Synergistic use of ground-based multi-instrument platforms and satellite recordings to investigate the aerosol-cloud-dynamic interaction in Cyprus

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Abstract

This study demonstrates the capability of the Cyprus Atmospheric Remote Sensing Observatory (CARO) to investigate aerosol–cloud–dynamic interactions through synergistic measurements from ground-based and satellite platforms. Co-located lidar and radar systems, including the Polly^{XT} multi-wavelength Raman-polarization lidar and the MIRA-35 Doppler cloud radar, were combined with satellite observations from the ATLID instrument aboard EarthCARE. A case study on 17–18 March 2025 revealed a lofted Saharan dust layer descending from approximately 6 km to 2 km altitude, followed by the formation of an ice-precipitating altocumulus cloud deck between 4 and 7 km. Radar reflectivity, Doppler velocity, and spectral width profiles confirmed hydrometeor sedimentation, vertical cloud layering, and virga signatures. CloudNet classification indicated mixed-phase conditions and potential aerosol–cloud interactions driven by mineral dust acting as ice-nucleating particles. In parallel, ATLID captured a regional-scale dust event on 4–5 March 2025, clearly resolving two distinct dust layers and an overlying cirrus layer. Lidar ratios and depolarization values from ATLID were consistent with ground-based Polly^{XT} measurements. These results highlight the value of multi-instrument synergy in characterizing complex atmospheric processes and affirm CARO's strategic role in satellite validation activities within the Eastern Mediterranean and Middle East and North Africa (EMMENA) region.

1. Introduction

Aerosol particles impact on earth's hydrological cycle and its climate through direct radiation effects in addition to the influence of cloud properties by acting as cloud condensation nuclei (CCN) or ice nucleating particles (INP), thereby modifying cloud microphysics, albedo, and precipitation processes. Assessing these multiscale effects has been a long-standing research area. However, the exact impacts of aerosol particles on the evolution of the different cloud types, precipitation, and the radiation budget remain uncertain (Seinfeld et al., 2016). Hence, this subject is still the source of the highest uncertainty in assessing climate change with many processes yet to be fully understood. For this reason, monitoring and characterization of aerosols and clouds physical and microphysical properties in different aerosol and meteorological conditions is of great importance to the atmospheric research community. Consequently, systematic monitoring and characterization of aerosol–cloud–radiation interactions under varying atmospheric conditions are a critical research priority.
To date, the most advanced observations of the atmosphere, and in particular of aerosols and clouds, are achieved by remote-sensing instrumentation. Passive and active remote sensing instruments on ground-based, airborne, and spaceborne platforms provide different aspects of information on atmospheric aerosols. Each technique alone is subject to indeterminacies that make it difficult to separate the effect of different aerosol parameters such as particle shape, composition, absorption, size distribution, and vertical distribution. This is why synergistic multi-instrument platforms must be employed in top-level atmospheric science. Meanwhile, the critical role of active remote sensing techniques in unraveling the vertical structure of atmosphere is essential for characterizing aerosol-cloud coupling on a process level. The Cyprus Atmospheric Remote Sensing Observatory (CARO) is operating ground-based lidar systems such as Polly^{XT}, in synergy with Doppler cloud radars and Doppler wind lidar to provide high-resolution vertical profiles of aerosol optical properties, cloud boundaries, and vertical motions.
To apply a measurement–modelling synergistic approach to address key environmental and atmospheric challenges, CARO's advanced ground-based infrastructure is also leading the ATARRI project (ATmospheric and solAR Research and Innovation in the Eastern Mediterranean). ATARRI aims to strengthen scientific knowledge and innovation in several core areas including a) dust modelling and forecasting (Di Tomaso et al., 2022), b) aerosol microphysics characterization through inversion modelling using GRAPS algorithm for aerosol characterization (vertically resolved and columnar) (Lopatin et al., 2021), c) relationship between aerosol, clouds and solar radiation using radiative transfer modeling and evaluation of satellite dust aerosol products to increase the readiness of CARO towards supporting cal/val for future satellite missions, and d) radiation solar modelling in urban areas and Solar energy assessment in different spatiotemporal scales (Theristis et al., 2023).
The region of the study and a novel and comprehensive active and passive ground-based remote sensing facilities of the Cyprus Atmospheric Remote Sensing Observatory (CARO), which is used in this research described in Sec. 2. Measurement results based on instrument synergy are presented and discussed in Sec. 3. The paper concludes with a discussion and summary of key findings in Sec. 4.

