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One year of tropospheric lidar measurements of aerosol extinction and backscatter

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Abstract
The aerosol lidar system operational at IMAA-CNR in Tito Scalo (PZ) (Southern Italy, 40°36′N, 15°44′E, 820 m above sea level) is part of the EARLINET project. Systematic lidar measurements of aerosol backscatter and extinction in the troposphere have been performed since May 2000. Aerosol backscatter measurements were performed at both 355 nm and 532 nm, while aerosol extinction coefficient were retrieved from simultaneous N_2 Raman backscatter signals at 386.6 nm. The observations were performed on a regular schedule of two night time measurements per week (around sunset) and one daytime measurement per week (around 13:00 UTC). Furthermore, special observations concerning Saharan dust outbreaks have been carried out. Starting in May 2000 the lidar measurements performed in Tito Scalo have been collected and analysed. Preliminary results regarding the first year of measurements are reported. In particular, the evolution of the aerosol integrated backscatter and extinction as well as of the mean value of the lidar ratio in the whole aerosol layer is reported. Results show clear evidence of seasonal variation of the observed parameters, with higher values and greater variability during summertime.

Key words *lidar – aerosol – EARLINET*

1. Introduction

Atmospheric aerosols, originated from both natural and anthropogenic sources, play a crucial role in changes of the global and regional climate as well as environmental pollution. Atmospheric aerosols considerably affect the Earth's radiation balance by both scattering and absorbing incoming and outcoming radiation (Ackerman and Chung, 1992). At present, the impact of the atmospheric aerosols on climate is not a well-known process because it involves both direct and indirect feedback mechanisms (Houghton *et al.*, 2001); this claims for a more accurate characterisation of aerosol optical properties and spatial distribution. Moreover, continuous monitoring of atmospheric aerosols is essential in view of their wide variability in space and time.

Lidar technology is now mature enough to provide quantitative measurements of the optical properties of the aerosols with high spatial and temporal resolution and with a high level of accuracy. In particular, the use of Raman lidar allows independent measurements of the aerosol extinction and backscatter as a function of height (Ansmann *et al.*, 1990).

The lidar system operational at IMAA-CNR in Tito Scalo (PZ) (Southern Italy, 40°36′N, 15°44′E, 820 m above sea level)

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provides independent measurements of the aerosol extinction and backscatter at 355 nm and backscatter measurements at 532 nm (Pappalardo *et al.*, 2001). This system is part of the EARLINET project: the first network of advanced lidar stations operating to provide a climatological database for the horizontal and vertical distribution and variability of aerosol over Europe (Boesemberg *et al.*, 2001). This lidar network is based on a total of 21 stations, as shown in fig. 1, located to provide significant coverage of the widely varying atmospheric conditions over Europe. Table I reports the list of all Institutions participating in the EARLINET project. The observations, almost simultaneous for each station, are performed on a regular schedule of two night time measurements per week and one daytime measurement per week. Daytime measurements are made around 13:00 UTC, while night time measurements are made around sunset; these times were selected to have one daytime measurement with a well developed boundary layer condition, and two observations with low background light to perform Raman extinction measurements and to monitor the dust layer that has developed during the day. In addition to the routine measurements, further observations are devoted monitor special events such as Saharan dust outbreaks, forest fires, photochemical smog and volcano eruptions. Lidar

