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Retrieval of aerosol profiles combining sunphotometer and ceilometer measurements in GRASP code

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A B S T R A C T

In this paper we present an approach for the profiling of aerosol microphysical and optical properties combining ceilometer and sun/sky photometer measurements in the GRASP code (General Retrieval of Aerosol and Surface Properties). For this objective, GRASP is used with sun/sky photometer measurements of aerosol optical depth (AOD) and sky radiances, both at four wavelengths and obtained from AErosol RObotic NETwork (AERONET), and ceilometer measurements of range corrected signal (RCS) at 1064 nm. A sensitivity study with synthetic data evidences the capability of the method to retrieve aerosol properties such as size distribution and profiles of volume concentration (VC), especially for coarse particles. Aerosol properties obtained by the mentioned method are compared with airborne in-situ measurements acquired during two flights over Granada (Spain) within the framework of ChArMEx/ADRIMED (Chemistry-Aerosol Mediterranean Experiment/Aerosol Direct Radiative Impact on the regional climate in the MEDiterranean region) 2013 campaign. The retrieved aerosol VC profiles agree well with the airborne measurements, showing a mean bias error (MBE) and a mean absolute bias error (MABE) of 0.3 $\mu m^3/cm^3$ (12%) and 5.8 $\mu m^3/cm^3$ (25%), respectively. The differences between retrieved VC and airborne in-situ measurements are within the uncertainty of GRASP retrievals. In addition, the retrieved VC at 2500 m a.s.l. is shown and compared with in-situ measurements obtained during summer 2016 at a high-atitude mountain station in the framework of the SLOPE I campaign (Sierra Nevada Lidar AerOsol Profiling Experiment). VC from GRASP presents high correlation (r = 0.91) with the in-situ measurements, but overestimates them, MBE and MABE being equal to 23% and 43%.

1. Introduction

Aerosols are a key piece in the Earth climatic system because they can increase the cooling or warming of the Earth surface depending on their properties (Boucher et al., 2013). Hence, columnar and vertical aerosol properties must be appropriately known to better understand their impact in the Earth energy balance and therefore on the Earth climate. Furthermore aerosol profiling is also relevant in the management of aviation traffic (Prata, 2009; Flentje et al., 2010).

Column-integrated microphysical and optical aerosol properties are commonly retrieved by sun/sky photometer measurements. This is the case of AERONET (AErosol RObotic NETwork; Holben et al., 1998), that derives aerosol optical depth (AOD) from multiwavelength measurements of direct beam sun irradiance, and uses these AOD values in combination with sky radiances measurements for obtaining aerosol properties such as aerosol size distribution, refractive indices, single scattering albedo (SSA), and phase function (Dubovik and King, 2000; Dubovik et al., 2006). However, this kind of measurements does not provide information about the vertical profile of these aerosol properties.

Lidar systems are capable of measuring the atmospheric backscatter profile at several wavelengths. The lidar signals are used for profiling optical and even retrieving microphysical aerosol properties applying different methods. These methods depend on the available lidar signals:

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elastic range corrected signal (RCS) is useful to provide aerosol backscatter (β) profiles (Klett, 1981, 1985; Fernald, 1984; Sasano, 1984); non-elastic (Raman) signal can be used for obtaining independent range-resolved extinction (α) and backscatter coefficients (Ansmann et al., 1990; Whiteman et al., 1992). Elastic and Raman lidar signals can be combined, usually by the so called 3β + 2α configuration, to obtain profiles of aerosol microphysical properties through different inversion techniques (e.g. Müller et al., 1999; Böckmann, 2001; Veselovskii et al., 2002, 2012; Chemyakin et al., 2016); many papers being already published for characterizing long-transport of biomass-burning (e.g. Veselovskii et al., 2015; Ortiz-Amezcua et al., 2017), volcanic aerosol (e.g. Navas-Guzmán et al., 2013), dust (e.g. Granados-Muñoz et al., 2016; Veselovskii et al., 2017) pollution (e.g. Wandinger et al., 2002; Noh et al., 2009; Veselovskii et al., 2013), and artic haze (Müller et al., 2004). In addition, linear particle depolarization ratio measurements allow the detection and assessment of non-spherical particles such as dust or volcanic aerosol (e.g. Ansmann et al., 2009, 2012; Tesche et al., 2009, 2011; Bravo-Aranda et al., 2013) and allows aerosol typing (e.g. Burton et al., 2012; Gross et al., 2013).

EARLINET (European Aerosol Research LIdar NETwork; Pappalardo et al., 2014), founded in 2000 and now part of ACTRIS (Aerosols, Clouds, and Trace gases Research InfraStructure; www.actris.eu/), does include nowadays 31 lidar stations, most of them operating multiwavelength Raman lidars. However, most Raman measurements are sparse and mostly limited to night-time. To retrieve vertical profiles of aerosol microphysics, several inversion techniques were developed within EARLINET/ACTRIS combining backscattering lidar and collocated AERONET sun/sky photometers such as LIRIC (Lidar Radiometer Inversion Code; Chaikovsky et al., 2008, 2016) and GARRLiC (Generalized Aerosol Retrieval from Radiometer and Lidar Combined data; Lopatin et al., 2013). The LIRIC code uses AERONET column-integrated retrievals plus backscattering lidar signals as inputs to provide vertical-resolved aerosol volume concentration (VC), both at fine and coarse mode. However, GARRLiC uses as inputs measured optical depth and sky radiances and the multiwavelength RCS from lidar to provide vertical-resolved aerosol microphysical and optical properties, both at fine and coarse mode, and also improves the classical AERONET columnar retrievals by providing intensive aerosol properties, like refractive indices or SSA, of fine and coarse modes, separately.