2. Methodology

The climatology of the observatory, ground-based facilities, and EarthCare satellite recording that have been used in this study are described in the following.

2.1 Measurement site

The Cyprus Atmospheric Remote Sensing Observatory (CARO) was established within the framework of the EXCELSIOR project and operates under the coordination of the Atmospheric Cluster of the Department of Climate and Environment at the ERATOSTHENES Centre of Excellence (ECoE). On the one hand, as a national facility dedicated to atmospheric research, CARO is equipped with a state-of-the-art, multi-instrument platform and is among the few observatories worldwide that fulfil the latest requirements for comprehensive atmospheric monitoring. On the other hand, CARO benefits from a strategic geographic location at the intersection of the Eastern Mediterranean, North Africa, and the Middle East (EMMENA region).

The geographical location of the CARO as well Cyprus is illustrated in Fig. 1. Cyprus, located in the most Eastern Mediterranean corner, exhibits Middle-East type atmospheric and climate conditions. Dry and hot weather prevails for long periods throughout the year. The Mediterranean Basin is well recognized by the IPCC as a hot spot for climate change, the impacts of which are expected to amplify further in the years to come, adding one more uncertainty factor in the area's development and growth. It is also located in one of the most vulnerable areas in Europe and the world concerning unknown future changes of precipitation patterns. Climate conditions, as well as air quality, are strongly affected by a mixture of aerosols, such as urban haze, originating mainly from urban and industrial cluster in SE Europe, but also from the Middle East and North Africa (Mamouri and Ansmann, 2016; Mamouri and Ansmann, 2017), by biomass-burning smoke from North (e.g., Black Sea countries), by mineral dust originating from arid regions in Turkey and Middle East deserts (often mixed with anthropogenic pollution), and by Saharan dust from North Africa (Nisantzi et al., 2015). In addition to the dust aerosols, some studies already have been done to show the long-range transport of wildfire smoke from the strong fire in the United States and Canada toward the Cyprus atmosphere (Mamouri et al., 2023; Ansmann et al., 2021). Since Cyprus is an island, marine aerosols play an important role, too. There are very few locations on Earth that experience such complex aerosol structures, vertical layering and mixtures which can dramatically influence cloud evolution, cloud lifetime, and precipitation processes. All the above make the CARO an ideal natural laboratory for studies of atmospheric composition and air quality aspects, climate change, aerosol-cloud interaction, and the weather-precipitation-dryness complex.

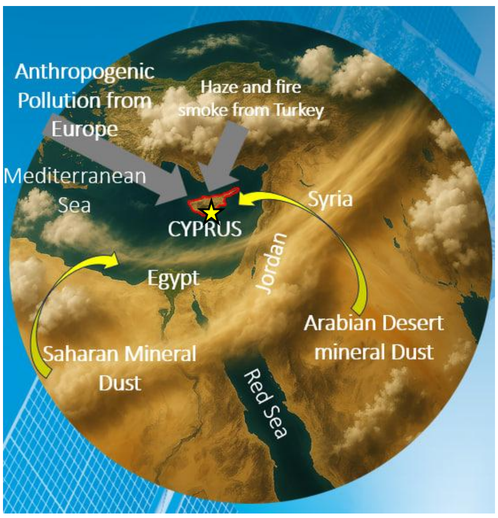

Figure 1- Geographical location of Cyprus that is impacted by a mixture of aerosol from surrounding area which have an impact on its atmospheric pollution. The location of the CARO is determined by a star.

2.2 Ground-based instrumentation

The CARO is located in Limassol, a coastal city in the southern part of Cyprus (34.677° N, 33.0375° E, 2.8 m above sea level). The core instrumentation is housed in two adjacent containers, which serve as the main operational hub of the observatory. In addition to these, the solar radiation instruments and the AERONET sun photometer are installed at two separate sites situated approximately 300 meters from the main containers. This spatial distribution is designed to minimize mutual interference and optimize measurements of atmospheric parameters under unobstructed sky conditions.

