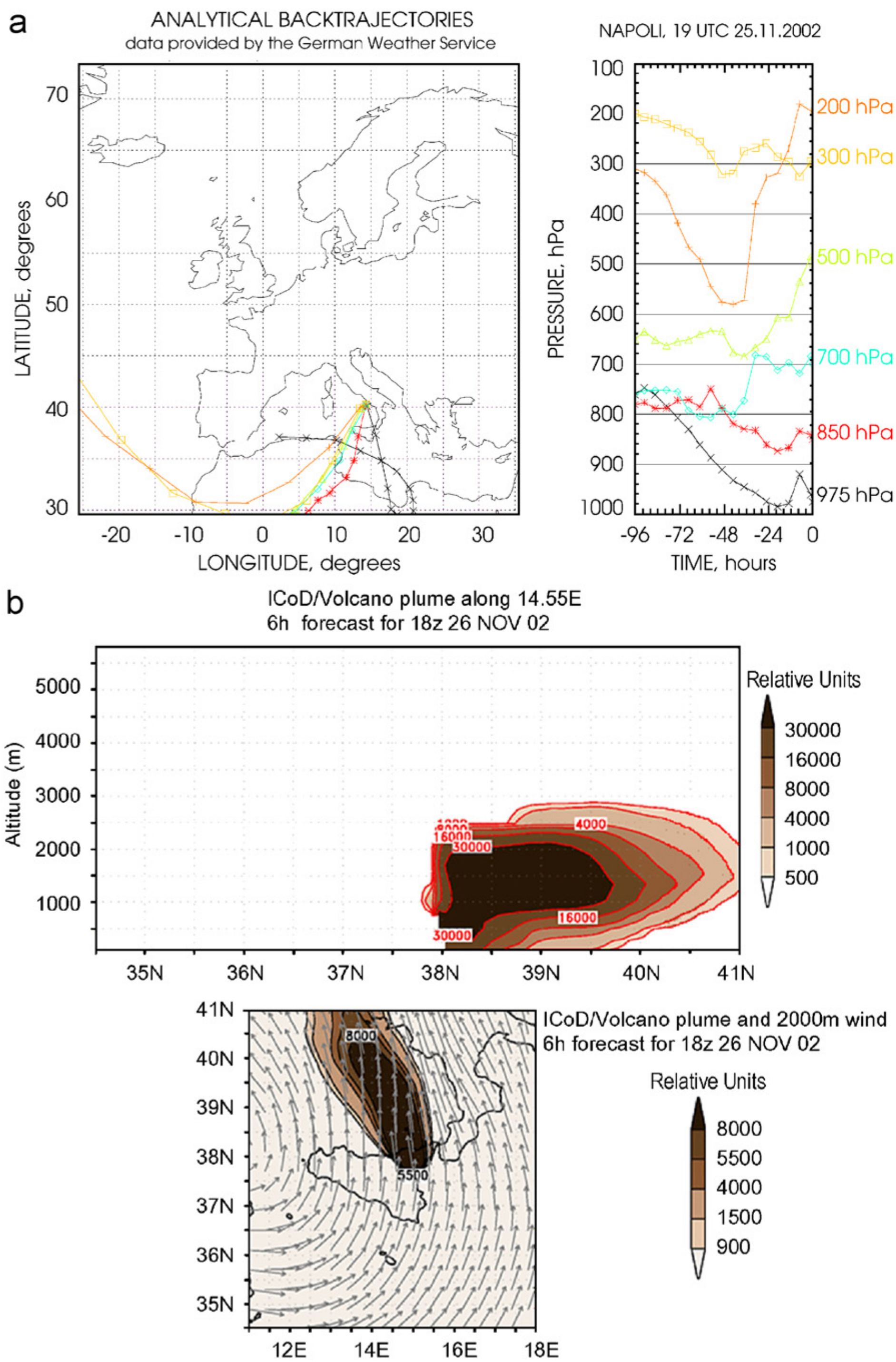

Fig. 7. Comparison between FLEXTRA model air-mass back-trajectory by German Weather Service (a) and DREAM model aerosol 3D profiles by ICoD (b) on November 25, 2002.

In order to further confirm the origin of these aerosol layers, both the FLEXTRA model back-trajectory and DREAM model aerosol 3D profiles are used for the last case, November 25, 2002, Naples, Italy, as shown in Fig. 7(a,b). The back-trajectory analysis, Fig. 7(a), shows that the trajectories of the air parcels at all pressure levels come from the south and in particular for 975, 850 and 700 hPa, corresponding to the altitude under 3 km, trajectories come directly from Mt. Etna. The DREAM model can give us 3D distribution of the volcanic aerosol. As shown in Fig. 7 (b), a vertical section through the model output along 14.55°E on November 26, 2002, volcanic aerosol extends from 1 to 3 km over the Naples lidar station (40.833°N, 14.183°E). The concordant results confirm again that the troposphere aerosol layers observed by lidar were directly from the Etna eruption.

5. Conclusion

The volcanic aerosol from Etna eruption during 2001 and 2002 was characterized for the first time, by the continental scale lidar network—EARLINET. Several unusual eruption cases were studied in detail in the period of July, August 2001 and November 2002. During these periods, the lidar stations of EARLINET network distributed all over Europe, were involved in the tropospheric aerosol measurements. Seven lidar stations from southern Europe observed unusual aerosol layers from 1 to 6 km altitude, resulting from the eruption of the Etna volcano. Lidar ratio and backscatter related Angstrom coefficient values suggest that the monitored aerosol layers are mostly made of sulfates and small absorbing particles as those due to Etna's eruption. Furthermore, the analyses from both back-trajectories from the FLEXTRA model based on ECMWF data and trajectories provided by the German Weather Service, and the aerosol 3D distribution from DREAM model operated by ICoD shows that in some cases the aerosol layers came directly from Etna and in some other cases aerosol layers originated from Etna's eruption and reached the lidar stations after several days of long-range transport. This later case is consistent with the previous studies (Varotsos et al., 2005, 2006).

Both the lidar ratio and backscatter related Angstrom coefficient analyses show that the volcanic aerosols from Etna eruption in 2001 and 2002 have similar properties. The lidar ratio of Etna volcanic aerosol is about 50–60 sr, which is quite different from the climatological mean lidar ratio (30–40 sr) in the altitude range of 2–6 km.

Both the high values of lidar ratio and backscatter-related Angstrom coefficient suggest that the observed volcanic aerosols are sulfates and typical of sub-micrometric ash particles.

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Appendix A. Supplementary materials

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.atmosenv.2007.10.020.

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