The Generalized Retrieval of Aerosol and Surface Properties (GRASP; Dubovik et al., 2014) code uses the heritage of AERONET inversion scheme (e.g. Dubovik and King, 2000; Dubovik et al., 2006) and is a versatile and open-source algorithm capable to obtain optical and microphysical aerosol properties from different sources of measurements (www.grasp-open.com). Recently, aerosol properties have been retrieved by GRASP using, among other information sources, satellite images (Kokhanovsky et al., 2015), polar nephelometer data (Espinosa et al., 2017) and different combinations with sun/sky photometer measurements: only spectral AODs (Torres et al., 2017); spectral AODs, sky radiances and polarized sky radiances (Fedarenka et al., 2016); and spectral AODs and sky camera images (Román et al., 2017a). The incorporation of the GARRLiC scheme in GRASP allows to combine AODs, sky radiances and RCS lidar values to retrieve columnar and vertical-resolved aerosol properties discerning between fine and coarse modes (Lopatin et al., 2013; Bovchaliuk et al., 2016; Benavent-Oltra et al., 2017).

Although the combination of lidar and sun/sky photometer measurements using GRASP with the GARRLiC scheme is promising, lidar systems are generally expensive and require supervision, so few stations have the set of measurements required to this end. An alternative to multiwavelength lidar systems could be the use of ceilometers, which were originally designed for studying cloud heights but recent ceilometer models are able to detect aerosol layers at altitudes of up to 10 km. Ceilometers only measure at one wavelength and are less accurate than classic lidars, but they are cheaper and more operative than multiwavelength lidar systems and they also can work continuously unattended. In fact, ceilometers have been previously used to obtain aerosol properties as PM2.5 (Li et al., 2017), PM10 (Münkel et al., 2007), aerosol backscatter coefficients (Heese et al., 2010; Wiegner and Geiss, 2012; Wiegner et al., 2014; Madonna et al., 2015) or aerosol hygroscopic growth (Haeffelin et al., 2016). Moreover, there are some programs nowadays as *E*-PROFILE, a program of EUMETNET (EUropean METeorological services NETwork), and the COST Action ES1303 TOPROF (TOwards operational ground based PROFiling with ceilometers, doppler lidars and microwave radiometers for improving weather forecasts) dealing with the harmonization and better characterization of ceilometer measurements and products; and there are also ceilometer networks, like the Iberian CEilometer NETwork (ICENET; Cazorla et al., 2017) among others (e.g., de Haij et al., 2007; Emeis et al., 2011), trying to provide ceilometer measurements in near-real time with devices every 100 km. These issues motivate to try to combine ceilometer measurements with sun/sky photometer in order to obtain some vertical aerosol information.

The main objective of this work is use for the first time the GRASP code to obtain aerosol vertical profiling of aerosol microphyscial properties combining AERONET sun/sky photometer measurements with the monochromatic RCS measured by a ceilometer at 1064 nm. The use of this proposed combination of measurements allows the retrievals of column-integrated aerosol microphysical properties, and we explore the possibility of obtaining vertically-resolved aerosol volume concentration. Another important goal is the quantification of the accuracy and uncertainty of all retrieved parameters through synthetic data and also by comparisons of retrieved parameters versus in-situ measurements.

This paper is structured as follows: Section 2 describes the used instrumentation during the different measurement field campaigns; Section 3 introduces the GRASP code and the methodology to retrieve the aerosol properties; a sensitivity study with synthetic measurements is developed in Section 4 in order to test the capability of the proposed GRASP scheme. Section 5 shows the main results about the comparison of the obtained aerosol retrievals against in-situ measurements and, finally, the main conclusions are summarized in Section 6.

2. Instrumentation and campaigns

2.1. Instrumentation at Granada station

Most of the instrumentation used in this work is installed on the rooftop of the "Andalusian Institute for Earth System Research" (IISTA-CEAMA) building at Granada, Spain (37.1638° N; 3.6051° W; 680 m a.s.l.). This instrumentation is managed by the Atmospheric Physics Group ("Grupo de Física de la Atmósfera"; GFAT) of University of Granada. Granada is a Spanish city located in the South-Eastern of the Iberian Peninsula, in a natural basin surrounded by –Sierra Nevada Mountains with peaks of up to 3300 m a.s.l., showing a Mediterranean climate (Csa in Köppen classification). The city is medium-size with a population about 235,000 inhabitants, which increases up to 530,000 including the metropolitan area, and non-industrialized being its main aerosol sources the domestic heating based on fuel oil combustion in winter and the heavy traffic along all year (Lyamani et al., 2010, 2011; Titos et al., 2012, 2014). Columnar aerosol pattern in the area is characterized by higher values in summer mostly associated with Saharan dust arrivals (Pérez-Ramírez et al., 2012; Mandija et al., 2016), while the lowest aerosol loads usually corresponds to the arrivals of Atlantic air-masses that clean the atmosphere (Pérez-Ramírez et al., 2016).

A CE318-T sun/sky/lunar (triple) photometer (*Cimel Electronique*) is operative on the mentioned station since March 2016 for providing day and night columnar aerosol optical properties (Barreto et al., 2013, 2016). GFAT also operates different sun/sky photometers (hereafter 'sunphotometers') which belong to AERONET and have participated in field campaigns in Spain, Brazil, Colombia and Bolivia, and have