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Characterization of Saharan dust layers over Naples (Italy) during 2000–2003 EARLINET project

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ABSTRACT

Vertically resolved observations of dust optical properties were carried out at the EARLINET station of Naples (southern Italy, 40.838° N, 14.183° E, 118 m above sea level) from May 2000 to August 2003. 45 outbreaks with a mean temporal length of about 4 days were observed, 40% of which were characterized by dust plume intrusion into the Planetary Boundary Layer.
The mean values of the altitude of base, top and of the thickness of the dust plume were derived. Dust optical properties were studied along the vertical profile in terms of statistical and climatological analysis of aerosol backscatter, extinction and lidar ratio measured inside the dust layer. Mean values of backscattering and extinction coefficients of $(1.2\pm0.1)\,10^{-6}\,m^{-1}\,sr^{-1}$ and $(0.61\pm0.06)\,10^{-4}\,m^{-1}$, respectively, were obtained in the whole observation period, while the mean value of LR at 351 nm resulted to be 47 ± 3 sr. Mean values of dust concentration and dust fluxes were also estimated. The highest values of concentration have been observed on spring and summer months resulting of $(150\pm60)\,\mu g\cdot m^{-3}$ and $(80\pm30)\,\mu g\cdot m^{-3}$, and mean dust fluxes were $(0.8\pm0.4)\cdot10^{-3}\,g\,m^{-2}\,s^{-1}$ and $(1.6\pm0.7)\cdot10^{-3}\,g\,m^{-2}\,s^{-1}$, respectively.
Finally, aerosol optical properties retrieved from lidar vertical profiles and sun-photometer measurement, in-situ sampling and models outcomes were used to fully examine the most intense dust outbreak observed during the whole study period.

1. Introduction

Tropospheric aerosols play a relevant role, in the Earth's radiative budget (Haywood et al., 2003). Nevertheless, the actual knowledge of the aerosol spatial and temporal distribution is still inadequate to carefully estimate the aerosol role on climate change, both on regional and on local scale (IPCC, Climate Change, 2007). Large uncertainties affect the current estimates of the aerosol properties arising from the lack of a systematic statistical survey during a long time period and in a large spatial scale, and from the large variability of aerosols sources, properties and distribution (Masmoudi et al. 2003). In order to overtake this uncertainty, several efforts have been made to improve measurements and data sets. In particular, the establishment in the last decade of networks performing systematic observation of optical, microphysical and radiative aerosol properties represented accordingly a substantial accomplishment. Within each network, local studies based on long data-sets were also performed with the aim to develop a long-term global climatology of the aerosol properties (Bösenberg et al., 2003; Holben et al., 1998; Kim et al. 2008).

The Mediterranean area is a unique case of study in terms of both climatic sensitivity and direct radiative forcing values (Hatzianastassiou et al., 2007) due to a large aerosol presence that is fostered by both meteorological conditions and long exposure to solar radiation. In particular, wide amount of dust (about 120 Tg yr^{-1}) is transported over large distances from North African region towards the Mediterranean (Escudero

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et al., 2006; Gerasopoulos et al. 2009; Muller et al. 2009; Papayannis et al. 2005, 2008, 2009; Pérez et al., 2006a,b) mainly because of low pressure systems, called Sharav cyclones, coming from Nord West direction (Barkan et al., 2004; Engelstaedter et al., 2006; Moulin et al., 1998). Northwards transport of dust follows a seasonal pattern with larger amounts of dust moved across the Mediterranean area during spring and summer months.

Nevertheless, according to the last IPCC report (IPCC, Climate Change, 2007) currently uncertainties in the radiative forcing effect of dust are still very high. These uncertainties depend on our incomplete understanding of dust related processes (as production, transport, entrainment, deposition and removal) and are largely determined by insufficient data on vertical distribution of desert dust aerosols and on their optical and microphysical properties (Papayannis et al., 2009; Pérez et al., 2006a,b). Moreover, also the coarse spatial resolution of soil data and meteorological fields in global models creates large uncertainty (Zender et al., 2003).

In particular, the radiative impact of the dust over the Mediterranean is still poorly known because the aerosol distribution is strongly influenced by complex synoptic meteorological conditions (di Sarra et al., 2001). In addition, currently used models are considered not still suitable to rightly describe physical and chemical processes involving dust along the transport path in the Mediterranean region (Kallos et al., 2007). For these reasons, in the last years the effort of the scientific community has been devoted to investigate and model regional and global transport of dust. In this respect, Israelevich et al. (2002) highlighted the importance to know the dust transport dynamics and the aerosol properties as well as their spatial and temporal correlation with high spatial and temporal resolution in order to study Mediterranean weather and climate.

Actually, several efforts have been made to understand the different phases of the dust cycle over Mediterranean and European area and to characterize vertical profiles, optical and microphysical properties, and chemical composition of aerosols during dust outbreaks. To this aim different instruments based on passive and active remote sensing techniques, in situ observations, satellite and radiosonde measurements and air mass trajectories were recently used (Bellantone et al., 2008; Di Iorio et al., 2009).

Moreover, several field campaigns have been carried out in Africa to investigate the role of dust aerosol on the regional climate. For instance, during Saharan Mineral Dust Experiment (SAMUM), vertically resolved observations of dust were simultaneously performed close to a source of desert dust and in remote areas (Ansmann et al., 2008; Muller et al., 2009; Tesche et al., 2009) with the aim to characterize dust particles close to dust sources and to quantify dust-related radiative effects. Nevertheless, the most of recent papers refer to a single events or to short-term campaigns (Guerrero-Rascado et al., 2009; Karam et al., 2010; Papayannis et al., 2005; Pavese et al., 2009; Tafuro et al., 2006; Wagner et al., 2009) whilst few of them concern the study on a systematic base of the dust optical properties measured in the Mediterranean area with high vertical and temporal resolution (Balis et al., 2004; Di Iorio et al., 2009; Gobbi et al., 2004; Kishcha et al., 2005; Mattis et al., 2008; Mona et al., 2006; Papayannis et al. 2008, 2009). Vertically resolved measurements with high spatial and temporal resolution provide the basis for a long-term global climatology of the dust properties and are also very important to validate satellite observations and evaluate global and regional aerosol dispersion models. In this respect, in order to improve the dust transport numerical models it is considered of fundamental importance to define the variability of the dust plume vertical extension and of its optical properties (as suggested by the Sand and Dust Storm Warning Advisory and Assessment System http://www.wmo.int/pages/prog/arep/wwrp/new/Sand_and_Dust_Storm.html).

This work is based on 3 years of systematic observations of tropospheric aerosol optical properties and spatial distribution performed over Naples under Saharan dust outbreaks conditions. Measurements here reported were carried out by means of a lidar system operating in the framework of the EARLINET (European Aerosol Research Lidar Network) network (Bösenberg et al., 2001). Data reported in this work were in part previously analyzed by Papayannis et al. (2008) in their study about Saharan dust intrusions over Europe. This paper intends to give a detailed study of Naples area where the observed aerosol layering is related to the sea-breeze circulation that influences both the planetary boundary-layer evolution and the observed aerosol vertical distribution (see Boselli et al., 2009). In particular, the mean optical properties of the aerosol observed over the city were studies through statistical and climatological analysis and their variability with the height were also evaluated to better characterize the dust plume vertical distribution. Seasonal dependence of the optical parameters measured in the dust plume was also analyzed.

The optical depth of dust plume was determined by taking into account the mean anthropic contribution to total optical depth as obtained on the base of 3 years of climatological data results (Boselli et al., 2009). The dust load so determined allowed us to estimate the concentration and the fluxes of the dust transported over the measurement area.