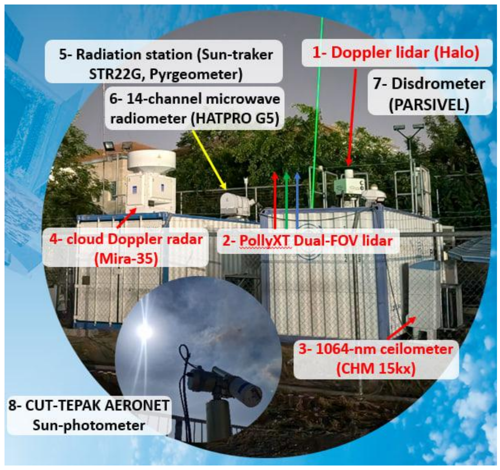

Figure 2- The main ground-based multi-instrument facility of the Cyprus Atmospheric Remote Sensing Observatory (CARO), hosting both active and passive remote sensing instruments, is located at 34.677° N, 33.0375° E, at an elevation of 2.8 m above sea level.

A comprehensive suite of active and passive cutting-edge instrumentation is deployed at the CARO to measure clouds, aerosols, radiation, and their interactions. The CARO's instruments are continually in operation to obtain long-term and episodic measurements of cloud and aerosol properties, precipitation, and related atmospheric characterization in the region's diverse climate regimes. The state of instrumentation of CARO is listed in the table 1 and it is shown in Fig. 2.

2.3 EarthCARE satellite

The EarthCARE (Earth Cloud, Aerosol and Radiation Explorer) satellite is a joint ESA–JAXA mission that was launched on 28 May 2024. This platform comprises a 94 GHz Doppler cloud profiling radar (CPR), atmospheric lidar (ATLID), a multispectral imager (MSI), and a three-view broadband radiometer (BBR). EarthCARE flies in a sun-synchronous orbit, with a descending-node local Equator crossing time of 14:00, an inclination of 97∘, a revisit time of 25 d and an altitude of 393 km. An important aspect of the EarthCARE mission is its focus on instrument synergy (Wehr et al., 2023; Eisinger et al., 2024). ATLID (ATmospheric LIDar) is a three-channel, linearly polarized, high-spectral-resolution lidar (HSRL) system operating at 355 nm (Donovan et al., 2024; van Zadelhoff et al., 2023). Because ATLID and Polly^{XT} both operate at 355 nm, they enable spectrally matched, high-precision comparisons of aerosol and cloud properties—crucial for validating spaceborne retrievals and improving satellite-ground synergy.

Active sensors preforming continues measurements in the CARO observatory includes:	
Instrument	Operational period
A) Polly^{XT} Dual-FOV: A multi-wavelength dual field of view Raman polarization Lidar (Engelmann et al. 2016, Jimenez et al. 2020a)	October 2020 to present
B) 35-GHz scanning polarimetric cloud Doppler radar (Görsdorf et al. 2015)	June 2024 to present
C) Doppler lidar HALO Photonics StreamLine XR	February 2023 to present
D) 1064nm lidar ceilometer Lufft CHM 15k	January 2024 to present
Passive sensors preforming continues measurements in the CARO observatory includes:	
E) Scanning microwave radiometer RPG HATPRO	June 2024 to present
F) Particle size spectrometer disdrometer OTT Parsivel2	January 2024 to present
G) AERONET Sun-photometer CUT-TEPAK CE318	April 2010 to present
H) Bentham DMc150 double monochromator spectrophotometer	December 2023 to present
I) Erythemal UV irradiance measurement, sky imager, radiation station	December 2023 to present

Table 1- List of active and passive instrumentation operating continuously at CARO in addition with operating period of each instrument.