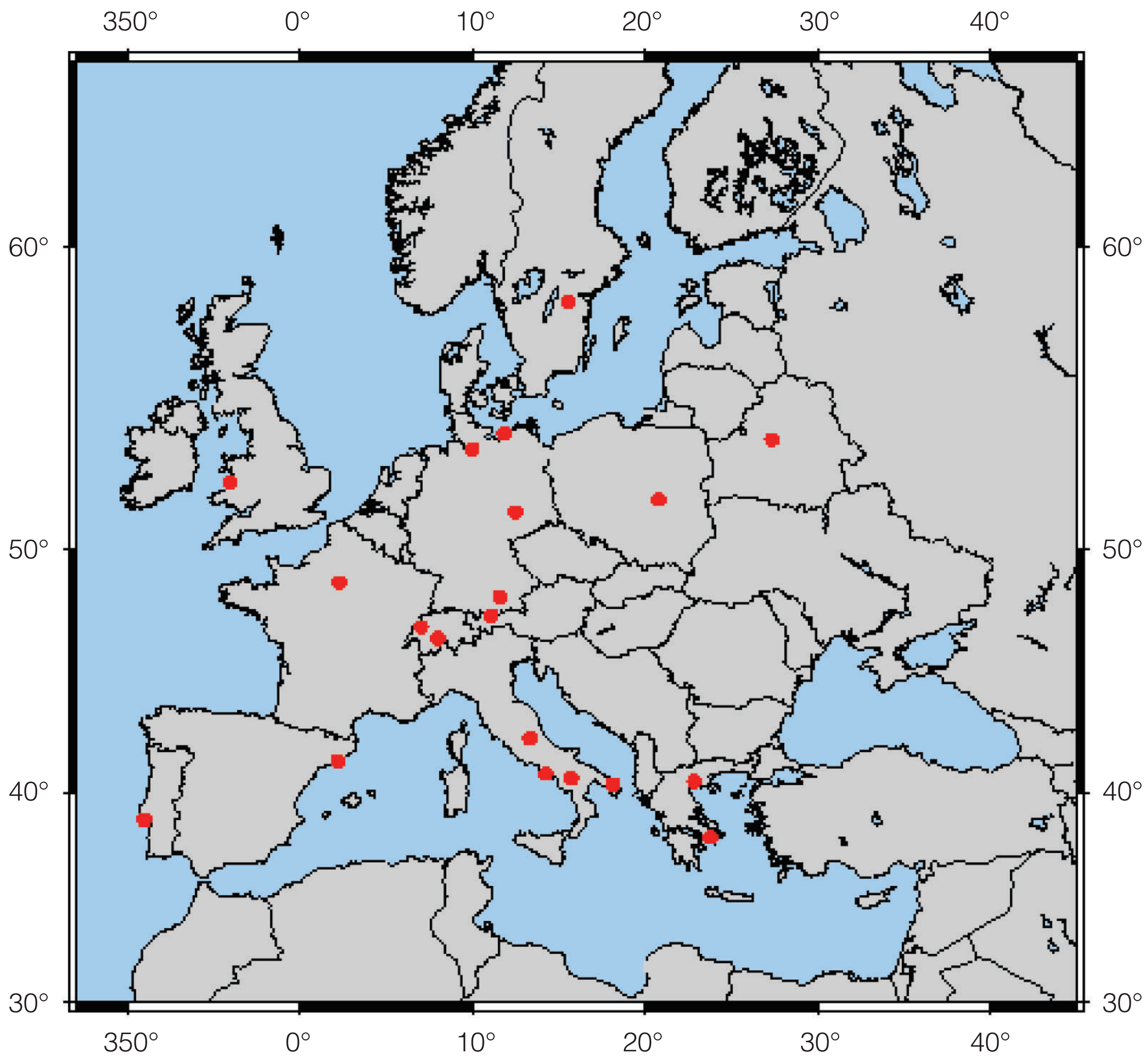

Fig. 1. Network of EARLINET stations.

Table I. EARLINET participating institutions.

Max Plank - Institut für Meteorologie	(D)
Universität Potsdam	(D)
Defence Research Establishment	(SE)
University of Wales Aberystwyth	(UK)
Centre National de la Recherche Scientifique Délégation Régional Île-de-France	(FR)
Institut für Troposphärenforschung	(D)
Leibniz Institut für Atmosphärenphysik an der Universität Rostock	(D)
National Technical University of Athens	(EL)
Aristotle University of Thessaloniki	(EL)
Universitat Poliytècnica de Catalunya	(E)
Istituto Nazionale per la Fisica della Materia, Napoli	(I)
Istituto Nazionale per la Fisica della Materia, Lecce	(I)
IMAA-CNR and Istituto Nazionale per la Fisica della Materia, Potenza	(I)
Università degli Studi - L'Aquila	(I)
Ecole Polytechnique Fédérale de Lausanne	(CH)
Observatoire Cantonal de Neuchâtel	(CH)
Institute of Physics of National Academy of Sciences of Belarus	(BY)
Instituto Superior Técnico	(P)
Ludwig-Maximilians Universität München	(D)
Fraunhofer Gesellschaft zur Förderung der angewandten Forschung e.V.	(D)

measurements are supported by a suite of more conventional observations. Back-trajectories derived from the operational weather prediction model of the German Weather Service are used to characterise the history of the observed air parcels.

Much effort has been devoted to assure data quality for all European stations, and for this purpose intercomparison experiments at system level as well as at algorithm level have been performed. The experimental intercomparison was made using transportable lidar systems. These were compared with each other in a first step, and then used for comparison with the fixed systems (Matthias *et al.*, 2001). The algorithm intercomparison was performed for both backscatter and extinction retrieval by using simulated elastic and Raman lidar signals (Boeckmann *et al.*, 2001).

The EARLINET project started on February 2000 with a duration of 3 years but the intention is to continue on a longer time scale. Regular measurements started on May 2000 and this is by far the largest data set on the vertical distribution of aerosol worldwide. In addition to the routine measurements, extended observations of Saharan dust episodes, mainly in the Mediterranean area, have been performed. The coordination of the special lidar measurements is performed by the lidar group of the National Technical University of Athens, using forecasted Saharan dust events data available on the World Wide Web (http://forecast.uoa.gr).

The use of all these data will contribute significantly to the quantification of aerosol concentrations, radiative properties, long-range transport and budget, and prediction of future trends. It will also contribute to improve model treatment on a wide range of scales and to a better exploitation of present and future data from satellite remote sensing for a variety of parameters.

Starting since May 2000, the lidar measurements performed in Tito Scalo have been collected and analysed. Preliminary results regarding the first year of measurements are presented and discussed in this paper.

2. Experimental

Two lidar systems are operational at IMAA in Potenza (Southern Italy, 40°36′N, 15°44′E, 820 m above sea level). The first lidar system is devoted to study tropospheric aerosols, while the second one is a Raman lidar devoted to water vapour measurements.

In this paper, we present aerosol measurements and for this reason a detailed description of the Raman lidar will not be reported here.

The aerosol lidar system is based on a Nd:YAG laser operating on fundamental, second and third harmonics with a repetition rate up to 20 Hz. The three harmonics are transmitted in a coaxial mode along the same optical path. The receiver consists of a vertically pointing telescope in Cassegrain configuration with a 0.5 m diameter primary mirror and a combined focal length of 5 m. The collected radiation is split into five channels by means of dichroic mirrors, and interferential filters are used to select the elastic backscattered radiation at 1064 nm, 532 nm and 355 nm, and the N_2 Raman shifted signals at 386.6 nm and 607.4 nm. Photomultiplier tubes are used as detectors. Signals from photomultipliers are amplified and sampled both in analog and photon counting mode. Analog signals are acquired by means of a digital oscilloscope (500 MHz) and a 12 bit transient digitizer board, while the photon counting chain is based on a fast discriminator (300 MHz) and a Multi Channel Scaler (MCS) board with a minimum dwell time of 5 ns. The overall lidar characteristics are reported in table II.

At present, the aerosol lidar system is used to perform two-wavelength tropospheric aerosol measurements. In particular, tropospheric aerosol observations are performed in terms of aerosol backscatter using the second (532 nm) and third (355 nm) harmonic of the Nd:YAG laser and in terms of aerosol extinction in the UV region. The aerosol extinction profiles are obtained using the Nitrogen Raman signals at 386.6 nm (Ansmann *et al.*, 1990). The other two channels at 1064 nm and 607.4 nm will be operational in the near future. Simultaneous measurements of two-wavelength aerosol backscatter and aerosol extinction allow the retrieval of important microphysical aerosol properties, such as size distribution (Sasano and Browell, 1989). By using the aerosol backscatter profile at 1064 nm and the aerosol extinction profile at 607.4 nm, it will also be possible to retrieve the refractive index (both real and imaginary part) (Böckmann and Niebsch, 1996; Müller *et al.*, 1998).

The lidar signals are integrated over 1 min, corresponding to 1200 laser shots, and with a vertical resolution of 15 m. So, the system measures the temporal evolution of atmospheric aerosol backscatter with high temporal and vertical resolutions.

