Aerosol-cloud interaction by lidar technique

O. Lecocq

Department of Applied Physics, University of Granada (Spain)

Abstract. Atmospheric aerosols have a strong impact on Earth's climate. However, the quantification of their influence is far from being completely achieved. One of the main sources of uncertainty about their effects resides in their still poorly understood interaction with clouds, which substantially affect their radiative forcing. This work presents the study of aerosol-cloud interaction by means of an elastic lidar system. It aims at understanding two features of the interaction. The influence of the relative position between cloud and aerosol layers as well as the change of aerosol optical properties in the forming stage of a cloud have been analyzed.

Keywords: aerosol, clouds, elastic lidar, interaction, interaction distance, twilight zone.

INTRODUCTION

Aerosol particles influence Earth's climate in many different ways. They directly affect the radiative balance by their interaction with short- and long-wave radiation. Their interaction with clouds, however, brings one of the main sources of uncertainty in climate studies. The mutual interaction between clouds and aerosol can affect greatly the net radiative forcing of aerosol particles. First, it has been documented that an increase in particles acting as cloud condensation nuclei can lead to an increase of the droplet number concentration, inducing a reduction of the mean droplet size. Smaller and more numerous droplets are linked with more reflecting clouds. This effect is known as the Twomey effect, or aerosol first indirect effect [1]. In this regard aerosol can thus have an indirect negative forcing on the climate. Besides of this, the collision-coalescence process can be diminished in contaminated clouds, altering precipitation patterns [2]. This "Albrecht effect" can extend the lifetime of clouds and thereby alter the radiative budget [3]. Absorbing aerosol particles can also prevent clouds growth, evaporate existing one and reduce surface heating [4]. Despite their capital influence on Earth's energy budget, these phenomena are still very poorly understood and inadequately quantified.

Many studies have been conducted to characterize the Twomey effect, most of them based on satellite data [e.g. 5]. However, one of the uncertainties lies in the influence of the relative altitude of aerosol and cloud layers. In other words, an interaction is clearly occurring but it is unclear until what distance it can be considered as significant. A few studies addressed this issue, but the threshold distance is still not obvious [6; 7]. In this context, lidar techniques are very helpful since they provide vertical profiles of aerosol and cloud features, enabling the analysis of aerosol and cloud properties simultaneously over a given place. This work is partially devoted to the study of the height-dependence of aerosol-cloud interactions.

It has also been suggested that the interaction between cloud and aerosol is not confined to the strict duration of the observable cloud [8]. Optical properties of aerosol particles may change in the temporal vicinity of a cloud. Again, the high spatial and temporal resolution of lidar profiles allows for the study of the evolution of aerosol optical properties during formation and disappearing stages of a cloud. The second part of this work will be dedicated to the analysis of aerosol optical properties during cloud formation process.

II. INSTRUMENTATION

This study has been performed by means of a Raman lidar model LR331D400 (Raymetrics, Greece). This lidar is operated routinely and during special campaigns at the Andalusian Institute for Earth System Research (IISTA-CEAMA, Granada, Spain). The station is member of EARLINET (European Aerosol Research Lidar Network) and AERONET (Aerosol Robotic Network). The lidar operates with a Nd:YAG (Neodymium-doped Yttrium Aluminum Garnet) laser at the fundamental wavelength of 1064 nm, and second and third harmonics at 532 and 355 nm, respectively. It has been operated with a pulse repetition frequency of 10 Hz. Although it can retrieve elastically and inelastically backscattered signals, only elastic signals have been used. Backscattered signal are registered at 1 min intervals and have a 7.5 m vertical resolution.

Additional data from the Granada station's SONA cloud camera and from sun-photometer data available on the AERONET website have been used as ancillary source of information.

III. METHODOLOGY

The aerosol indirect effect can be defined as the change in cloud optical or microphysical properties as a function of the change in aerosol load. Thus, the aerosol-cloud interaction (ACI) has to be quantified by some relation between the two parameters. Various relations are found in the literature [e.g. 9;10]. Because aerosol integrated backscatter (IB_{part}) and cloud integrated backscatter (IB_{cloud}) can easily be derived from lidar observations, ACI indexes are calculated in this study using the following equation:

$$ACI_{index} = \frac{\partial \ln IB_{cloud}}{\partial \ln IB_{part}} \quad (1)$$

Therefore, ACI_{index} is calculated as the slope of the linear regression of $ln(IB_{cloud})$ as a function of $ln(IB_{part})$.