The study area is described in Section 2, instrumentations and methods are discussed in Section 3. Results of the statistical analysis of the dust optical properties are showed in Section 4. Finally, the strongest dust event occurred over the study area was analyzed as a case study.

2. Study area

The CNISM Lidar station is located on North West direction with respect to the Naples city, at 118 m a.s.l. The measurement area is characterized by very high aerosol content, mainly located below the Planetary Boundary Layer (PBL), arising from both human activities and natural sources. The main sources of anthropogenic aerosols are combustion, industrial activities, vehicular traffic and domestic heating. The city is located on the coast of the Tyrrhenian Sea. As a consequence of its central location in the Mediterranean basin, the city of Naples is affected by long-range transport of aerosols both of anthropogenic origin arising from industrialized areas of Europe and of natural origin, as volcanic ashes, desert's dust and sea salt. Being relatively close to the African continent, the Naples area represents an ideal site to study the transport of dust particles across the Mediterranean Sea toward the European continent. In fact, most of the air mass trajectories coming from North Africa pass over Naples directly.

3. Methodology and data analysis

Measurements here discussed were carried out using a Raman lidar system operating at a wavelength of 351 nm, as described in Boselli et al. (2003). From Lidar measurements aerosol backscattering $\beta^{aer}(z)$ and extinction $\alpha^{aer}(z)$ coefficients profiles were retrieved with a final temporal resolution of 30 min and a vertical resolution of 60 m and 180 m, respectively.

The $\alpha^{aer}(z)$ coefficient at laser wavelength was retrieved by means of the method introduced by Ansmann et al. (1990) from Nitrogen Raman lidar signal measured at 382 nm during night-time.

The retrieval of the $\beta^{aer}(z)$ coefficient at 351 nm from night-time measurements was performed by using the Raman method (Ansmann et al., 1992). This method is based on simultaneous detection of both elastic and Nitrogen Raman lidar echoes. In a different way, the retrieval of the $\beta^{aer}(z)$ coefficient at 351 nm from daytime measurements was obtained by using the Klett–Fernald algorithm (Klett, 1981; Fernald, 1984). This method requires a hypothesis on the extinction-to-backscattering ratio (LR) value, which choice should be carefully evaluated to prevent large uncertainty on the retrieved value of the backscattering coefficient. For daytime measurements we fixed the LR values taking into account the source regions of the air masses reaching the study area and having as references the values of LR determined by the nearest Raman measurements.

During the EARLINET project several intercomparison experiments were carried out to test the performance of the instrumentation involved in the project (Matthias et al., 2004) and the algorithms used to retrieve aerosol backscattering (Böckmann et al., 2004) and extinction coefficients (Pappalardo et al., 2004).

According to the EARLINET protocol, lidar measurements were systematically carried out three times a week (Monday at noon time and evening, Thursday in the evening) in clear sky conditions. Additional observations were performed during Saharan dust outbreaks and other special events (for instance forest fires and volcanic eruptions). Moreover, long time series of continuous measurements lasting for more than 24 h were also carried out to study the evolution of the aerosol layers during complete diurnal cycles.

Dust measurements were taken on alerts of the Atmospheric Modeling Weather Forecasting Group of the University of Athens (Greece), and online forecast of Euro-Mediterranean Centre on Insular Coastal Dynamics (ICoD-Malta). Forecasts are based on DREAM (Dust Regional Atmospheric Module) model (Nickovic et al., 2001).

Analytical back-trajectories from German Weather Service were used (Kottmeier and Fay, 1998) to identify the sources of the aerosol reaching the area under study. Dust outbreaks were identified by crossing the forecasts with 96 hours back-trajectories.

The results here presented include cases corresponding to intrusions of the mineral dust in the PBL.

In our measurements, the PBL top height was defined as the height corresponding to the absolute minimum value of the first order derivative of the logarithm of the range corrected signal (RCS) (Menut et al., 1999). Moreover, the gradient behavior was analyzed in order to evaluate the top and the bottom of the aerosol layers.

For layers located above the PBL, the base was fixed at the first point corresponding to a strong increase in the backscatter profile (Matthias et al., 2004). The top of the dust layer was defined as the altitude at which both the aerosol backscatter and its first derivative become null within the experimental errors (Papayannis et al., 2008).

It is worth to point out that seeping of mineral dust layer into the PBL could yield wrong information from the derivative method. In these cases analytical back-trajectories were used to verify the African origin of the air masses arriving over the measured area at lower altitude levels (900 and 850 hPa pressure levels). These levels are the most representative for the upper part of the planetary boundary layer (PBL) whose top height is on average located at 1500 m a.s.l. over the measurement area (Boselli et al., 2009). Therefore, when both back-trajectories and DREAM dust concentration profiles highlighted the presence of dust in the PBL, the base height of the dust layer was assumed at the minimum altitude level sampled in the backscatter profile.

A statistical approach was followed in order to study the mean optical properties of the aerosol observed over the city and to evaluate its variability with the height. In particular, a statistical analysis of mean optical properties of the dust plume was performed in terms of α, β and LR as measured inside the identified dust plumes. Moreover, seasonal dependence of the optical parameters was also analyzed.

In order to analyze the dust vertical distribution, the optical parameters were integrated over five different atmospheric layers of a thickness of 1000 m starting from the ground level. The integration over the lowest altitude range was done considering constant down to the ground the value of backscattering and extinction coefficient obtained at the minimum height level sampled by the lidar (typically 500 m for extinction and 250 m for backscattering). This assumption is based on the fact that after the sunset the atmosphere mixed well in the first 500 m. Such a procedure introduces an error not larger than 10% (Bösenberg et al., 2003).

The evaluation of the dust plume optical depth (OD_s) allowed us to estimate dust concentrations and fluxes. In fact, the dust load M (gm^{-2}) can be related to OD_s through the equation:

$$M = OD_s / \sigma_\lambda.$$

In the above reported equation, σ_λ is the specific extinction cross section (m^2g^{-1}) that depends on the chemical composition of the particles and on the distance from the source. A constant specific extinction cross section value of $0.60 \pm 0.04\ m^2g^{-1}$ was assumed at 351 nm. This value was obtained by extrapolating data reported for dust by Gerasopoulos et al. (2009), according to the wavelength dependence and assuming a value of -0.15 ± 0.02 for the Angstrom coefficient.

The urban area of Naples is characterized by local and anthropogenic aerosol sources that could largely contribute to the measured total OD, especially when dust seeps into the PBL. Moreover, as reported in ours previous study (Boselli et al., 2009) the sea-breeze circulation can influence the observed aerosol vertical distribution promoting the development of layer structures above the PBL. In order to correctly estimate the dust loading of the observed events, the OD contribution of aerosol not related to dust (OD_A) at different altitude levels should be evaluated. To this aim a mean vertical profile of dust free extinction coefficient was obtained from the results of 220 days of regular lidar measurements (Boselli et al., 2009). From this profile, the values of OD_A in the range of each detected dust plume were retrieved. These values were subtracted to the measured OD to evaluate the OD_S due to pure dust.

From the corrected dust load and taking into account the measured dust plume thickness T, we estimated the mean seasonal value of dust concentration inside the plume as $C = M/T$.

In order to estimate dust fluxes we used a synergic approach combining model outcomes with lidar results. In particular, from the back-trajectories we evaluated the horizontal wind speed (v_x) by considering the mean distance covered in the last 24 h before reaching Naples. Then the dust flux F was calculated as: $F = C\ v_x$ and assuming the dust concentration as constant with the altitude in the dust plume layer.