3. Data analysis and results

Systematic aerosol lidar measurements in Tito Scalo (PZ) started in May 2000 on a regular base of three measurements per week according to the schedule of the EARLINET project. The two night time measurements have been performed every Monday and Thursday in a time window of $-2\,h \div +3\,h$ around sunset, while daytime measurements have been performed every Monday in a time window of $-1\,h \div +1\,h$ around 13:00 UTC. Daytime measurements provide aerosol backscatter profiles at both 355 nm and 532 nm, while during night time, Raman measurements are also possible providing aerosol extinction profiles at 355 nm.

Lidar measurements have been always performed following this schedule with the sole exception of prohibitive meteorological conditions. At the moment, in the period May 2000-October 2001, we have collected more than 35000 files, corresponding to about 600 h of measurements.

Minimum duration of a measurement is 60 min. Nevertheless, records of several hours, up to 16 h, of continuous measurements have also been carried out to monitor special events or to follow the evolution of the Planetary Boundary Layer (PBL). Row data are integrated over

1 min, corresponding to 1200 laser shots, and with a vertical resolution of 15 m; final aerosol backscatter profiles are obtained by averaging 30 single measurements corresponding to about 30 min and with a vertical resolution of 60 m, according to the EARLINET demand. Aerosol extinction profiles are also obtained on average of 30 single measurements, but in this case the vertical resolution varies from 60 m up to 350 m, depending on the statistics.

For daytime measurements, aerosol backscatter profiles at both 355 nm and 532 nm are retrieved starting from elastic lidar signals using an iterative procedure based on the assumption of constant extinction-to-backscatter ratio (lidar ratio) within the aerosol layer (Di Girolamo *et al.*, 1999). This assumption could be too strong in presence of various layers corresponding to different aerosol types with different optical thickness. In such a case, it is

Table II. IMAA-CNR aerosol lidar system.

Laser source: Nd: YAG laser (Continuum-NY60)			
Wavelength and pulse energy		1064 nm E_{MAX} = 600 mJ	
		532 nm E_{MAX} = 300 mJ	
		355 nm E_{MAX} = 170 mJ	
Maximum pulse repetition rate		20 Hz	
Beam divergence		< 0.5 mrad	
Pulse duration		5 ÷ 7 ns	
Receiver: Cassegrain telescope			
Primary mirror diameter		0.5 m	
Combined focal length		5 m	
Field of view		0.2 ÷ 2 mrad	
Spectral selection: Interference filter			
Wavelengths		355 nm, 532 nm, 387 nm, 607 nm, 1064 nm	
Bandwidth		< 1.0 nm	
Out of band rejection		$\leq 10^{-8}$	
Transmission efficiency		~ 35%	
Detectors: Photomultipliers			
THORN EMI 9202 QB		355 nm, 532 nm, 387 nm, 607 nm	
HAMAMATSU R1767		1064 nm	
Acquisition			
Photon counting		**Analog**	
EG&G Ortec Turbo MCS		IMETEC 12 bit transient digitizer	
Minimum dwell time	5 ns	Number of channels	2
Bandwidth	150 MHz	Sampling rate	30 MHz
		Min. sampling time	33 ns
PHILLIPS SCIENTIFIC		TEKTRONIX	
Fast discriminator		Digital oscilloscope	
Bandwidth	300 MHz	Number of channels	3
		Bandwidth	500 MHz

not possible to assume a constant value of the lidar ratio along all the path and then different values for different layers must be considered. The typical values of lidar ratio used are taken from literature with the support of the direct and independent aerosol extinction measurements at 355 nm performed in Tito Scalo during night time, when Raman measurements are available (Pappalardo *et al.*, 2000). In this case, no assumption on the lidar ratio values is required to retrieve the backscatter profile in the UV. At 532 nm the iterative procedure is still employed, also for night time measurements, but the values of the lidar ratio used in the algorithm are related to those measured at 355 nm. The aerosol extinction coefficient is determined from the N_2 Raman backscattering signals through the application of the algorithm proposed by Ansmann (Ansmann *et al.*, 1990, 1992). Both algorithms for the

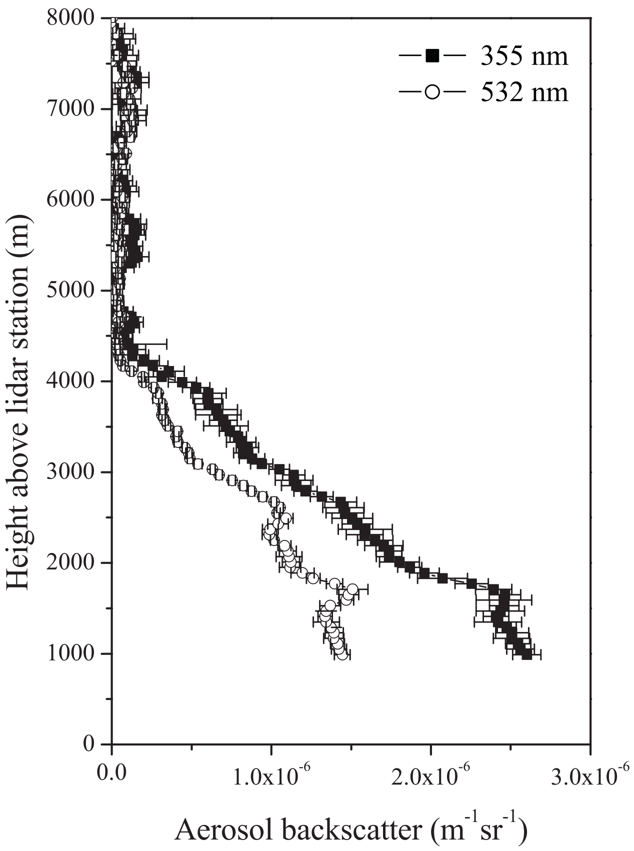

Fig. 2. Vertical profiles of the aerosol backscatter at both 355 nm (solid squares) and 532 nm (open circles) measured in Tito Scalo on 20 September 2000 (19:56-20:27 UTC).

