Systematic lidar observations of Saharan dust layers over Athens, Greece, in the frame of the EARLINET project (2004-2006)

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ABSTRACT

We present a statistical analysis of Saharan dust events observed over Athens, Greece, in a three-year period from January 1, 2004 up to December 31, 2006. The observations of the vertical aerosol profile were performed by the multi-wavelength (355-532-1064-387-607 nm) Raman lidar system of the National Technical University of Athens (NTUA) operated in the city of Athens (37°98' N, 23°77' E), Greece, in the frame of the European Aerosol Research Lidar Network (EARLINET-ASOS) project. The number of dust events was greatest in late spring, summer, and early autumn periods. Multiple aerosol dust layers of variable thickness (680-4800 m) were observed. The center of mass of these layers was located in altitudes between 1600 and 5800 m. However, the mean thickness of the dust layer typically stayed around 2700 m and the corresponding mean center of mass was of the order of 2900 m. The top of the dust layer ranged from 2000 to 8000 m, with a mean value of the order of 4700 m. Mean aerosol optical depths (AOD) and extinction-to-backscatter ratios (lidar ratios, LR) of the desert aerosols ranged from 0.35 to 0.65 at 550 nm, and from 40 to 100 sr at 355 nm, respectively, within the lofted dust plumes.

1. INTRODUCTION

Aerosols are very important constituents of the atmosphere. They scatter and absorb solar and terrestrial radiation **(**direct effect) and alter the physical, optical, and lifetime properties of clouds and thus the precipitation formation **(**indirect effect), as they act as cloud condensation nuclei [1]. Mineral dust is an important component of the atmospheric aerosol loading. It is estimated that the mineral dust accounts for about 75% of the global aerosol mass load and 25% of the global aerosol optical depth [2]. The African continent, especially its northern part (Sahara desert), the Saudi Arabian regions, as well as the Asian continent (eastern areas), are the main sources of dust around the globe [3-5].

In the frame of the EARLINET [6] and the EARLINET-ASOS projects [7] special emphasis was given to monitor the optical properties of dust particles in the Eastern Mediterranean region, as obtained by the analysis of lidar data obtained during case studies of specific dust outbreaks occurred over Greece [8-9].

In this paper we present a statistical analysis of the Sahara dust events observed over Athens, Greece, in a three-year period from January 1, 2004 up to December 31, 2006. Section 2 of this paper gives a brief presentation of the lidar measurements over Athens, as well as a brief description of the BSC Dust Regional Atmospheric Model (BSC/DREAM). It presents also the criteria applied to characterize an aerosol layer as dust layer and discuss the monthly averages of dust occurrences observed and forecasted over Athens. Section 3 focuses on the lidar data analysis, supported by satellite (MODIS: Moderate Resolution Imaging Spectroradiometer) aerosol observations, during dust events in the reported period. Finally, Section 4 presents our concluding remarks.

2. METHODOLOGY AND MEASUREMENTS

2.1 Lidar measurements over Athens within EARLINET

The lidar system of the National Technical University of Athens (NTUA) is located at the NTUA Campus (37.97^{o}N, 23.79^{o}E, 200 m above sea level-asl.). It started performing systematic measurements on February 2000, as an elastic backscatter lidar system to measure the vertical profiles of the aerosol backscatter coefficients at 355 and 532 nm. Later, the system undertook major hardware upgrades (e.g. on mid-2001 addition of a Raman (N_2) channel at 387 nm, redesign of the detection box and its optical components during the year 2003, late 2007 and early 2008 addition of a Raman (N_2) channel at 607 nm, and finally on late 2008 use of new interference filters at 387 and 607 nm) to provide, independently, the vertical profiles of the aerosol backscatter and extinction coefficients at both 355 and 532 nm. Therefore, the selected period of measurements (January 1, 2004 up to December 31, 2006) provides homogeneous lidar data during a period of 3 full years.