4. Results and discussion

Regular lidar observations of Saharan dust transport events in the troposphere started in Naples in the framework of the Earlinet project in 2000. From May 2000 to August 2003 about 290 days of measurements corresponding to 860 lidar profiles of atmospheric aerosols optical parameters were carried out in Naples. 466 of the measured profiles, corresponding to 97 days of measurement, were related to Saharan dust outbreaks.

The total number of Saharan dust outbreaks observed in Naples in the study period was 45 and for 36 of these alerts were received. 9 further dust events were identified by means of a comparative analysis between lidar profiles and air masses back-trajectories supported by the outcomes of the DREAM model and the Navy Aerosol Analysis and Prediction System (NAAPS) model provided by the Naval Research Laboratory.

As shown by Frontoso et al. (2007) the majority of the Saharan Dust events (more than 80%) occurred in presence of two main patterns: the first pattern is related to a combination of a depression system located in the Atlantic ocean and an anti-cyclonic system located in North Africa, whereas the second one corresponds to a depression system located mainly in western or central Mediterranean. This last pattern is often associated with strong Saharan dust episodes over the measurement area.

In Fig. 1 the trajectories of air mass reaching Naples at the altitude corresponding to 700 hPa during all the observed Saharan dust outbreaks are reported. The back-trajectories analysis revealed that desert dust follows two main directions from the source to Southern Italy (Pisani, 2005). The two main directions of dust are showed in Fig. 1 together with the percentage of the air masses following each direction.

In agreement with lidar observations performed over Europe (Papayannis et al., 2008), the seasonal distribution of the Saharan dust outbreaks observed in Naples shows a predominance (above 70%) of sand transport events during spring and summer. This seasonal distribution is probably due to a low-pressure system coming from Nord West direction

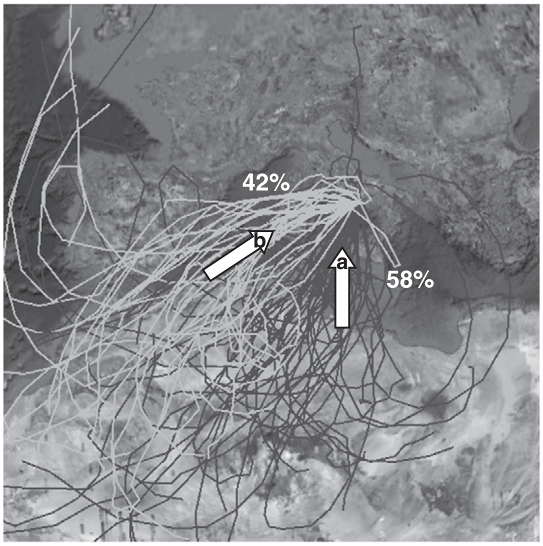

Fig. 1. Cluster analysis of back-trajectories of air masses ending over Naples at 700 hPa pressure level (about 3000 m) for the period 2000–2003. Main directions were showed together with the percentage of the measurement days corresponding to each pathway.

(Prospero et al., 1981) that is more frequent in warm than in cold seasons.

The mean length of registered events was 4.5 ± 0.5 days. This means that every year we measured in about 20% of the days a dust intrusion that increases the atmospheric aerosol load over the study area.

Data corresponding to dust intrusion into the boundary layer were selected by a cross-comparative analysis of lidar results and models outcomes as detailed in the methodology. In Figs. 2 and 3 the vertical profiles of aerosol backscatter and extinction coefficients, the measured LR and the concentration profile provided by the DREAM model for two different situations are showed. Aqua-MODIS daily level-3 data of aerosol optical depth at 550 nm are also reported. Fig. 2 shows the results of lidar observations performed on May 7, 2003 around sunset (18:48–19:18 UT) together with the DREAM model outcome. Both show a Saharan dust layer between 3000 and 6500 m of altitude. At lower height the differences between the measured data and the model results can be ascribed to the local anthropogenic aerosol that is not considered in the model. The back-trajectories show that air masses coming from Sahara desert reach the Naples lidar station above 700 hPa, corresponding to about 3000 m of altitude.

In this case the LR value measured in the Saharan dust layer was typical of desert aerosol (38 ± 3 sr) while a LR value of (55 ± 9 sr) is found at lower altitude, according to the presence of smaller particles in the PBL.

A different situation is reported in Fig. 3, showing the results of measurements performed on August 21, 2003 around the sunset (18:38–19:08 UT). According to the back-trajectories analysis, in this day the Saharan dust affects lower layers inside the PBL, which top height was estimated at 1050 m.

Unlike the previous case, on August 21, 2003 we didn't observe a considerable change of LR below (44 ± 5 sr) and above (42 ± 1 sr) the estimated PBL top height as a result of