CARO actively participates in the calibration/validation (CAL/VAL) activities of the EarthCARE mission as part of the CORAL project (EVID39). This contribution is very important due to two different reasons, including CARO geographical location as well as its multi-instrument infrastructure. Within this project, ATLID level 1 (ATL_NOM_1B) and level 2 (ATL_EBD_2A and ATL_AER_2A) products have been compared with ground-based Polly^{XT} recordings. For level 1 products, the signal ratio (Mie cross-polar signal divided by the Mie co-polar signal) has been compared for different processing baselines for atmospheric scene containing dust aerosols and Cirrus clouds. For level 2 products, the lidar ratio and the particle linear depolarization ratio at 355nm obtained from ATLID and the ground-based Polly^{XT} operating in Limassol, Cyprus have been compared.

3. Measurement results based on instrument synergy

To comprehensively understand the vertical structure of aerosols and clouds—especially their interactions under specific meteorological conditions—a synergistic analysis using co-located lidar and radar observations is essential. In the following sections, results from each instrument are presented and discussed.

3.1 Aerosol monitoring using Dual-FOV Polly^{XT}

Figure 3 illustrates the temporal evolution of the range-corrected signal from Polly^{XT} lidar observations at the Cyprus Atmospheric Remote Sensing Observatory (CARO) during 17–18 March 2025, with a temporal resolution of 30 s and vertical resolution of 7.5 m. Figs. 3a and b show the attenuated backscatter coefficient at 1064 nm and the volume depolarization ratio at 532 nm, respectively. These measurements enable aerosol typing and vertical profiling with high temporal detail, as established in Polly^{XT} system applications.

The lidar signal reveals a pronounced dust layer detected between ~3 and 6 km during the early morning of 17 March, characterized by elevated backscatter and volume depolarization ratios exceeding 0.25—typical indicators of non-spherical, coarse-mode mineral particles. This layer persisted between 05:00 and 13:00 UTC while gradually descending to ~2 km, forming a more compact stratified structure. The observed signatures align with long-range Saharan dust transport patterns over the Eastern Mediterranean, confirmed by HYSPLIT trajectory analysis and consistent with prior studies in the region (Mamouri and Ansmann, 2016).

After 13:00 UTC, lidar data indicate the onset of cloud formation above the dust layer, at altitudes between 4.0 and 4.5 km. The spatial and temporal coincidence of the dust layer with this cloud deck suggests a potential aerosol–cloud interaction. Mineral dust is known to act as efficient ice-nucleating particles (INPs) and giant cloud condensation nuclei (CCN), capable of altering cloud microphysics by increasing droplet number concentration or triggering heterogeneous freezing (Ansmann et al., 2021). The persistence of the cloud structure until approximately 06:00 UTC on 18 March, and the lack of similar formation under cleaner conditions, further supports the hypothesis that the dust layer contributed to cloud development.

These observations underscore the importance of lofted dust layers in modulating cloud formation in the Eastern Mediterranean, where complex interactions between aerosols and meteorological conditions prevail.

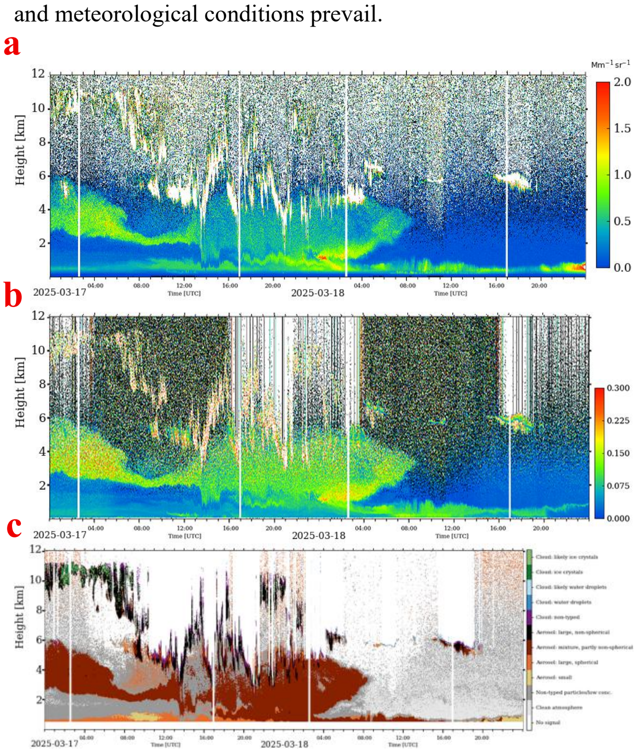

Figure 3- Illustrative measurement examples of aerosol layers observed with Polly^{XT} at CARO, up to the cirrus level (12 km height) on 17 March until 18 March 2025 at a) 1064nm attenuated backscatter coefficient and b) 532nm depolarization ratio. c) Output of the lidar-based aerosol type classification algorithm (Baars et al., 2016).

