Dual-Field-of-View Depolarization approach using the Polly^{XT} Raman Lidar: Characterization of aerosol-cloud interactions in the semi-arid climate of Cyprus.

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Introduction

Aerosols are a key parameter when referring to atmospheric studies or advanced climate research. Their role in influencing Earth's energy balance or the formation, lifetime and evolution of clouds has long been studied, but no clear conclusion on their contribution to climate forcing has yet emerged. This leaves us with high uncertainties in both the aerosol-radiation interactions (ARI), as well as in aerosol-cloud interactions (ACI). The latter one especially, exhibits one of the largest uncertainties among all the forcing parameters. According to the Fifth Assessment Report (AR5) of IPCC, the radiative forcing of aerosol-cloud interactions was estimated as -0.45 W/m^2 with uncertainties ranging from -1.2 to 0 W/m^2, whereas the last report (AR6) of IPCC refined these numbers to -0.7 ± 0.5 W/m^2, highlighting in both cases that these values rely on moderate and not high confidence [1], [2]. This last statement showcases how important it is for extensive, detailed, and in-depth studies of these interactions to be conducted now more urgently than ever, as these significant uncertainties arise due to the incomplete understanding of how clouds develop during certain aerosol and weather conditions.

The novel Dual-Field-of-View (DFOV) polarization lidar approach, developed by C. Jimenez et al., 2020, comes as a competent solution to the aforementioned challenges [3]. This method works just by using lidar's data and is able to provide crucial information about the microphysical properties of liquid-water, or even, mixed phase clouds. Properties such as the Cloud Droplet Number Concentration (N_d), their effective radius (R_e), the cloud extinction coefficient (α), and the Liquid Water Content (LWC). Additionally, by using products like the quasi backscatter coefficient and by implementing Doppler Lidar's data, the cloud condensation nuclei (CCN) concentration and the vertical wind below the cloud base can be retrieved, and therefore, the influence of certain type of aerosols and their concentration in relation also to the behavior of the wind, can yield to an unprecedent view of aerosol-cloud interactions.

In this study, data acquired by the Cyprus Atmospheric Remote-Sensing Observatory (CARO) National Facility of the Eratosthenes Centre of Excellence, and more precisely by the Polly^{XT} Raman Lidar and the Halo Photonics (Snoopy) Doppler Lidar, are used to analyze cases of liquid-water or mixed-phase clouds in Limassol. By applying the DFOV Depolarization approach on these cases, cloud properties are able to accurately be retrieved for the first time in the region of Eastern Mediterranean, Middle East and Northern Africa (EMMENA), further contributing to ACI studies.

Methodology

The lidar instrument used is part of the third generation of Polly^{XT} systems and it is installed within a dedicated container at the facility. It functions autonomously and operates continuously, whereby using a diode-pumped laser it is able to emit linearly polarized light at three wavelengths – 1064 nm, 532 nm, and 355 nm – at a pulse repetition rate of 100 Hz, while at the same time it measures the nitrogen Raman signals as it is equipped with channels for the wavelengths of 387, 407, and 607 nm. Fig. 1 below presents the setup of the instrument, depicting all the channels and specifying which ones belong to the far-range receiver, which ones to the near-range one, and the channels that measure the cross-polarized backscattered light (noted with the symbol ⊥) [4, 5].

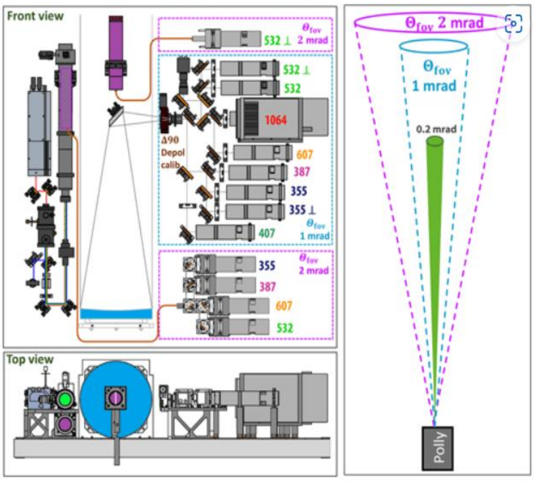

Figure 1. Scheme of the optical setup of the 3rd generation Polly^{XT} Raman lidar as used in [5].

The DFOV polarization lidar method works by using the depolarization ratios of two different FOVs of the 532 nm channels. This is necessary, as the narrower FOV channels (θ_{in} = 1 mrad) look at a slightly different area of the cloud than the wider ones (θ_{out} = 2 mrad), therefore two perspectives are created, whereby comparing the two signals, the multiple scattering effects caused by the cloud droplets can be separated, and the retrieval of clouds' properties becomes possible [5]. As a first step, cloudy days are studied and after necessary signal corrections, the cloud base height (z_{bot}) is estimated with a temporal resolution of 3 minutes, followed then by the calculation of the DFOV ratio by dividing the integrated depolarization ratio of the inner FOV 532 nm signals (δ_{in}) to the integrated depolarization ratio of the outer FOV 532 nm signals (δ_{out}) between z_{bot} and a reference height inside the cloud (z_{ref}) as can be seen below in Eq. 1.

$$\bar{\delta}_{rat}\ (z_{bot}, z_{ref}) = \frac{\bar{\delta}_{in}(z_{bot}, z_{ref})}{\bar{\delta}_{out}(z_{bot}, z_{ref})} \tag{1}$$