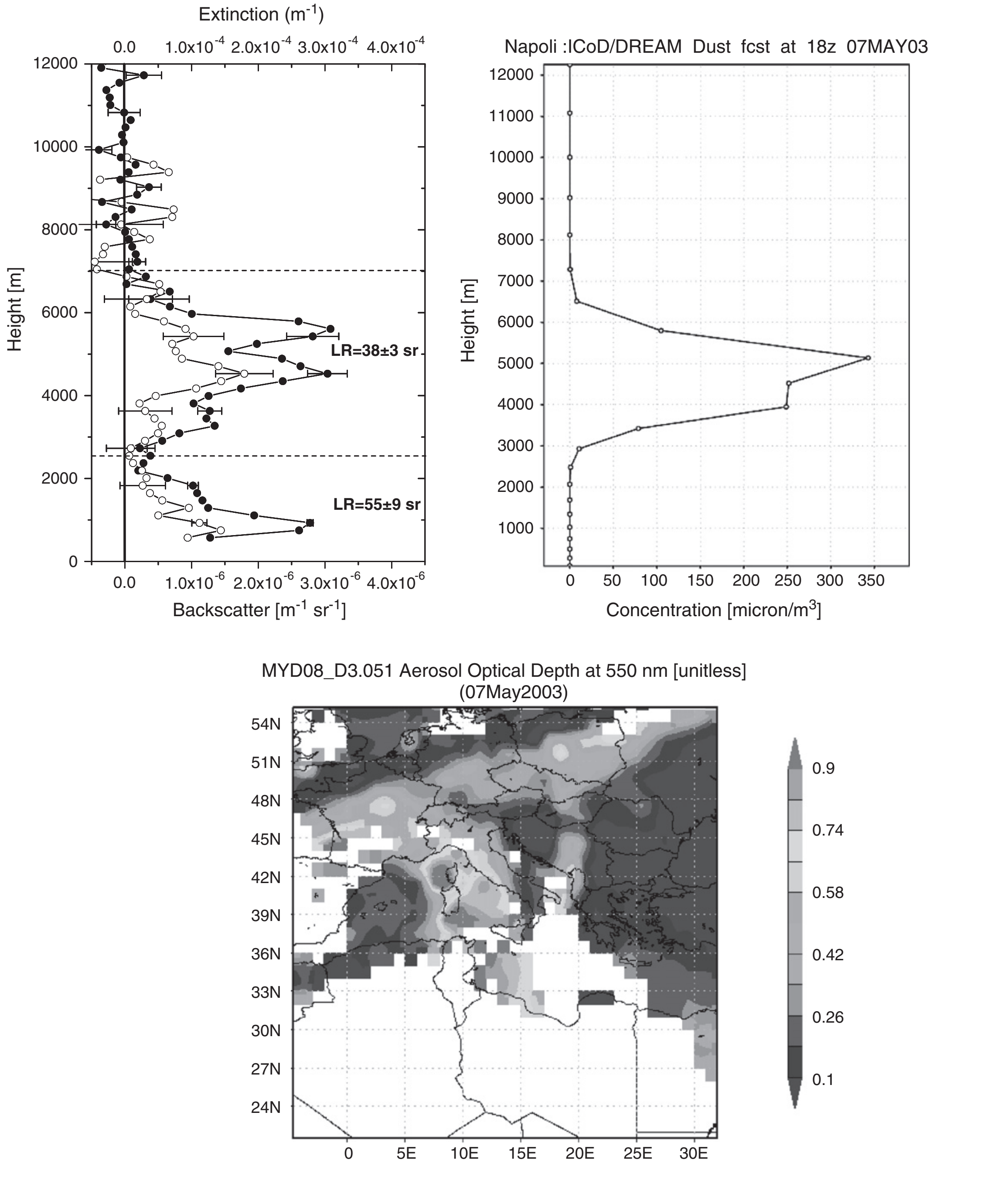

Fig. 2. Aerosol backscatter lidar profiles and corresponding concentration profiles provided by the DREAM model as obtained on May 7, 2003. Aqua-MODIS daily level-3 data of aerosol optical depth at 550 nm for May, 7 are also showed. In this case the dust layer was well-separated from the PBL.

both downward transport of larger dust particles and mixing phenomena.

In the period under consideration, about 40% of the observed events (18 events out of 45) seeped into the boundary layer. The relative occurrence of Saharan dust cases affecting the lowest atmospheric level is greater than that estimated by Papayannis et al. (2008) on average over the European continent (about 5%). This result is related to the closeness of the measurement area to the Sahara desert. It also has to be mentioned that a larger study period was investigated in the analysis here presented.

4.1. Dust layer vertical distribution

The vertical extension of the dust layers observed during the whole study period was studied by determining the base

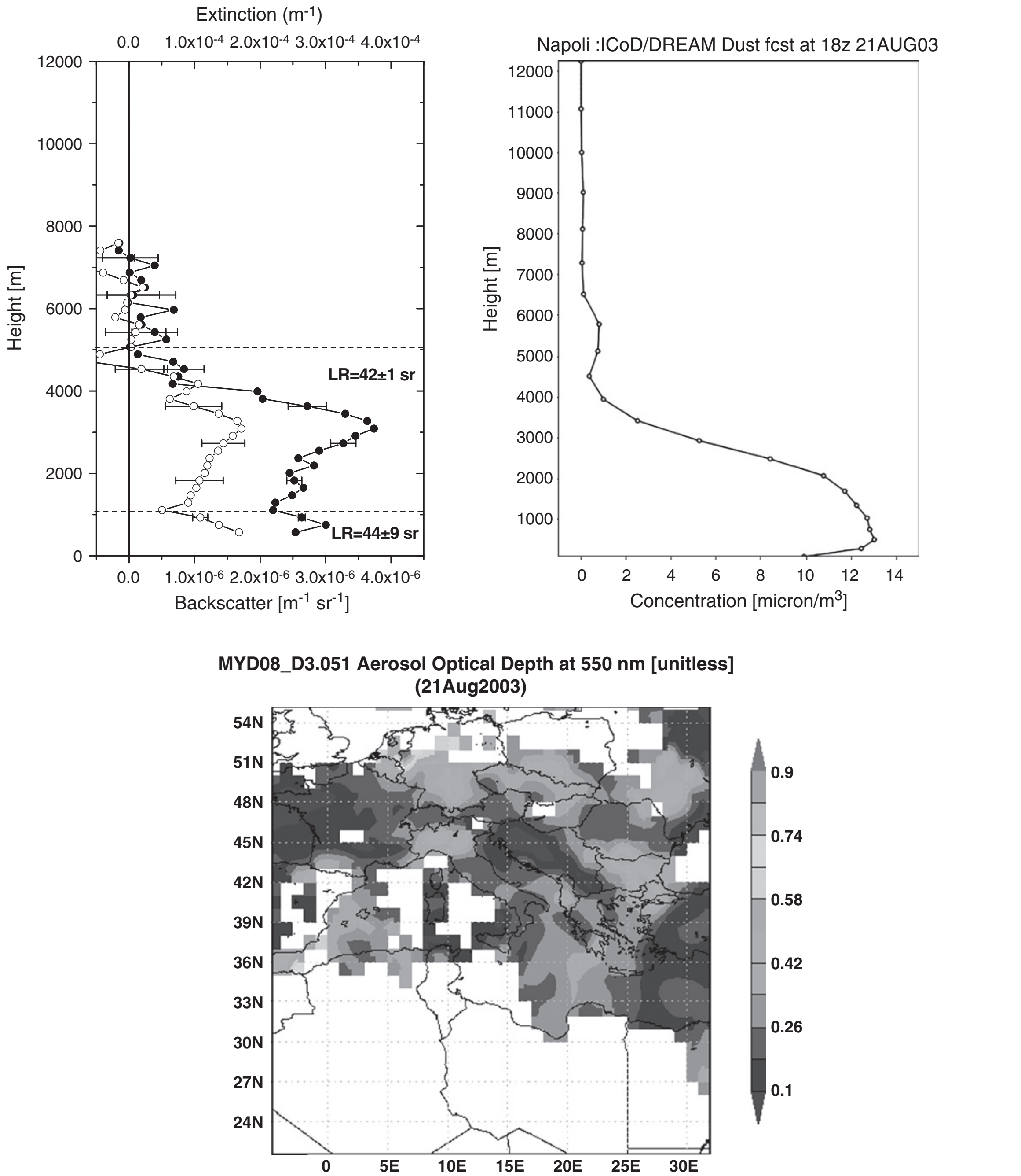

Fig. 3. Aerosol backscatter lidar profiles and corresponding concentration profiles provided by the DREAM model as obtained on August 21, 2003. Aqua-MODIS daily level-3 data of aerosol optical depth at 550 nm for August 21 are also showed. This case is related to a Saharan dust intrusion in the PBL.

and top height, and the thickness of the plume. Fig. 4 shows the count distributions of the base, top and thickness obtained for each of the observed events, while mean values and standard errors are reported in Table 1. The obtained results fit with those reported by Papayannis et al. (2008) corresponding to a shorter period.

The analysis of the observed events showed a large variability of the Saharan dust clouds vertical extension. In particular, dust has been observed up to 8700 m. Nevertheless, it was confined below 5000 m of height in about 60% of the observed events. On the other hand, 85% of the dust plumes had a base height lower than 2000 m.

A correlation analysis of the thickness with the base of the dust layer highlights that higher bases correspond to thinner layers. Moreover, as showed in Fig. 5, a larger variability of the thickness is observed for lower bases.