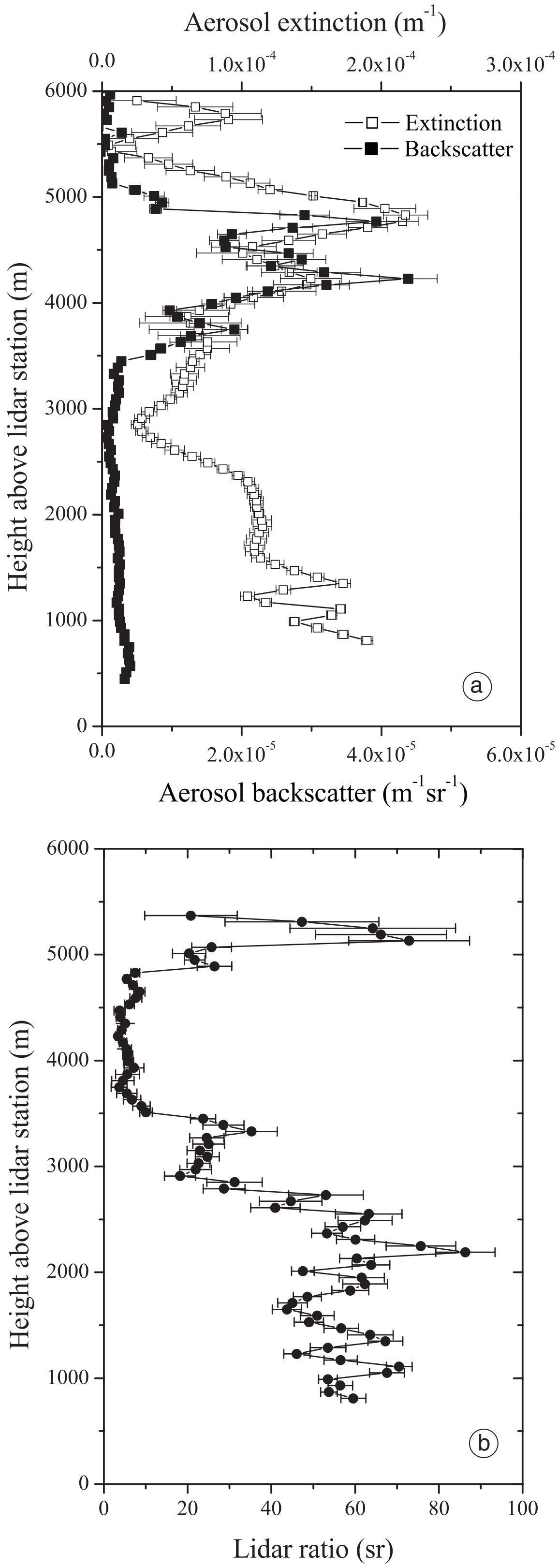

Fig. 3a,b. Vertical profiles of the aerosol backscatter (solid squares) and extinction (open squares) at 355 nm (a), vertical profile of the lidar ratio at 355 nm (b); Tito Scalo, 16 October 2000 (18:46 - 19:05 UTC).

aerosol backscatter and extinction retrieval have been successfully compared within the EARLINET community (Böckmann *et al.*, 2001).

Typical profiles of the aerosol backscatter at 532 nm and 355 nm obtained in Tito Scalo are shown in fig. 2; these profiles are typical for after sunset conditions. The aerosol backscatter profiles at both 355 nm and 532 nm extend up to 8 km of height and correspond to an integration time of about 30 min (36000 laser shots) with a vertical resolution of 60 m. Aerosol backscattering profile at 532 nm has been derived from the elastic lidar signal (Fernald, 1984; Di Girolamo *et al.*, 1999), while the aerosol backscatter profile at 355 nm has been derived from the simultaneous elastic lidar signal at 355 nm and the corresponding Raman Nitrogen signal at 386 nm (Ferrare *et al.*, 1998).

Figure 3a shows typical profiles of the aerosol backscatter and extinction. Both profiles extend up to 6 km of height above the lidar station. Clouds are present between 3800 m and 5000 m of height above lidar station. The corresponding lidar ratio profile, reported in fig. 3b, shows high values, ranging from 80 sr to 20 sr, at low height and up to the cloud base, with a mean value of 48 sr. Meanwhile, inside the cloud the lidar ratio decreases to lower values, ranging from 6 up to 20 sr with a mean value of 11 sr, in agreement with values reported by Ansmann *et al.* (1992).

The error bars reported in the figures refer to statistical errors that are calculated using a Montecarlo procedure. The Montecarlo procedure calculates the errors also in case of smoothed data, low statistics and extinction retrieval, when an analytical approach is not possible. This procedure is based on a random extraction of new lidar signals, each bin of which is considered as a sample element of a gaussian probability distribution with the experimentally observed mean value and standard deviation. The extracted lidar signals are then processed to retrieve a set of solutions from which the standard deviation as a function of the height is estimated. As shown in the figures, backscatter errors are within 10% up to 3.5 km and less than 20% in the cloud; regarding the extinction, errors are within 10% up to 2.5 km and less than 40% in the cloud.

As previously mentioned, more than 600 h of lidar measurements have been performed in Tito Scalo in the first year of systematic observations, but, to start a statistical analysis of the measurements, only 30 min per day, for both daytime and night time measurements, have been processed and analysed. Typical lidar profiles start from 650 m above the lidar station, where there is full overlap between the transmitted laser beam and the telescope field of view, and extend up to 8 km of height.