In order to get reliable and quantitative lidar aerosol data several techniques and methods have to be combined. For example, the standard backscatter lidar technique is appropriate to retrieve the aerosol backscatter profile (b_{aer}) mostly for small optical depths, as in clean areas, assuming a reference height in an aerosol-free area (upper troposphere) [10]. The resulting average uncertainty on the retrieval of b_{aer} (including both statistical and systematic errors and corresponding to 30-60 min. temporal resolution) in the troposphere is of the order of 20-30% [6]. To overcome this large uncertainty associated with this technique, the Raman N_2 lidar technique was adopted and implemented [11], as discussed previously. In this case, the uncertainties of the retrieved b_{aer} vertical profiles are of the order of 10-15%. The vertical profiles of b_{aer} referring to measurements performed before the local sunset time (~19:00 UT) were retrieved by using the Klett technique [10], assuming a lidar ratio value equal to 45 sr. This value is typical for a

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mixture of dust and marine aerosols at mid-latitudes [8]. Since the Raman lidar signals have a very low intensity, the Raman lidar measurements are possible only during nighttime conditions.

2.2 The BSC/DREAM dust model

The dust forecast is based on the operational outputs (aerosol dust load) of the BSC/DREAM model(http://www.bsc.es/projects/earthscience/DREAM/) [12]. The model simulates or predicts the 3-dimensional field of the dust concentration in the troposphere. The resolution of the model is set to 50 km in the horizontal and to 15 km in the vertical. Recently, BSC/DREAM was coupled to the combined photochemical forecast MM5-EMEP-CMAQ modelling system to provide an integrated air quality model with remarkable improvement in the discrete and skill-scores evaluation of PM_{10} exceeds in the Iberian Peninsula [13].

2.3 Dust events occurrences

A set of three criteria has been applied to characterize the aerosol lidar data as “Saharan dust” profiles following the directions given by Papayannis et al. [8]: a) presence of a distinct aerosol dust layer using the first derivative of the lidar signal, b) aerosol layer’s origin is the Saharan region and c) forecast by the BSC/DREAM model. Following those criteria over 3 years of regular and special measurements, we identified aerosol layers related to Saharan dust outbreaks for a total of 79 days. The relative monthly distribution of the number of observed/forecasted dust days is presented in Fig.1 (hatched/white columns). We see that two relative maxima are observed in May and September, while the larger number of Saharan dust observations is found in the April-September period (Fig. 1). The low number of dust intrusions during the cold period (October-March) can be related to the low dust emission over the Saharan region typical of this period [5], the possible aerosol wash-out during their way to Europe and to the strong seasonal behaviour of the dust transport in the Mediterranean area [8].

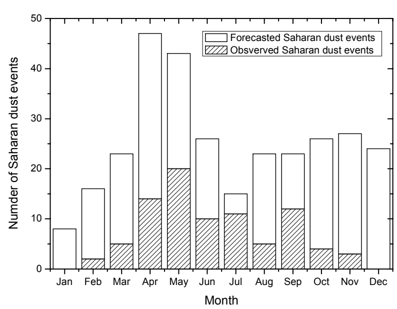

Figure 1. *Number of days per month in which Saharan dust intrusions wee forecasted and observed over Athens during 3 years of lidar measurements (January 2004-December 2006).*

In this paper we decided to consider for our statistical analysis only the strong dust events over our site, for which the forecasted total dust load was higher than 1.0 g/m^2 (equivalent to AOD>0.5 at 550 nm) [14]. Using this criterion we limited our aerosol vertical profiles to 40 out of the 79 available days (Fig. 2). From that figure we see that two maxima are observed: May and September. For the rest of the months, the observed number of dust events follows a nearly Gaussian distribution, centred around June. Ancillary observations to locate the Saharan dust plume over a measuring site included satellite aerosol-related data [aerosol load from MODIS (Moderate Resolution Imaging Spectroradiometer) and real-color pictures from the SeaWiFS (Sea-viewing Wide Field-of-view Sensor) sensors] for mutual comparison with the aerosol data from dust forecast models were used. Cloud screening (water or ice clouds) is performed prior to the storage of the data into the central database.

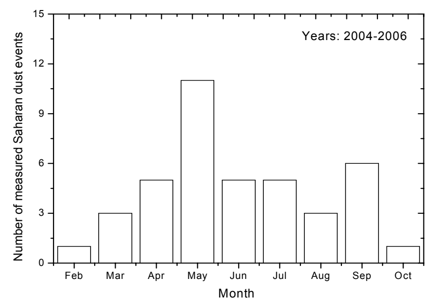

Figure 2. *Number of days per month in which strong Saharan dust intrusions were observed over Athens during 3 years of lidar measurements (January 2004-December 2006).*

3. RESULTS AND DISCUSSION

In this section we focus on the statistical analysis of the vertical aerosol profiles during Saharan dust events concerning the aerosol dust layering and the integrated backscatter values.