Seasonal dependence of these parameters shows that the highest extent of the dust plume was measured on summer

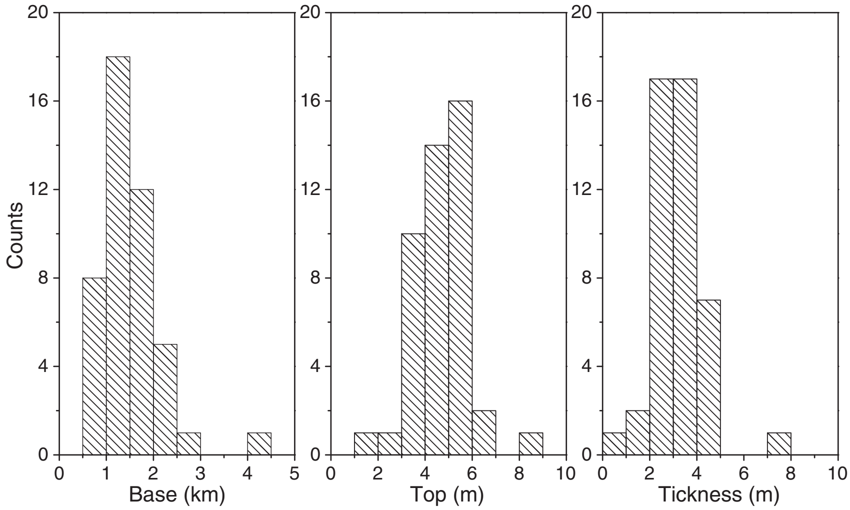

Fig. 4. Count distributions of the dust plume thickness, top height and base height. The reported values correspond to lidar measurements performed in the period May 2000–August 2003.

(thickness 3700 ± 480 m), when the highest values of the dust layer top were measured. On the other hand, low and thin dust layers were observed on winter (thickness 2400 ± 300 m, top height 3800 ± 220 m). Both these results could be related to the larger intensity of the Saharan dust transport events and to the higher convective activity observed on warm season. In fact, in these seasons, near the source strong convection can lift a large amount of dust particles into the atmosphere (Ansmann et al., 2009) in high and thick layers because of the large amount of energy involved in their elevation mechanism. Moreover, during long range transport dust particles can move downward because of gravitational settling, subsidence phenomena and sedimentation processes. In particular, on summer, due to the high convective activity, the local PBL top height can reach elevated altitudes (above 2000 m), making possible the dust injection from high to lower levels during the PBL evolution and further lowering the base of the observed layer.

4.2. Dust layer optical properties

4.2.1. Mean optical properties

The mean optical properties of the dust plume were studied by means of a statistical analysis of β^{aer}, α^{aer} and LR values measured inside the dust layers. Fig. 6 shows the frequency distributions of these parameters. Data distributions show large standard deviations related to modifications of particles shape and dimension and of dust composition during the transport processes. As reported in Table 2, mean values of backscattering and extinction coefficients of $(1.2 \pm 0.1)\,10^{-6}\,\mathrm{m}^{-1}\,\mathrm{sr}^{-1}$ and $(0.61 \pm 0.06)\,10^{-4}\,\mathrm{m}^{-1}$ respectively, were obtained in the whole observation period. Moreover, mean value of LR resulted to be 47 ± 3 sr, in agreement with theoretical and experimental values reported in the literature for Saharan dust (Ackermann, 1998; Mona et al., 2006; Müller et al., 2007; Muller et al., 2009; Papayannis et al., 2008).

The study of the seasonal variability of mean optical properties measured in the dust layer (Table 2) highlights that larger values of the mean aerosol extinction are observed during warm seasons. In fact, the estimated dust concentration results higher on spring and summer months with mean values around $(150 \pm 60)\,\mu\mathrm{g\,m}^{-3}$ and $(80 \pm 30)\,\mu\mathrm{g}\cdot\mathrm{m}^{-3}$, respectively. Lower mean dust concentrations were measured on winter and autumn resulting less than $(50 \pm 20)\,\mu\mathrm{g\,m}^{-3}$ on average. The observed seasonal variability of estimated mean dust concentrations is in agreement with the modeled seasonal mean concentration profiles in the central Mediterranean. reported by Papayannis et al. (2008). Moreover, mean dust fluxes resulted $(0.8 \pm 0.4)\cdot 10^{-3}\,\mathrm{g\,m}^{-2}\,\mathrm{s}^{-1}$ and $(1.6 \pm 0.7)\cdot 10^{-3}\,\mathrm{g\,m}^{-2}\,\mathrm{s}^{-1}$

Table 1
Mean values and standard errors of base, top and thickness of the Saharan dust layers.

	Mean value
Base (m)	1500 ± 90
Top (m)	4600 ± 170
Thickness (m)	3100 ± 160

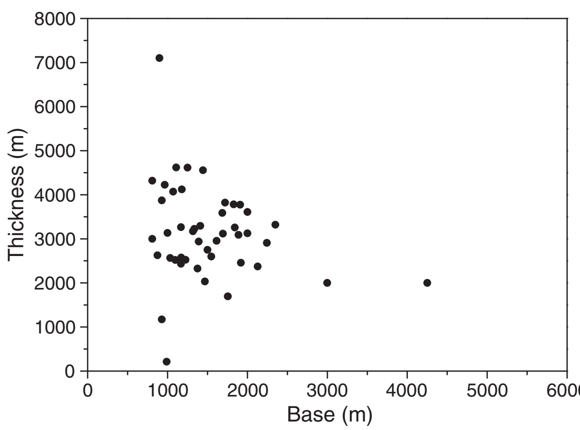

Fig. 5. Scatter-plot of the thickness versus the base of the plume corresponding to measurements performed from May 2000 to August 2003.

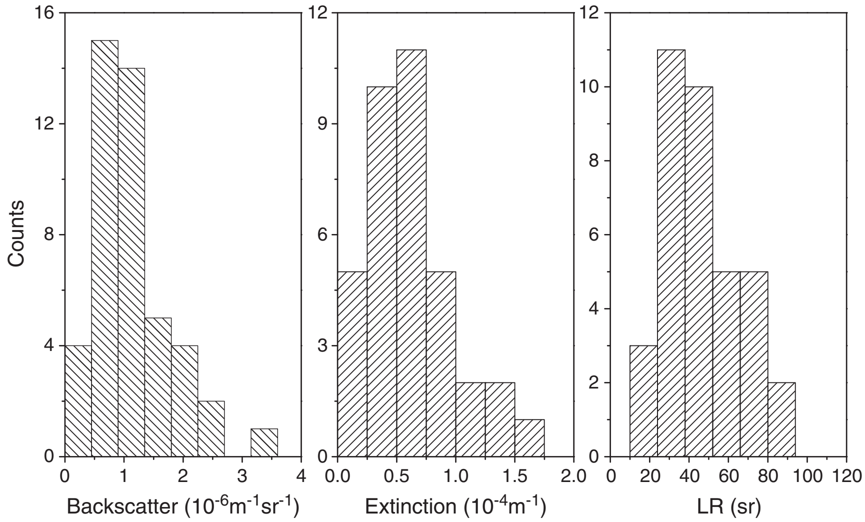

Fig. 6. Count distributions of aerosol backscatter (β^{aer}), extinction (α^{aer}) and lidar ratio (LR) mean values within the desert dust layer for the whole observation period.

on summer and spring, respectively, whereas fluxes lower than $(0.4 \pm 0.1) \cdot 10^{-3}$ g m^{-2} s^{-1} were obtained on autumn and winter months.

The obtained results could be related to seasonal variability of low pressure systems that in warm season favors the northward motions of air masses from North African coast toward the Mediterranean Basin (Moulin et al., 1998).

The LR dependence on the dust plume altitude shows that larger LR values correspond to lower base heights (Fig. 7) of the dust plume. In particular, LR values larger than 60 sr were found when the base of the plume was located below 1000 m, due to the mixing of the dust particles with local aerosols. Moreover, the LR did not show a clear dependence with the thickness of the dust layer.