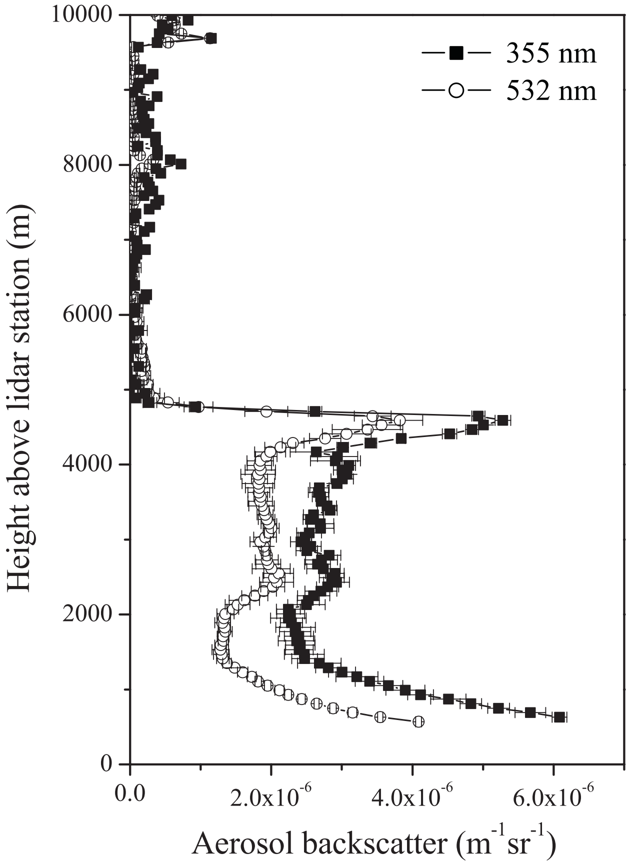

Fig. 4. Vertical profiles of the aerosol backscatter at both 355 nm (solid squares) and 532 nm (open circles) measured in tito Scalo on 31 August 2000 (19: 20 - 19:50 UTC).

In one year of measurements, many different meteorological conditions and presence of special events, such as forest fires and Saharan dust, have been monitored. As an example, fig. 4 shows a typical lidar profile of aerosol backscatter, at both 355 nm and 532 nm, in presence of Saharan dust. Figure 4 reports lidar measurements performed in Tito Scalo on 31 August 2000, in the case of a large Saharan dust event. Several distinct dust layers are present extending from 2 km up 5 km

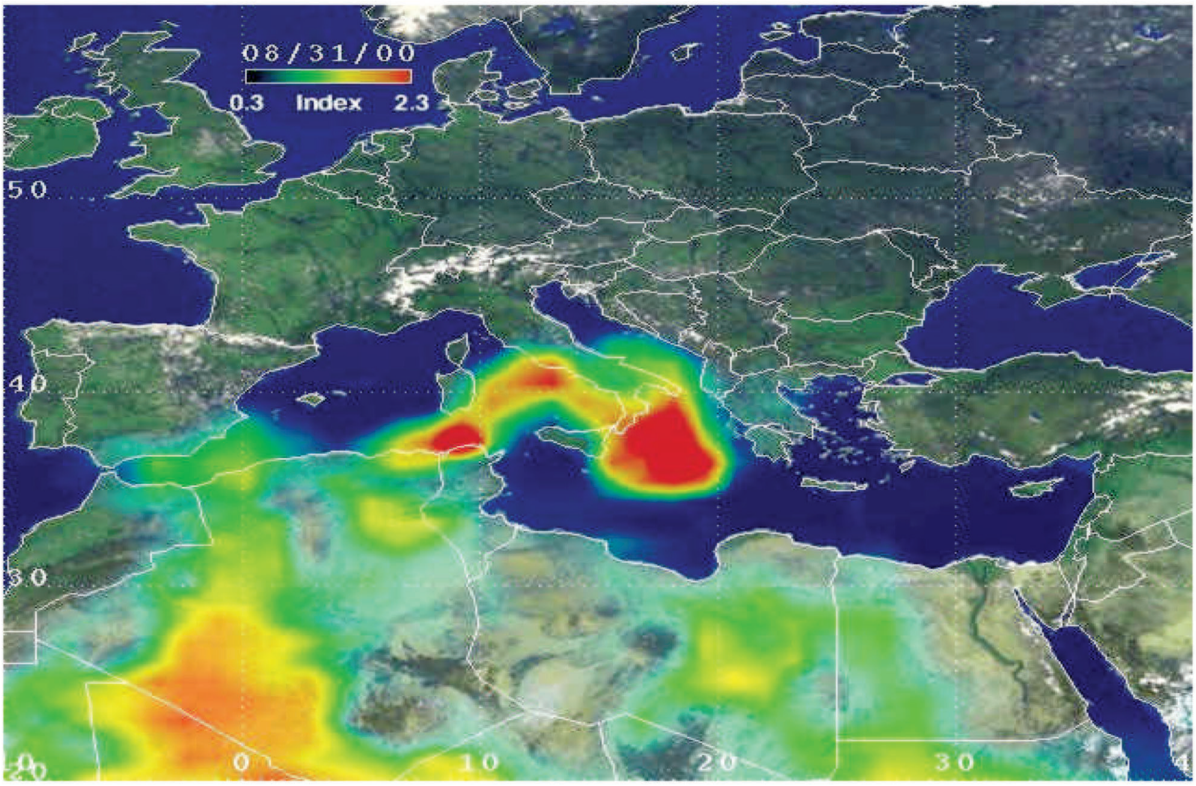

Fig. 5. The EP/TOMS aerosol index data for 31 August 2000.