Fig. 3c presents the output of the lidar-based aerosol type classification algorithm (Baars et al., 2016), which combines intensive optical properties—such as particle linear depolarization ratio and lidar ratio—to distinguish between aerosol types. The output confirms the presence of dust at various altitudes, as well as cirrus clouds interacting with the upper boundary of the aerosol layer.

3.2 Cloud monitoring using doppler cloud radar

While Polly^{XT} lidar measurements provide high-resolution insights into aerosol vertical distribution, their ability to penetrate optically thick cloud structures is inherently limited due to strong backscatter extinction at cloud base. During this case study, the lidar signal becomes fully attenuated at the lower boundary of the cloud layer (around 4–4.5 km), making it impossible to retrieve detailed information about the cloud interior or its vertical extent using lidar alone. This limitation underscores the importance of co-located radar observations to provide a complete picture of cloud microphysics and dynamics. Figure 4 presents measurements from the MIRA-35 Doppler cloud radar deployed at CARO.

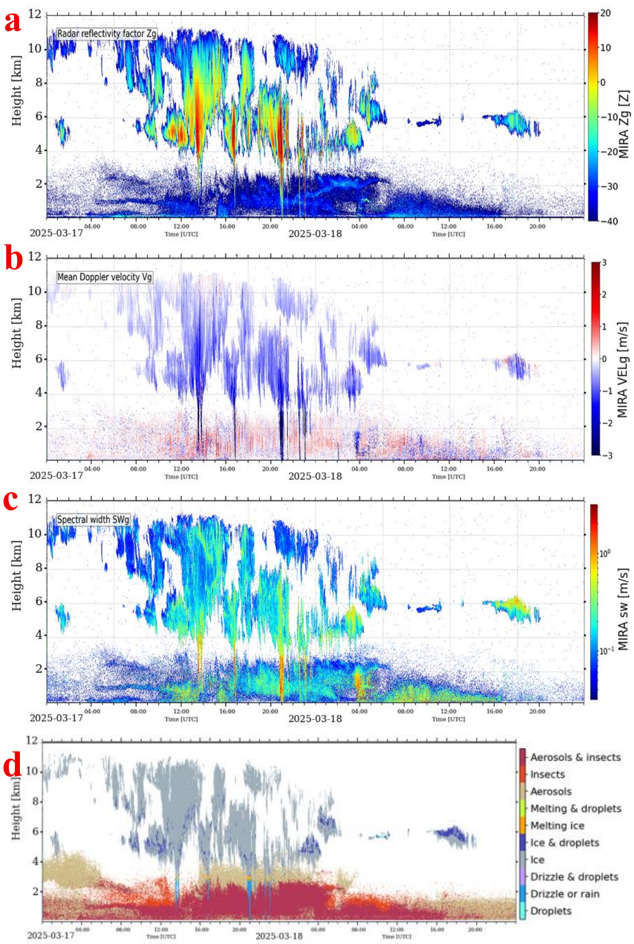

Figure 4- Time–height cross-sections of MIRA-35 cloud radar observations at the CARO during 17–18 March 2025. a) Radar reflectivity factor (Z, in dBZ), b) mean Doppler velocity (in m s^{-1}; negative values indicate downward motion), and c) spectral width (in m s^{-1}), d) CloudNet target classification.