Changes in the LR could be also related to changes in both sources and transport path (Engelstaedter et al., 2006). With the aim to detect possible correlations, a detailed study of the LR variability with air mass origin and path was performed. Results show that larger LR values (mean LR of 49 ± 3 sr) correspond to back-trajectories coming from South (pattern “a” of Fig. 1) whereas lower LR values (mean LR of 41 ± 3 sr) were measured when air masses came from south-west direction, with a longer path over the Mediterranean Sea (pattern “b” of Fig. 1). The obtained results could be ascribed to the presence of stronger dust events in the first case and to maritime aerosol contamination in the second case. Moreover, gravitational settling could also contribute to the observed results according to a difference of about 1000 km in the path followed by the air masses coming from African continent along the two above-mentioned patterns.

Table 2
Mean values of aerosol extinction (α^{aer}), backscattering (β^{aer}) and lidar ratio (LR) measured in the dust layers and corresponding to different seasons. The mean values in the whole study period are showed in bold.

	αx10^{-4} (m^{-1})	βx10^{-6} (m^{-1} sr^{-1})	LR (sr)
Spring	0.65 ± 0.11	1.4 ± 0.1	40 ± 4
Summer	0.79 ± 0.11	1.3 ± 0.2	57 ± 6
Autumn	0.24 ± 0.03	0.6 ± 0.1	36 ± 5
Winter	0.57 ± 0.13	1.5 ± 0.8	46 ± 8
	0.61 ± 0.06	**1.2 ± 0.1**	**47 ± 3**

4.2.2. Vertical variability of mean optical properties

The vertical variability of mean optical properties of the dust layer was also studied by means of a statistical analysis of β^{aer}, α^{aer} and LR values measured inside five different atmospheric layers (i.e. 0–1 km, 1–2 km, 2–3 km , 3–4 km, 4–5 km). This study gives an insight on dust injection from high to lower level during long range transport phenomena. The results are summarized in Table 3. As shown in Table 3, the lowest atmospheric layer is characterized by the largest mean values of α^{aer} and β^{aer} ($(2.5 \pm 0.4)\,10^{-4}$ m^{-1} and $(4.5 \pm 0.6)\,10^{-6}$ m^{-1} sr^{-1}, respectively) as result of the mixing between sand particles and local aerosol. Moreover, mean values of α^{aer} and β^{aer} result unchanged from 1 to 4 km (about 10^{-4} m^{-1} and 2.5 10^{-6} m^{-1} sr^{-1}, respectively) while in the range 4–5 km lower α^{aer} and β^{aer} mean values of $(0.8 \pm 0.1)\,10^{-4}$ m^{-1} and $(1.6 \pm 0.2)\,10^{-6}$ m^{-1} sr^{-1}, respectively were measured. Therefore, the presence of homogeneous and well mixed layers characterizes the range from 1 to 4 km, while gravitational settling of larger sand particles could explain the values obtained above 4 km of altitude.

As to the LR vertical variability, the obtained mean values and data distributions are reported in Table 3 and Fig. 8, respectively. In particular, in Fig. 8 the frequency hystograms of LR are shown together with the normal distributions that fit the data. As Fig. 8 shows, in the range 0–1 km data are fitted by a bi-modal distribution (modal values: $m_1 = 34 \pm 1$, $m_2 = 83 \pm 2$) that reflects the contributions of dust and local aerosols. The highest modal value in this altitude range is related to fine particles of local anthropogenic origin. Above 1 km of altitude a single mode normal distributions fit the data. Moreover, the LR mean value decreases from 1 to 5 km, according to a higher content of larger sand particles at higher altitude.

The altitude dependence of the aerosol extinction and backscatter peak values, α_{max} and β_{max}, was also studied as

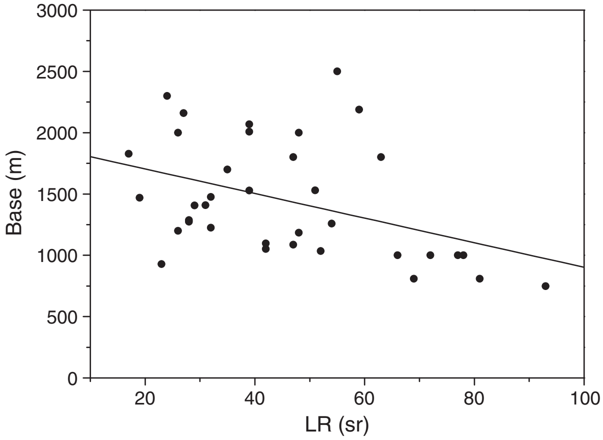

Fig. 7. Scatter plot of lidar ratio versus the dust plume base height for nighttime measurements. The result of the linear regression applied to the data is also showed.

further parameter to consider for an in deep investigation of the dust plume vertical distribution. The distributions of the corresponding altitudes $z(\alpha_{max})$ and $z(\beta_{max})$ are shown in Fig. 9. For both mean values of about 2500 m were found. Measurements show a large variability of α_{max} and β_{max} peak values that range from 10^{-5} to 10^{-3} m^{-1} and from $3\,10^{-7}$ to $1.2\,10^{-5}$ m^{-1} sr^{-1}, respectively. Nevertheless, more than 70% of data correspond to α_{max} values lower than $2\,10^{-3}$ m^{-1} and to β_{max} values lower than $4\,10^{-6}$ m^{-1} sr^{-1}.

4.2.3. The 29th August 2003 dust event

The strongest dust outbreak observed in the study period occurred on 29th August 2003. Its characterization represents a step to better understanding of atmospheric aerosol properties during severe dust outbreak and to highlight the impact of dust on the PM mass concentrations at ground. The synoptic situation was characterized by a high-pressure system extending from Northern Africa to the Western Mediterranean. The effect of the anticyclone of African origin contributes to the advection of warm and dry air from Northern Africa to the Italian peninsula; therefore, dust particles were transported away from the source toward Italy as the AOD data from Aqua-MODIS show (Fig. 10).

Vertical profiles of the aerosol backscatter coefficient measured at 13:30UT and 17:30UT are reported in Fig. 11a, while aerosol extinction and LR profiles simultaneously measured at 17:30UT are reported in Fig. 11b. Both figures show a Saharan dust layer between 1000 and 6000 m of altitude, according to DREAM model outcome. Back-trajectories for the 19:00 UT arrival time show air masses coming from Sahara desert over Naples lidar station between 850 and 500 hPa pressure levels, corresponding to 1500–5500 m of altitude.

Vertical profiles of the aerosol backscattering coefficient show that different ranges of altitude were interested by the dust layer, with a progressive intrusion into lower altitudes.

Table 3
Mean values of aerosol extinction (α^{aer}), backscattering (β^{aer}) and lidar ratio (LR) measured in five different atmospheric layers (0–1 km, 1–2 km, 2–3 km, 3–4 km,4–5 km).