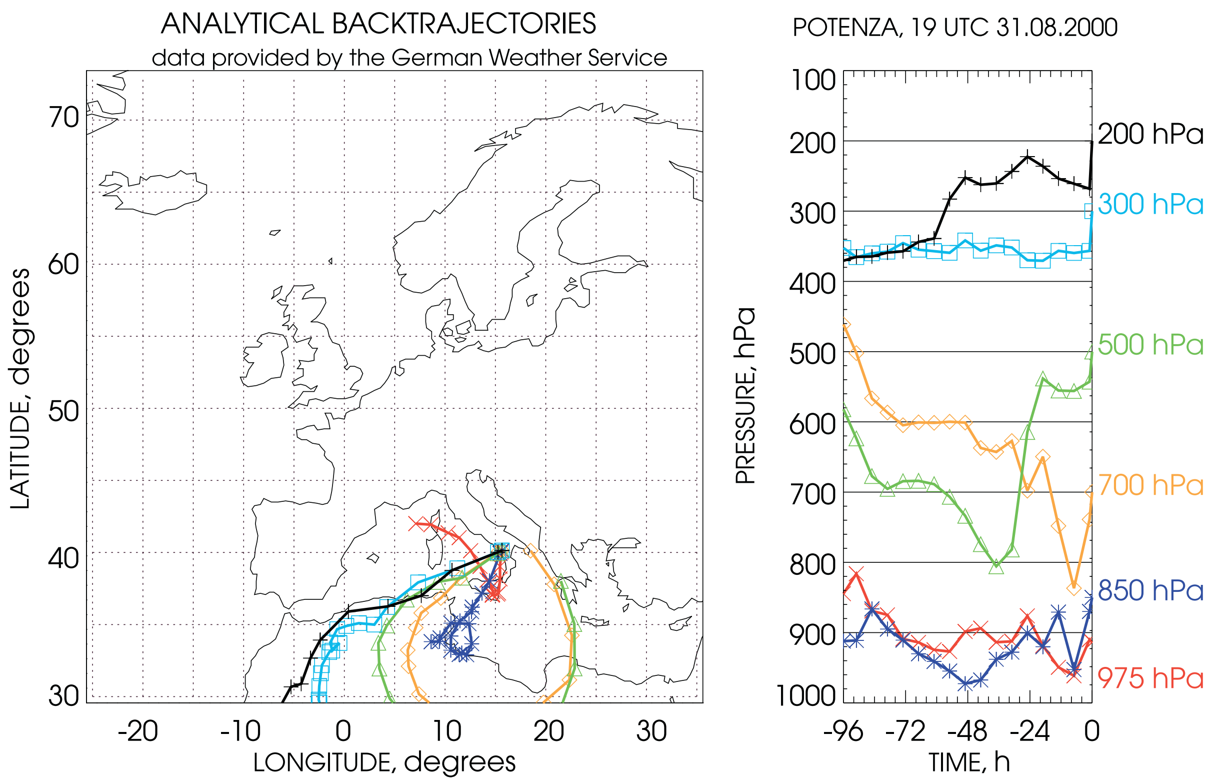

Fig. 6. 96-h air mass backtrajectory analysis for air masses ending over Potenza on 31 August, 2000 at 19 UTC.

above the lidar station, with a pronounced peak at 4.5 km of 5.3×10^{-6} m^{-1} sr^{-1} at 355 nm and 3.8×10^{-6} m^{-1} sr^{-1} at 532 nm. Figure 5 shows the image of the Total Ozone Mass Spectrometer (TOMS) for the same day where there is clear evidence of the presence of a large amount of aerosol above Southern Italy with an aerosol index of the order of 3. The 96-h backtrajectory analysis, provided by the German Weather Service, for the same day is reported in fig. 6. This figure shows clearly the Saharan origin of the dust layers observed in Tito Scalo; in particular, it is evident that the air masses ending over Tito Scalo (Potenza) at all levels (850-hPa up to 200-hPa) on 31 August, 2000 at 19 UTC had originated from the Saharan region, where probably they were enriched with large dust loads, explaining the presence of dust layers with the high aerosol backscatter values observed in Tito Scalo above 2 km of height.

In the following, we report the first preliminary results obtained from a statistical analysis of one year of systematic lidar measurements of aerosol backscatter and extinction performed in Tito Scalo.

Aerosol is typically present up to about 2.5 km of height during spring-summer period and up to about 2 km during autumn-winter (PBL plus residual layer). In case of special events such as Saharan dust outbreaks, forest fires or Etna eruption, dust layers at higher altitudes are observed. In the first kilometer of height above the lidar station, representative of the PBL and of a part of the residual layer, peak values of aerosol backscatter of 1×10^{-5} $m^{-1}sr^{-1}$ at 355 nm and 5×10^{-6} $m^{-1}sr^{-1}$ at 532 nm were observed during summertime. Aerosol backscatter mean values calculated during the whole first year of measurements are 6×10^{-6} $m^{-1}sr^{-1}$ at 355 nm and 3×10^{-6} $m^{-1}sr^{-1}$ at 532 nm during summertime and 3×10^{-6} $m^{-1}sr^{-1}$ at 355 nm and 2×10^{-6} $m^{-1}sr^{-1}$ at 532 nm during wintertime. Peak values of the aerosol extinction profile, always in the first kilometer of height above the lidar station, of about 3×10^{-4} m^{-1} have been observed in summertime, while mean values are around 4×10^{-5} m^{-1} in summertime and 2×10^{-5} m^{-1} in wintertime.

Figure 7a shows the integrated aerosol backscatter (IB) at 355 nm and fig. 7b at 532 nm for all the night time measurements. The data have been integrated along the whole aerosol layer inclusive also of layers present at higher altitude due to special conditions. The selection of the integral limits for the calculation of IB is decided case by case considering the lowest probed height and the highest height affected by an uncertainty less than 15% for the aerosol backscatter. This choice depends on the fact that we intend to start the analysis of our data by considering the whole amount of aerosol that we can measure in the low troposphere. Lidar data with clouds are not considered for this analysis.

In fig. 7a,b, special measurements, related to the presence of Saharan dust, are reported in a different colour (black). It must be pointed out that Saharan dust events are also observed during the autumn-winter period. The values of the integrated aerosol backscatter range from 2×10^{-4} sr^{-1} to 1×10^{-2} sr^{-1} with a mean value of 4×10^{-3} sr^{-1} at 355 nm and from 1×10^{-4} sr^{-1} to 1×10^{-2} sr^{-1} with a mean value of 2.3×10^{-3} sr^{-1} at 532 nm. Peak values are evident in June for both wavelengths, and summertime period seems to be characterised by higher values with respect to the wintertime period. Data related to Saharan dust observations seem to be not affected by this seasonal variation and are characterised by mean values of about 5.3×10^{-3} sr^{-1} at 355 nm and 3.6×10^{-3} sr^{-1} at 532 nm.

Figure 8 shows the integrated aerosol extinction (*i.e.* the optical thickness τ_A) obtained from Nitrogen Raman measurements at 355 nm. In the figure, both regular and special (Saharan dust) measurements are reported and also in this case the data are integrated in the whole aerosol layer. The selection of the integral limits for the calculation of τ_A is again decided case by case considering the lowest probed height and the highest height affected by an uncertainty less than 30% for the aerosol extinction. The values of τ_A range from 0.02 to 0.75 with a mean value of 0.2. Higher values are evident in the period May - September 2000, while autumn-winter time is characterised by lower values of aerosol extinction. Aerosol extinction profiles are not so numerous as backscatter profiles, because sometimes it is not possible to retrieve the aerosol extinction profile from Raman channel due to low statistics. From fig. 8 we observe that also for extinction measurements it seems that Saharan dust data do not follow the typical