The simultaneous measurements of IB_{cloud} and IB_{part} were obtained by integration of the backscatter profile using the Klett-Fernald method [11;12]. Since this method requires the previous knowledge of the aerosol type, ancillary information, such as AERONET sun-photometer data and aerosol models (NAAPS, SKIRON and BSC DREAM8b) has been consulted. Background, dark current and range corrections were applied to the signal before obtaining the profiles. Backscatter profiles at altitudes of incomplete overlap were modeled assuming a height-independent backscatter that matches the first reliable value where the full overlap is reached. Lidar data were average over 10 min for the vertical interaction and over 5 min for the temporal evolution of aerosol optical properties. The interaction distance, *d*, has been taken as the vertical distance between the cloud base and the top of the underlying aerosol layer.

IV. RESULTS AND DISCUSSION

A. Aerosol-Cloud Interaction in the Vertical Coordinate

A selection of cases covering a wide range of interaction distances *d* between aerosol and cloud layers, from complete coupling to large separation distances has been done with the aid of time series of range corrected signals (RCS), available on the GFAT webpage (atmosfera.ugr.es). The entire data base (starting from February 20007 to May 2014) has been consulted. Data corresponding to part of the selected days with the targeted conditions has been separated into intervals of 10 min. In total, 520 profiles were potentially available. However, only 35 of them (about 7%) could be used as most of the data failed to generate valid lidar profiles. This is due to the high optical thickness of clouds which made that in most of the cases, the laser beam did not make its way through the cloud, resulting in very noisy profiles or no information above it. Unfortunately, the above-cloud part of the signal is needed to calibrate the profile. It is very important to note that the data base used was only dedicated to the characterization of aerosol particles without regards to the clouds, and generally cloudy days are discarded. The goal behind these measurements is thus far from ACI considerations. This explains the small number of profiles finally used.

The ACI_{index} was calculated at 532 and 1064 nm for $d < 250$ m and $d > 250$ m for days with predominant mineral dust aerosol during summer months. For $d < 250$ m, the ACI_{index} has a value of -3.0 $\pm$ 0.5 at 532 nm, and -2.4 $\pm$ 0.7 at 1064 nm. The same difference between the channels is found between for the R_{corr} coefficient, taking values of 0.85 at 532 nm whereas it only reaches 0.75 at 1064 nm. This suggests that the 532 nm channel performs better at highlighting the ACI. The reason for this lies in the spectral dependence of the aerosol, which is greater than that of the cloud. This leads to a greater value of IB_{part} at 532 nm, with an IB_{cloud} similar at both wavelengths, resulting in a greater slope of the regression line taken as ACI_{index}. This effect will be stronger as the spectral dependency of the aerosol is higher.

As expected, the ACI_{index} for $d > 250$ m is much smaller. Its value is -0.9 $\pm$ 1.5 and -0.5 $\pm$ 0.9, respectively for the 532 and 1064 nm channels. The observed decrease of the ACI with increasing *d* is consistent with results found in the literature [e.g. 6;7].

B. Temporal Evolution of Aerosol Particle Properties in the Twilight Zone

As suggested by [8], the interaction between clouds and aerosol may not be confined only to the interval in which a cloud can actually be observed. In this work an attempt was made to verify the existence of the so-called twilight zone, by studying the temporal evolution of the IB_{part} and the backscatter-related Ångström exponent (AE) during the period preceding the cloud. The 23^{rd} of May 2013, day during which the gradual formation of a cloud could be observed was selected with the aid of RCS time series. The predominant aerosol is from anthropogenic origin. The corresponding data was separated into intervals of 5 min. The IB was computed between 2000 and 3000 m, height range where the cloud is eventually appearing. The mean backscatter-related AE was calculated with two pairs of wavelength (AE 355-532, AE 532-1064). The results have shown that the IB is gradually rising before the cloud (+50% between 20:00 and 20:30 UTC, cloud is appearing around 20.40 UTC), and that the AE 532-1064 drops significantly about 10 min before the cloud. After the cloud has passed, both parameters tend to return to their original values. The existence of the twilight zone is thus clearly confirmed.