Fig. 4a displays the radar reflectivity factor (Z, in dBZ), which reveals the internal structure of the cloud layer extending from approximately 4 km up to 10 km. The observed reflectivity values range from –20 to 20 dBZ, characteristic of lightly precipitating or non-precipitating ice-precipitating altocumulus clouds. These values are indicative of the presence of supercooled liquid water and ice-phase hydrometeors, with potential for mixed-phase conditions. Fig. 4b shows that mean Doppler velocity, in which consistently negative values reflect downward motion of hydrometeors. In particular, sedimentation within the 4.5–6.5 km range points to the presence of drizzle or ice crystal fall streaks originating from the upper cloud deck. Fig. 4c presents the spectral width, representing the distribution of particle velocities within the radar sampling volume. Enhanced spectral width around cloud top, suggested enhanced turbulence or wind shear in the upper troposphere, potentially contributing to cloud mixing and the cloud lifetime. Fig. 4d presents the Cloudnet target classification product for 17–18 March 2025 at CARO, based on synergistic retrievals from Polly^{XT} lidar, MIRA-35 Doppler cloud radar, and a microwave radiometer. The classification identifies a dominant mid-level cloud layer with ice and mixed-phase characteristics, falling hydrometeors below the cloud base, and intermittent virga. This product confirms the multi-phase nature of the observed cloud system and supports the interpretation of aerosol–cloud interactions, particularly the potential role of lofted mineral dust as ice-nucleating particles.

3.3 EarthCARE aerosol product comparison with Polly^{XT}

The synergistic observational strategy at CARO includes not only co-located lidar–radar ground-based measurements but also intercomparison with spaceborne sensors such as EarthCARE's ATLID lidar. Although EarthCARE's ground track does not pass directly over the CARO site, a spatial window of ±100 km is considered for satellite overpass selection. This threshold offers a reasonable trade-off for ATLID–Polly^{XT} intercomparison, especially considering the quasi-horizontal homogeneity of aerosol layers over the Eastern Mediterranean. The selected radius can be adjusted based on individual case studies and prevailing meteorological conditions. Figure 5a illustrates the spatial location of CARO (marked with a yellow circle with black outline) and the 100 km comparison radius (white circle), overlaid on a true-colour MSG-SEVIRI satellite image captured on 5 March 2025. EarthCARE ground tracks within the 100 km domain for the mission's 25-day repeat cycle are shown, with descending (daytime) and ascending (night-time) passes depicted in yellow and red, respectively. This snapshot shows an intense dust outbreak over the region, where a lofted Saharan dust layer (~6 km altitude) coincided with a lower-level dust plume transported from Syria, sweeping across Cyprus and the Eastern Mediterranean. Figure 5b presents a comparison between ATLID level 2 aerosol product (ATL_EBD_2A baseline AD) with orbit number 04357and orbit frame D (04357D) which overpassed on 04 March 2025 at 23:30 UTC (cyan line), and Polly^{XT} recordings on 04 March 2025 (light blue line) and 05 March 2025 (dark blue line). The satellite-derived profiles clearly resolve the two-layer dust structure: the elevated Saharan layer and the lower Middle Eastern dust plume. ATLID retrievals indicate lidar ratios of approximately 45 sr for the lower layer and 50 sr for the upper layer, consistent with typical values for Middle Eastern and Saharan dust, respectively. A cirrus cloud layer is also detected at ~8 km, with ATLID-retrieved lidar ratio and depolarization values consistent with ice cloud properties. Notably, both dust layers and the cirrus layer exhibit depolarization ratios exceeding 0.30, confirming the presence of non-spherical particles—dust and ice crystals alike. These results demonstrate ATLID's capability to capture vertically stratified aerosol layers and cirrus clouds with optical properties that are broadly consistent with ground-based Polly^{XT} lidar observations, strengthening the potential for synergistic satellite–ground validation in the Eastern Mediterranean.