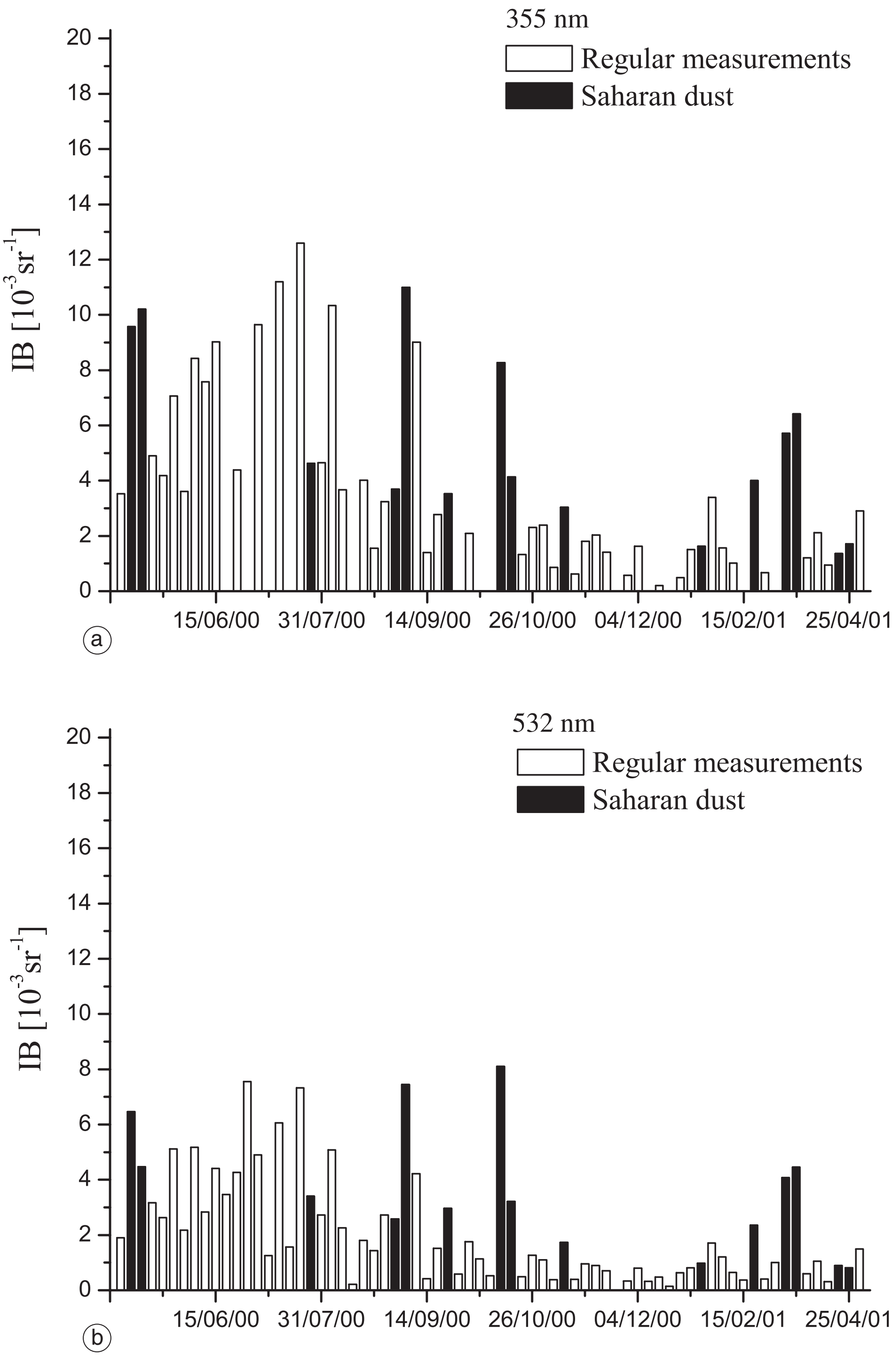

Fig. 7a,b. Integrated aerosol backscatter at 355 nm (a) and 532 nm (b) for all night time lidar measurements in Tito Scalo in the period May 2000 - April 2001. Regular measurements are reported in white, Saharan dust measurements are reported in black.

seasonal variation we observed in Tito Scalo under normal conditions. Moreover, the values of τ_A recorded during Saharan dust episodes are the highest we observed in wintertime.

Figure 9 reports the mean lidar ratio values obtained for each measurement (both regular and special) in the whole aerosol layer (PBL, residual layer, and higher dust layers when pre-

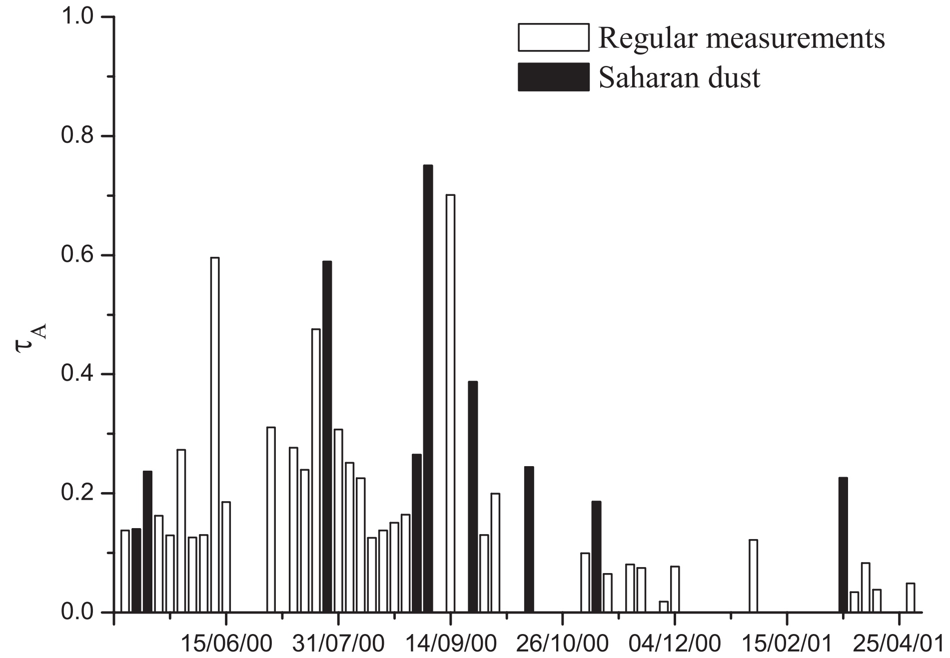

Fig. 8. Integrated aerosol extinction at 355 nm for all night time lidar measurements in Tito Scalo in the period May 2000 - April 2001. Regular measurements are reported in white, Saharan dust measurements are reported in black.