In future works it would be interesting to compare these observed changes with data from the RPG-HATPRO microwave radiometer routinely operated at Granada station to carry out hygroscopicity studies.

CONCLUSION

This study represents the first attempt to study the ACI by remote sensing techniques at Granada station. The database used was the principal weakness, since it was only made use of pre-existing data that were not recorded with the aim of studying ACI. Only 7% of the potentially available profiles could be used.

Despite the small number of profiles, interesting results have been found. The decrease of ACI with height, such as the decrease of the ACI_{index} from -3.0 to -0.9 between the two distance categories, consistent with other works, has been shown. Even thought a more accurate analysis with more specific interaction distance categories could not be performed, the analysis was made using two different wavelengths, which is an improvement compared to previous studies. It revealed that the 532 nm channel gives higher values of ACI_{index} than the 1064 nm one.

The remaining uncertainty calls for further studies on the topic. These should be conducted implementing a new specific measuring protocol specially dedicated to the study of ACI. Additional information such as the evolution of relative humidity, as measured by a microwave radiometer, would enrich the results by allowing for hygroscopicity studies.

ACKNOWLEDGMENTS

This study has been made possible thanks to the work of the members of the GFAT who took the measurements, as well as the persons involved in AERONET, the NAAPS, SKIRON and DREAM aerosol models for providing this study with relevant data.

I would like to express my profound personal gratitude to Juan Luis Guerrero Rascado, the supervisor of this study, to have shown a particular enthusiasm, devotion and availability during all the processes of the research.

Last but not least, I would like to thank my parents, friends and fellow students who supported me throughout this project.

REFERENCES

1. Twomey, S., "Pollution and planetary albedo", *Atmos. Environ.*, 8, 1974, pp. 1251–1256.
2. Albrecht, B. A., "Aerosols, cloud microphysics, and fractional cloudiness", *Science*, 245, 1989, pp. 1227–1230.
3. Andreae,M.O., Rosenfeld, D., Artaxo, P., Costa, A.A., Franck, G.P., Longo, K.M. and Silva-Dias, M.A.F., "Smoking rain clouds over the Amazon", *Science*, 303, 2004, pp. 1337–1342.
4. Ackerman, A. S., Toon, O.B., Stevens, D.E., Heymsfield, A.J., Ramanathan, V. and Welton, E.J., "Reduction of tropical cloudiness by soot", *Science*, 288, 2000, pp. 1042–1047.
5. Bréon, F.M., Tanré, D. and Generoso, S., "Aerosol effect on cloud droplet size monitored from satellite", *Science*, 295, 2002, pp. 834-838.
6. Costantino, L., and Bréon, F.M., "Analysis of aerosol-cloud interaction from multisensory satellite observations", *Geophys. Res. Lett*., 37, L11801, doi:10.1029/2009GL041828, 2010.
7. Guerrero-Rascado, J. L. and Preißler, J., "Cloud-aerosol interaction estimated by Raman lidar", Book of extended abstracts of "Quinta Reunión Española de Ciencia y Tecnología de Aerosoles", D4-1 – D4-6, ISBN: 978-84-7834-662-2, 2011.
8. Koren, I., Remer, L.A., Kaufman, Y.J., Rudich, Y., and Martins, J.V., "On the twilight zone between clouds and aerosols", *Geophys. Res. Lett.*, 34, L08805, 2007.
9. Feingold, G., Remer, L.A., Ramaprasad, J., and Kaufman, Y.J., "Analysis of smoke impact on clouds in Brazilian biomass burning regions: An extension of Twomey's approach", *J. Geophys. Res.*, 106, 22, 2001, 2001, pp. 907-922.
10. Lihavainen, H., Kerminen, V.M. and Remer, L.A., "Aerosol–cloud interaction determined both in situ and satellite data over a northern high-latitude site", *Atmos. Chem. Phys*, 10, 10987–10995. DOI: 10.5194/acp-10-10987-2010, 2010.
11. Fernald, F. G., Herman, B.M., and Reagan, J.A., "Determination of Aerosol Height Distribution by Lidar", *J. Appl. Meteorol*., 11, 1972, pp. 482-489.
12. Klett J. D., "Stable analytic inversion solution for processing Lidar returns", *Appl. Opt*., 20, 1981, pp. 211-220.