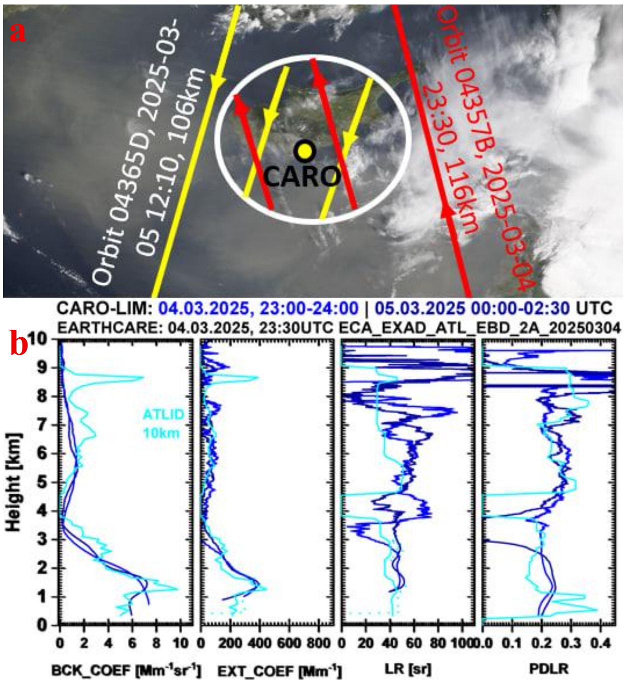

Figure 5- a) MSG-SEVIRI true-colour satellite image showing an intense dust event over the Eastern Mediterranean on 5 March 2025. The yellow circle indicates the CARO location, and the white circle denotes a 100 km radius around the station used for EarthCARE–Polly^{XT} comparison. EarthCARE ground tracks (descending: yellow, ascending: red) within this radius during the mission’s 25-day revisit cycle are overlaid. b) comparison between ATLID Level 2 aerosol product (ATL_EBD_2A_04357D) retrieved from Earthcare overpass on 04 March 2025 at 23:30 UTC (Cyan line) with PollyXT recordings on 04 March (light blue line) and 05 March (dark blue line) 2025., showing two distinct dust layers—one lofted (~6 km) Saharan layer and a lower (~1–3 km) Middle Eastern plume—alongside a cirrus cloud at ~8 km. Lidar ratios (~45–50 sr) and depolarization ratios (>0.30) confirm the presence of mineral dust and ice-phase cloud particles.

4. Discussion and conclusion

This study demonstrates the value of synergistic remote sensing using ground-based multi-instrument platforms and satellite lidar observations to investigate aerosol–cloud–dynamic interactions in the Eastern Mediterranean. The observations during the 17–18 March 2025 dust-influenced case captured a well-structured dust layer that persisted for several hours and provided the necessary atmospheric conditions for cloud formation. The transition from a stable aerosol layer to a mixed-phase altocumulus cloud illustrates the potential role of Saharan mineral dust in ice nucleation and stratiform cloud development. The synergy between lidar and radar is evident in this case: lidar successfully characterizes the aerosol layer that likely preconditioned the atmosphere for cloud formation, while radar provides detailed insights into the internal structure, dynamics, and microphysical properties of the resulting cloud system. The observed coupling between the descending dust layer and the development of an optically thick stratiform cloud highlights the complex interplay between aerosols and cloud processes in the Eastern Mediterranean. The cloud system observed between 13:00 UTC on 17 March and 06:00 UTC on 18 March exhibits characteristics of an ice-precipitating altocumulus cloud, including its mid-tropospheric altitude (~4–7 km), the transition from liquid to mixed-phase and ice layers, and the occurrence of drizzle and melting precipitation signatures below cloud base.

The radar reflectivity (–20 to 20 dBZ), downward Doppler velocity, and enhanced spectral width all point to the presence of an ice-precipitating altocumulus layer. CloudNet target classification further confirmed a multi-phase cloud structure, with clear indicators of glaciation and precipitation development, consistent with previously observed dust–cloud interaction mechanisms in the region.

Simultaneously, ATLID observations from the EarthCARE mission on 4–5 March 2025 captured a two-layer dust structure and an overlying cirrus cloud, with lidar ratio ~40-50 sr and depolarization ratios exceeding 0.30. These satellite-based retrievals were found to be in excellent agreement with Polly^{XT} ground-based measurements in terms of aerosol layer height, composition, and optical properties. The successful characterization of both Saharan and Middle Eastern dust in ATLID’s level 2 product confirms its capability for vertically resolved aerosol profiling and strengthens the case for space–ground validation synergy.

Overall, the combined Polly^{XT}, MIRA-35, and ATLID observations highlight the atmospheric composition complexity in the Eastern Mediterranean and demonstrate the effectiveness of multi-instrument approaches for disentangling aerosol–cloud–precipitation interactions. CARO’s strategic location and advanced instrumentation make it a crucial observatory for contributing to the EarthCARE mission and broader climate and air quality research across the EMMENA region.

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