	α x10^{-4} (m^{-1})	βx10^{-6} (m^{-1} sr^{-1})	LR (sr^{-1})
0–1 km	2.5 ± 0.4	4.5 ± 0.6	65 ± 5
1–2 km	1.3 ± 0.2	2.5 ± 0.4	50 ± 3
2–3 km	1.1 ± 0.2	2.5 ± 0.5	44 ± 2
3–4 km	1.0 ± 0.1	2.5 ± 0.7	41 ± 3
4–5 km	0.8 ± 0.1	1.6 ± 0.2	46 ± 4

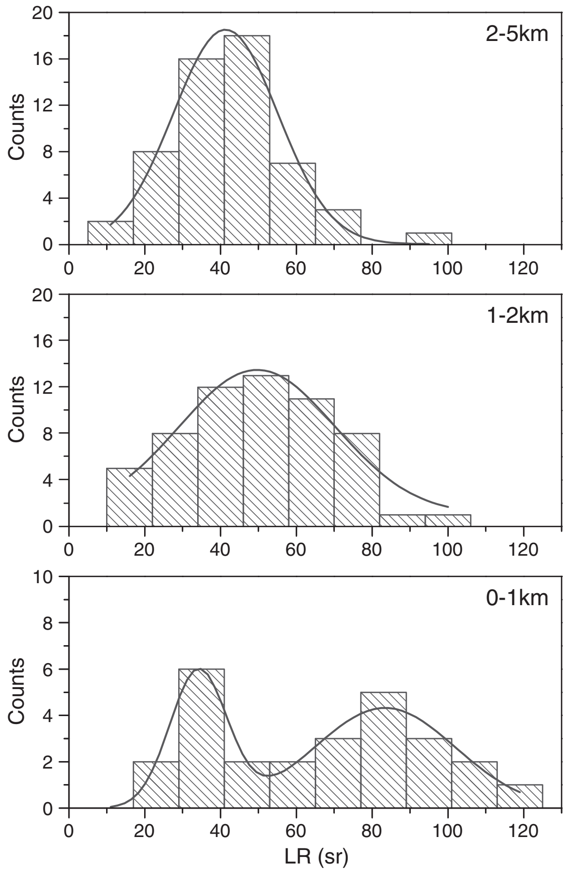

Fig. 8. Count distributions of lidar ratio measured in three different atmospheric layers (0–1 km, 1–2 km, 2–5 km). Measurements refer to the observation period May 2000–August 2003.

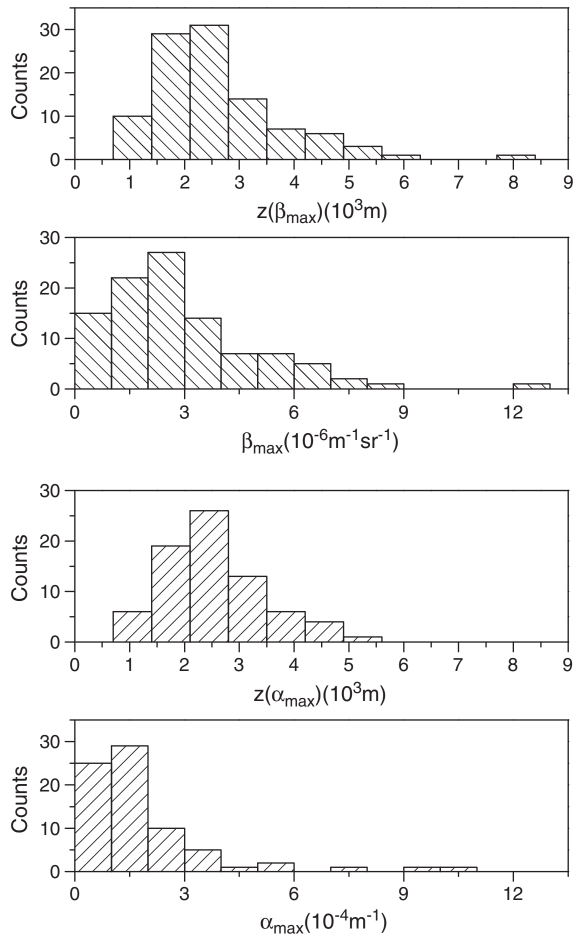

Fig. 9. Count distributions of aerosol extinction and backscatter peak values (α_{max} and β_{max}) measured in the Saharan dust plume and of the corresponding altitudes ($z(\alpha_{max})$ and $z(\beta_{max})$).

Measured values of optical depth (OD) and integrated backscatter (IB) in the dust layer at 17:30 UT are 0.92 ± 0.04 and $(1.59 \pm 0.04)\,10^{-2}$ sr^{-1}, respectively, which are the highest values measured in the whole study period. An OD value from 0.4 to 0.8 was provided from the NAAPS model on 29th August 2003.

The LR mean value we measured is 65 ± 3 sr, in agreement with large values detected in the dust plume during extreme events in Europe (Guerrero-Rascado et al., 2009; Mattis et al., 2002; Mona et al., 2006). This large value of the LR could be partly ascribed to the non-sphericity of the particles (Ansmann et al., 2003; Mattis et al., 2002) that increases the LR for the same aerosol type. Moreover, during this event, the mineral aerosol concentration grows up inside the PBL and the mixing with pollution related smaller particles, could also explain an increase of the LR value (Müller et al., 2000).

For this event, a mean dust concentration of about $(250 \pm 20)\,\mu g\,m^{-3}$ in the plume (1000–5500 m) was found and a mean flux of $(3.5 \pm 1)\,10^{-3}$ gm^2s^{-1} was estimated.

Moreover, in this day NAAPS model provided a dust surface concentration between 40 and 80 $\mu g\,m^{-3}$ in the measurement area.

In order to study a possible correlation between the aerosols observed in the lower troposphere and ground measurements of PM10 concentrations, the data of the Campania Air Quality Regional Network (AQRN) were analyzed (http://www.arpacampania.it).

Generally, an increase of the PM10 concentration at ground could be due to gravitational settling, subsidence phenomena and sedimentation processes of the aerosol coming from long range transport phenomena.

As Fig. 12 shows, the time dependence of the PM10 daily concentration was the same in all the five provinces of the region, even if there is a distance between 30 and 70 km among them. This behavior allows asserting that the increase in the PM10 concentrations was mainly related to the impact of Saharan dust at ground rather than to anomalous emissions from local sources. In particular, the maximum values of PM10 daily concentration were observed on 29 August in all the measurements stations of the AQRN, when lidar measurements showed in Naples a considerable amount of dust particles in the lower troposphere.

In order to provide information on the relative influence of coarse-versus-fine mode aerosols along the atmospheric column and to confirm the impact of Saharan dust on PM10 measured at ground, the AERONET measurements performed in Rome, about 200 km from our lidar site, were analyzed. Level 2.0 (cloud screened and quality assured) daily data of columnar aerosol OD at 440 nm (OD_C) and Angstrom exponent at 870 nm and 440 nm (α_C) measured at Rome highlight a large amount ($OD_C = 1.01$) of large particles ($\alpha_C = 0.12$) along the atmospheric column on 29th August 2003. The daily mean values of OD_C and α_C values measured in Rome with the sun-photometer are reported in Fig. 12 for the 26th August-1st September period. As Fig. 12 shows, the maximum values of OD_C and the minimum value of α_C were measured on 29th August. In Fig. 13 the size distributions retrieved from the sun-photometer at different measurement times are reported. As this figure shows, the values of OD_C and α_C correspond to particles in coarse mode ($1\,\mu m < r < 10\,\mu m$).

5. Conclusions

Systematic lidar observations of aerosol optical properties during Saharan dust intrusions were performed from May 2000 to August 2003 over Naples in the frame of EARLINET project.

We followed 45 Saharan dust outbreaks with a mean temporal length of about 4 days. We observed a predominance (above 70%) of sand transport events during spring and summer. Moreover, about 40% of the observed events (18 events on 45) were characterized by intrusion of the sand plume in the PBL.

From a statistical analysis the mean values of the altitude of base, top and of the thickness of the dust plume resulted 1500 ± 90 m, 4600 ± 170 m and 3100 ± 160 m, respectively. The study of the seasonal variability of these properties highlights that the lowest base position and the highest extent of the dust plume take place on summer.

The mean optical properties of the sand plume were determined from the analysis of aerosol backscatter, extinction and LR at 351 nm measured inside the dust layers. Mean values of backscattering and extinction coefficients of $(1.2 \pm 0.1)\,10^{-6}\,m^{-1}\,sr^{-1}$ and $(0.61 \pm 0.06)\,10^{-4}\,m^{-1}$, respectively, were obtained in the whole observation period, while the mean value of LR resulted to be 47 ± 3 sr.