When the lidar technique is applied to characterize the aerosol vertical profile during a dust event, the following layer properties can be derived from the aerosol backscatter profile: the top (z_t), base (z_b), layer thickness and centre of mass, following the procedure proposed by Mona et al. [15]. Thus, the base of the dust aerosol layer corresponds to the lowest point of a strong increase in the aerosol backscatter profile over the retrieved Planetary Boundary Layer (PBL) height. On the other hand the top of the desert dust layer is located at an altitude at which the aerosol backscatter becomes zero within the experimental error. Knowing the base and the top of the dust layer, its thickness can be calculated. The center of mass is estimated by the calculation of the backscatter weighted altitude (z_c) [15], where β represents the aerosol backscatter coefficient:

$$z_c = \frac{\int_{z_b}^{z_t} z \cdot \beta(z) dz}{\int_{z_b}^{z_t} \beta(z) dz}$$

Thus, the estimate of the center of mass gives us information about the altitude where the most relevant part of the aerosol load is located [15].

Following the above mentioned methodology, we calculated the base, the top, the center of mass and the thickness of each Saharan dust profile for our selected cases.

We thus, found, that for the discussed period (January 2004-December 2006), multiple aerosol dust layers of variable thickness (680–4800 m) were observed. The center of mass of these layers was located in altitudes between 1600-5800 m. The mean thickness of the dust layer typically stayed around 2700 m and the corresponding mean center of mass was of the order of 2900 m. The top of the dust layer ranged from 2000 to 8000 m, with a mean value of the order of 4700 m. The base of the dust layer typically stayed around 1960 m, with values ranging from 1200 and 3740 m.

These findings, for most of these variables, are consistent (less than 8% difference is found) with the respective results given for the station of Athens by Papayannis et al. [8] for the period May 2000-December 2002. The exception holds for the mean values of dust layer thickness and center of mass (differences of the order of 20-22% were found), as well as for the base (max value) and thickness (min value) of the dust layer, where differences of the order of 20-26% were observed.

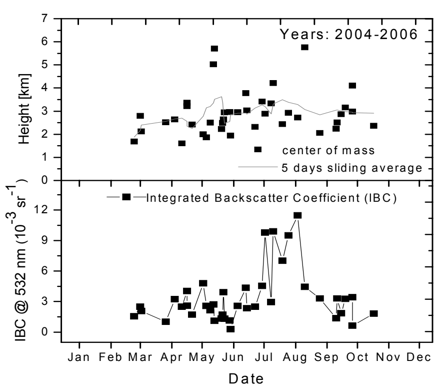

Figure 3*. Annual cycle of the backscatter weighted altitude of the desert dust layer (z_c) (upper part) and of the integrated backscatter coefficient (IBC) (lower part) for the three-years period (January 2004-December 2006). The solid line in the upper figure is the 5-days sliding average.*

In Figure 3-upper part we present the annual cycle of the backscatter weighted altitude of the desert dust layer (z_c) and in the lower part the integrated backscatter coefficient (IBC) for the selected period, both retrieved from lidar backscatter data obtained at 532 nm. The solid line in the upper figure is the 5-days sliding average. We observe an intense variability of the center of mass altitude during May and August, which are the months with the higher dust loadings, the stronger dust events and hence, in this period the stronger dust variability may occur [8].

From the IBC annual variability we conclude that even if the occurrences of dust episodes are more often during spring, their intensity is higher on late summer. These findings are in agreement with those of Mona et al. [15]. In that study, the authors observed these maxima on optical depth at 355 nm over Italy mainly during late summer.

4. CONCLUSIONS

The main aim of this work was to present a statistical analysis on the geometrical properties of Saharan dust vertical distribution over Athens, Greece, for a three year period lidar measurements (2004-2006). Springtime (April-May) is the period of the maximum dust event occurrence as indicated both from lidar and MODIS measurements. Lidar observations reported multiple aerosol dust layer and variable thickness (680-4800 m) appearances. The mean center of mass of these layers was approximately calculated at 2900 m, with limited cases of events reaching altitudes over 5000 m. In addition, mean layer thickness was found to be 2700 m and mean top of the layer at 4800 m.