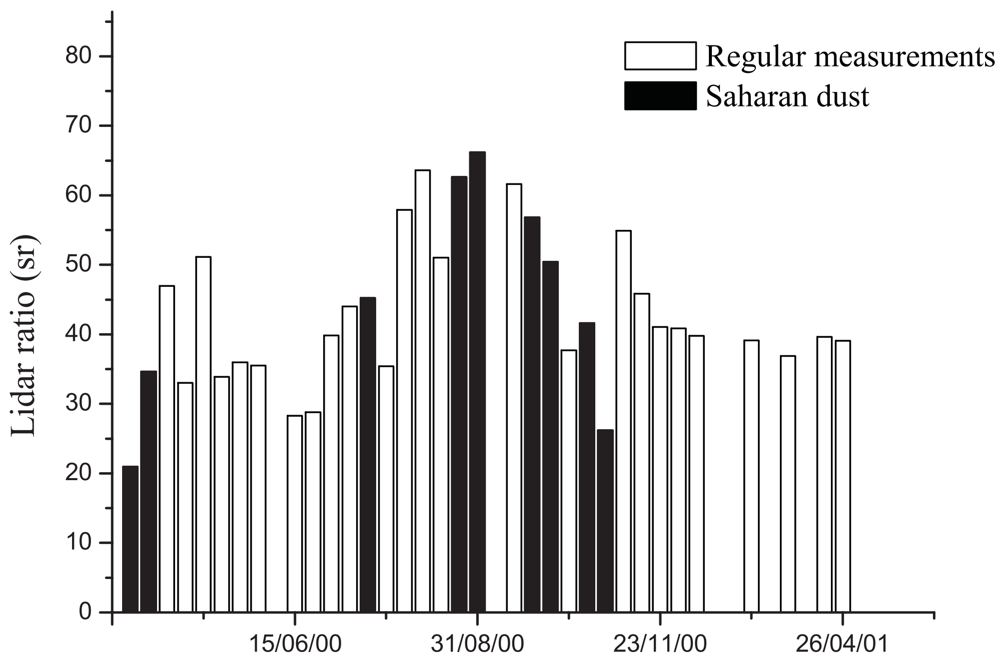

Fig. 9. Mean lidar ratio values at 355 nm for all night time lidar measurements in Tito Scalo in the period May 2000 - April 2001. Regular measurements are reported in white, Saharan dust measurements are reported in black.

sent). Lidar ratio values range from 25 to 65 sr, with higher values in summer period. Again it seems that Saharan dust data are not affected by seasonal variation. The mean value of the lidar ratio for the whole aerosol layer in one year of systematic observations is 43 ± 11 sr. Higher values of the lidar ratio, observed in spring-summer period, can be attributed to the presence

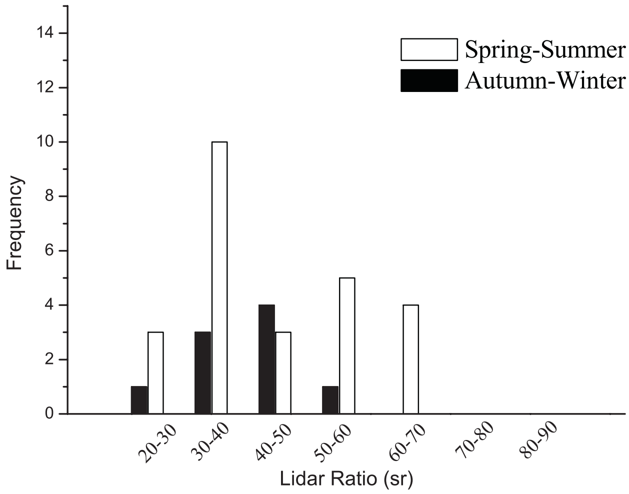

Fig. 10. Frequency of the monthly averaged lidar ratio values at 355 nm for both spring-summer (April-September) and autumn-winter (October-March) periods.

of high absorbing particles which results also in the higher extinction values shown in fig. 8, as well as to the presence of a high concentration of small particles originated primarily by forest fires, very common in this period of the year in our area (Anderson *et al.*, 2000).

In fig. 10, we report the frequency of the monthly averaged lidar ratio values for both spring-summer (April-September) and autumn-winter (October-March) periods. We considered 10 sr intervals starting from 20 sr up to 90 sr. It is evident in fig. 10 that spring summertime values are higher and more wide spread with respect to the wintertime values. If we assume an almost Gaussian distribution for both autumn-winter and spring-summer values, we obtain a central value of 41 sr with $\sigma = 8$ sr and central value of 44 sr with $\sigma = 12$ sr, respectively. Different factors could contribute to the wider variability observed for the summertime period. Among others, the presence of many forest fires, with the consequent production of small particles of ash and soot in the atmosphere, the more intense rural activity and the more effective air mass transport, all these resulting in a larger variability of the aerosol types with respect to a more stagnant condition characteristic of the wintertime period (Anderson *et al.*, 2000; Ackermann, 1998; Evans, 1988).

4. Conclusions

Systematic lidar measurements of aerosol backscatter and extinction have been made since May 2000 in Tito Scalo (PZ) Southern Italy in the framework of the EARLINET project. Backscatter measurements have been performed at both 355 nm and 532 nm, while aerosol extinction measurements, through the application of the Raman lidar technique, have been performed at 355 nm. Beyond lidar measurements performed three times per week on a regular schedule, further special lidar observations have been devoted to study Saharan dust outbreaks.

Preliminary results obtained starting from a statistical analysis of the first year of measurements in Tito Scalo have been reported. Seasonal variations have been observed for aerosol integrated backscatter and extinction.

In the near future these data will be compared with data of other stations of the EARLINET project with the main goal of studying vertical and horizontal transport of the aerosol over Europe. The use of these data will also contribute to improve model treatment on a wide range of scales and to a better exploitation of present and future data from satellite remote sensing for a variety of parameters.

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