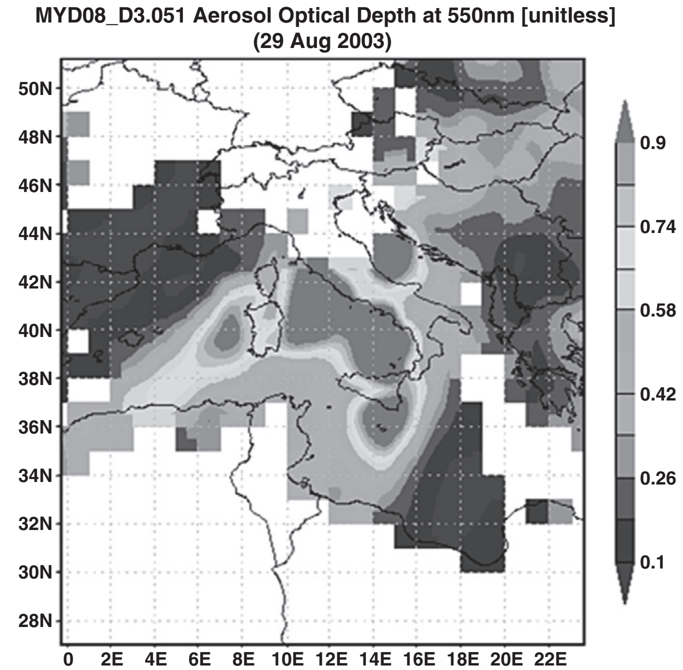

Fig. 10. Aqua-MODIS daily level-3 data of aerosol optical depth at 550 nm for August 29 2003.

Dust concentration in the plume resulted highest on spring and summer months with mean values around $(150 \pm 60)\mu g \cdot m^{-3}$ and $(80 \pm 30)\mu g \cdot m^{-3}$, respectively. Values lower than $(50 \pm 20)\mu g \cdot m^{-3}$ were obtained on winter and autumn.

LR variability with air mass origin and path was also studied. Results showed a mean LR of 49 ± 3 sr at 351 nm during dust event, corresponding to back-trajectories coming from South whereas a LR mean value of 41 ± 3 sr was measured when air masses came from south-west direction crossing the Mediterranean Sea.

LR vertical variability study highlighted larger LR mean values (LR $= 65 \pm 5$ sr) below 1 km according to a larger contribution of fine particles of local anthropogenic origin. Moreover, a decrease of the LR with height was observed according to the presence of large sand particles in the plume.

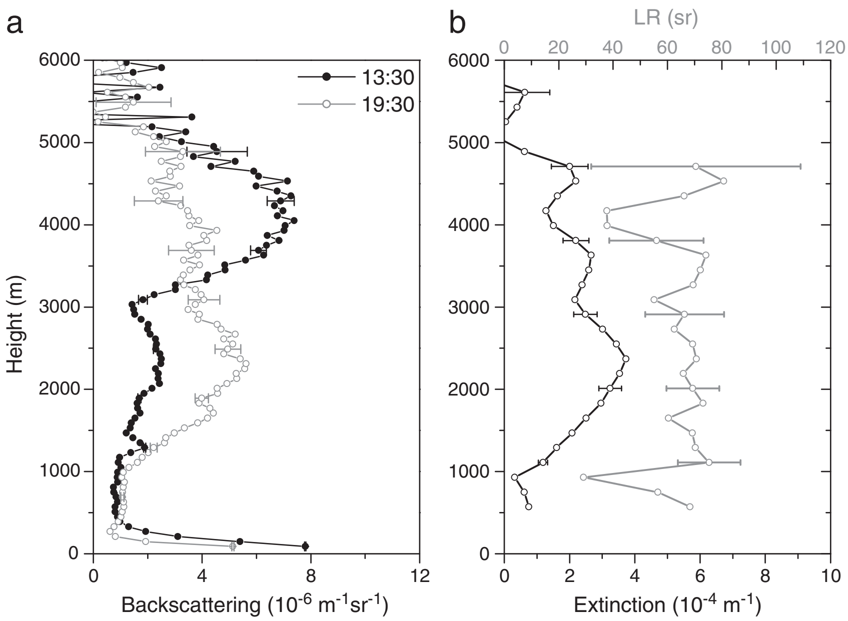

Fig. 11. 29 August, 2003. Vertical profiles of the aerosol backscatter coefficients measured at 13:30UT and 19:30UT (10a); vertical profiles of aerosol extinction and LR measured at 19:30UT (10b). Data reported in the figure correspond to a time integration of 30 min.

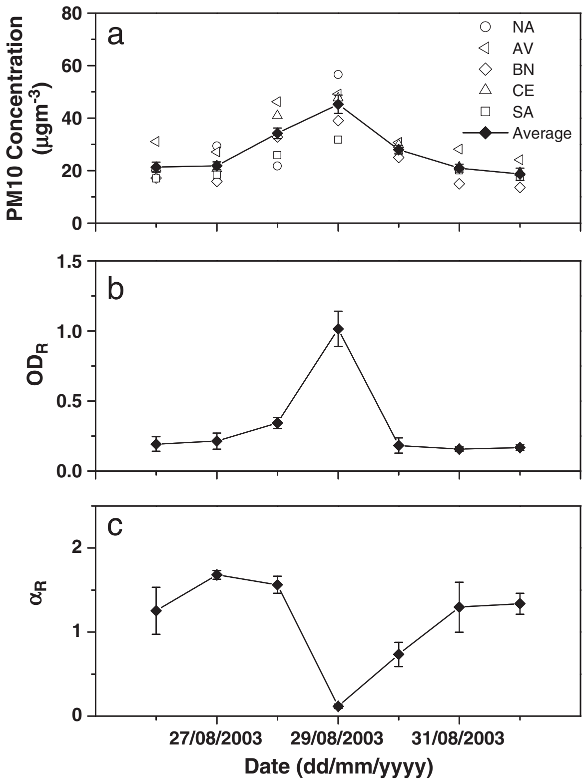

Fig. 12. PM10 daily concentrations (mg m^{-3}) at ground level measured at Naples(NA), Avellino (AV), Benevento (BN), Caserta (CE) and Salerno (SA) from 26 August to 1 September 2003 (Fig. 12a); daily values of aerosol OD_R at 440 nm (Fig. 12b) and α_R (440 nm/870 nm) (fig. 12c) derived from sun-photometer observations carried out at Rome in the same period.

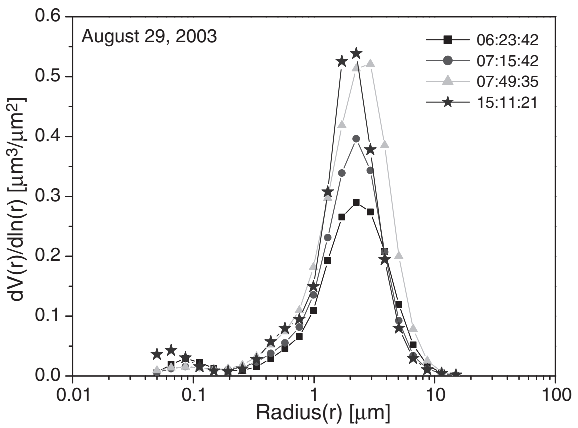

Fig. 13. Aerosol volume size distribution derived from sun-photometer measurements carried out in Rome on 29 August 2003.

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