BSC/DREAM model aerosol dust climatology showed also predominant dust events for April and May periods. In addition, comparison of lidar retrieved backscatter coefficients and model calculated dust load showed fairly good agreement comparing the vertical profiles of dust aerosols. Trying to quantify the dust contribution to the Athens area, except from the obvious facts of its contribution to the spring months but also to the June-September period, we have to keep in mind that lidar dust analysis becomes difficult with the presence of clouds.

Using only lidar or sun-photometric dust climatology data, this leads to an underestimation of the dust effect especially in the winter months were the presence of clouds is more often. In the present study only 2 dust cases have been reported from lidar measurements during the winter period.

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REFERENCES

[1] Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M., Van Dorland, R., 2007: Changes in Atmospheric Constituents and in Radiative Forcing. *In: Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor and H. L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

[2] Kinne, S., et al., 2006: AeroCom initial assessment: Optical properties in aerosol component modules of global models, *Atmospheric Chemistry and Physics*, **6**, pp. 1815–1834.

[3] Duce, R.A., 1995: Sources, distribution and fluxes of mineral aerosols and their relationship to climate.

Aerosol Forcing on Climate, Carlson, R.J., and Heintzenberg, J., (Eds.), Wiley, New York, pp. 43-72.

[4] Laurent, B., B. Marticorena, G. Bergametti, J. F. Léon, N. M. Mahowald, 2008: Modeling mineral dust emissions from the Sahara desert using new surface properties and soil database, *Journal of Geophysical Research*, **113**, D14218, doi:10.1029/2007JD009484.

[5] Marticorena, B., G. Bergametti, B. Aumont, Y. Callot, C. N'Doumé, M. Legrand, 1997: Modeling the atmospheric dust cycle: 2. Simulation of Saharan dust sources, *Journal of Geophysical Research*, **102**, pp. 4387-4404, 1997.

[6] Bösenberg, J. et al., 2003: A European aerosol research lidar network to establish an aerosol climatology, *MPI-Report*, pp. 317, Max-Planck Inst. für Meteorology, Hamburg, Germany.

[7] Pappalardo, G., et al., 2009: EARLINET coordinated lidar observations of Saharan dust events on continental scale, *IOP Conf. Series: Earth and Environmental Science*, **7**, 012002, doi:10.1088/1755-1307/7/1/012002.

[8] Papayannis, A., et al., 2008: Systematic lidar observations of Saharan dust over Europe in the frame of EARLINET (2000-2002), *Journal of Geophysical Research*, **113**, D10204, doi:10.1029/2007JD009028.

[9] Amiridis, V., D. Balis, S. Kazadzis, A. Bais, E. Giannakaki, A. Papayannis, C. Zerefos, 2005: Four-year aerosol observations with a Raman lidar at Thessaloniki, Greece, in the framework of European Aerosol Research Lidar Network (EARLINET), *Journal of Geophysical Research*, **110**, D21203, doi:10.1029/2005JD006190.

[10] Klett J.D., 1985: Lidar inversion with variable backscatter/extinction ratios, *Applied Opt*ics, **24**, pp. 1638-1643.

[11] Ansmann A., M. Riedesell, U. Wandinger, C. Weitkamp, E. Voss, W. Lahmann, W. Michaelis, 1992: Combined Raman Elastic-Backscatter lidar for vertical profiling of moisture, aerosol extinction, backscatter, and lidar ratio, *Applied Physics*, **B55**, pp. 18-28.

[12] Nickovic, S., G. Kallos, A. Papadopoulos, O. Kakaliagou, 2001: A model for prediction of desert dust cycle in the atmosphere, *Journal of Geophysical Research*, **106**, pp. 18113-18129.

[13] Jiménez-Guerrero, P., C. Pérez, O. Jobra, J. Baldasano, 2008: Contribution of Saharan dust in an ingrated air quality system and its on-line assessment, *Geophysical Research Letters*, **35**, L03814, doi:10.1029/2007GL031580.