Next, the droplet effective radius (R_e), cloud extinction coefficient (α), the cloud droplet number concentration (N_d), and the liquid water content (w_l) are then calculated as follows:

$$R_e\ (z_{ref}) = R_0 + R_1 \times \bar{\delta}_{rat} + R_2 \times \bar{\delta}_{rat}^2 + R_3 \times \bar{\delta}_{rat}^3 \tag{2}$$

$$\alpha\ (z_{ref}) = a_0(R_e, z_{bot}) + a_1(R_e, z_{bot}) \times \bar{\delta}_{in} + a_2(R_e, z_{bot}) \times \bar{\delta}_{in}^2 \tag{3}$$

$$N_d\ (z_{ref}) = \frac{1}{2\pi k}\alpha(z_{ref})R_e^{-2}(z_{ref}) \tag{4}$$

$$w_l\ (z_{ref}) = \frac{2}{3}\rho_w \alpha(z_{ref})R_e(z_{ref}) \tag{5}$$

where, R_0, R_1, R_2, and R_3 are polynomial coefficients that depend on the lidar instrument setup, $a_0(R_e, z_{bot})$, $a_1(R_e, z_{bot})$, and $a_2(R_e, z_{bot})$ are coefficients derived from polynomial regression analysis for the given z_{bot}, R_e (z_{ref}) and $\bar{\delta}_{in}$, and ρ_w is the liquid-water density. k parameter is described as the cubic power of the ratio of the volume mean droplet radius (R_V) to the effective radius, as follows:

$$k = \frac{R_V^3}{R_e^3} \tag{6}$$

All the above equations are described in detail in the referenced paper number [3].

In addition, for those same days, the lidar product of the quasi backscatter coefficient (β^{quasi}) and the vertical wind obtained from the Doppler Lidar are used, with the first one serving as an approximation of the particle backscatter coefficient, which through the POLIPHON [6] method analysis, CCN concentration can be estimated.

Results and Discussion

In the figures below, the atmospheric conditions, the input parameters, as well as the retrieved parameters of this method are presented. As an example, February 21st, 2025, is used as low-level clouds were identified, while the CCN concentration, and the vertical wind information were available throughout the day. On each time-height plot, black or white dots represent the height of the cloud base.

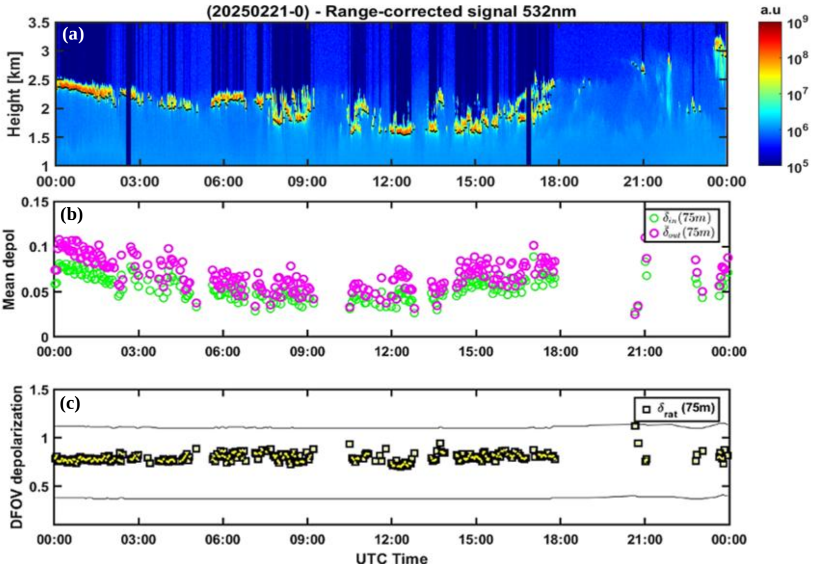

Figure 2. Plots of the input parameters for the DFOV method. Plot (a) shows the range-corrected 532 nm far-range signal, (b) the integrated depolarization ratios from the inner FOV (green) and the outer FOV (pink) 532 nm channels, and (c) the ratio of the DFOV depolarization ratios for each cloud base point (black lines indicate the boundaries of the acceptable values, based on the z_{bot} and the $R_e(z_{ref})$).

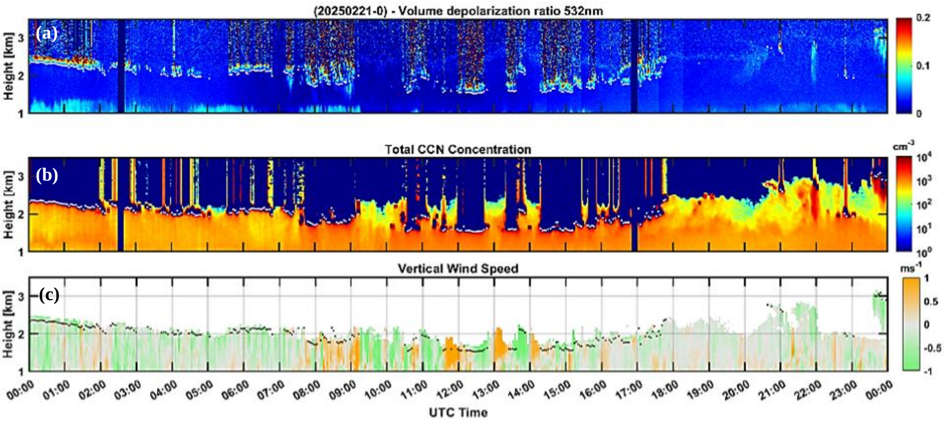

Figure 3. Time-height plots of (a) the volume depolarization ratio at 532 nm of the inner FOV, (b) the total CCN concentration, and (c) the vertical wind for that day.

At first glance, the errorbar plots (c) and (d) of Fig. 4 present an inversely proportionate behaviour as expected. The alteration, however, of the N_d isn't easily interpretable as it relies on both the vertical wind behaviour and the CCN concentration, the type of which also plays an important role in cloud formation processes.