Assessing Aerosol and Cloud Geometrical Features and Types over the Mediterranean: Insights from CALIPSO, CLOUDSAT and EarthCARE Missions

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Abstract: In this study, we use space-borne radar observations to analyze the geometrical properties and classify aerosol and cloud types over the Western, Central, and Eastern Mediterranean regions. Specifically, we exploit long-term measurements from the CALIPSO and CloudSat mission, complemented by more recent observations from the Earth Clouds, Aerosols and Radiation Explorer (EarthCARE) mission. Together, these space-borne datasets ensure observational continuity and offer enhanced insight into the Mediterranean aerosol and cloud climatology.

1. Introduction

Earth's climate system and weather are affected by clouds, which play an indispensable role in modulating the global radiative budget [1]. Uncertainties attached to cloud properties lead to uncertainty in climate projections. Thus, monitoring the vertical structure of clouds is crucial [2]. The Mediterranean region is recognized as a climate “hot spot,” characterized by pronounced variability in cloud systems, ranging from frontal and convective clouds to intense cyclonic systems [3]. Despite the importance of clouds over the Mediterranean basin for both climate science and regional impacts, observational studies of this region remain limited.

Space-based radar products from the CALIPSO (https://science.nasa.gov/mission/calipso/) and CloudSat (https://www.cloudsat.cira.colostate.edu/) missions are used to provide statistics on aerosol and cloud properties observed over the Mediterranean during the period 2007- 2022 and 2007-2017, respectively. CALIOP, the principal instrument on board the CALIPSO satellite, part of the NASA A-Train, was a standard dual wavelength (i.e., 532 and 1064 nm) backscatter lidar, operating a polarization channel at 532 nm [4], providing high-resolution profiles of the attenuated backscatter of aerosols and clouds since 2006. CloudSat’s payload, the Cloud Profiling Radar (CPR), was the first space-based 94-GHz (W-band) radar, enabling vertically resolved observations of cloud structure on a global scale.

The long-term CALIPSO and CloudSat record is extended by the more recent observations from the Earth Clouds, Aerosols and Radiation Explorer (EarthCARE) mission (https://www.esa.int/Applications/Observing_the_Earth/FutureEO/EarthCARE). EarthCARE satellite mission is a joint endeavour developed by the European Space Agency (ESA) and the Japan Aerospace Exploration Agency (JAXA) and features a 94 GHz Doppler Cloud Profiling Radar. EarthCARE CPR observations offers a unique opportunity for the collection of a global dataset of vertical motions and microphysics in clouds and precipitation, providing continuity and enhanced insight into the Mediterranean cloud climatology.

In this work, space-based radar products from CALIPSO, CloudSat and EarthCARE missions are used to generate statistics of aerosol and cloud types and properties over the

Mediterranean. Three sub-regions (i.e., West, Central and Eastern Mediterranean) are selected for analysis, as shown in Fig. 1.

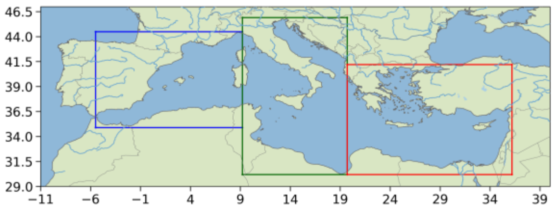

Figure 1. Aerosol and cloud data analysis above West, Central and East Mediterranean.

2. Methodology and Dataset

The CALIPSO mission was launched on 28 April 2006 and began routine operations starting from June 2006 until the end of its primary mission phase in 2023, flying in formation with other satellites in the A-Train constellation. CALIPSO carried the CALIOP lidar, a dual-wavelength (532 nm and 1064 nm) elastic backscatter lidar designed to provide high-resolution vertical profiles of clouds and aerosols. CALIOP had a vertical resolution of 30–60 m in the lower troposphere and coarser resolution (up to 180 m) at higher altitudes, with a horizontal footprint of approximately 70 m and along-track sampling every 333 m. CALIPSO operated in a Sun-synchronous orbit with equator crossing times near 01:30 and 13:30 local time, enabling coordinated observations of atmospheric structure and composition.

The study utilizes measurements from the CALIPSO mission, processed within the LIVAS database, a three-dimensional, multi-wavelength global aerosol and cloud optical dataset designed for spaceborne lidar applications [5]. LIVAS is derived from CALIPSO observations and provides vertically resolved, climatological profiles of aerosol optical properties at key potential laser wavelengths (355, 532, 1064, 1570, and 2050 nm), along with corresponding cloud optical properties at 532 nm, ensuring consistency with space-based lidar measurements.

The CloudSat cloud profiling radar (CPR) [6, 7] was launched on 28 April 2006 and has been operating since 2 June 2006. From then until the end of operations in December 2023, CPR provided the first continuous global record of vertical cloud structure and vertical profiles of cloud liquid water and ice content. CloudSat flew in the A-Train constellation of satellites. It operated at 94 GHz and has a sensitivity of−30 dBZ. Radar reflectivities were sampled every 240 m and had an effective vertical resolution of approximately 500 m. Profile spacing was about 1 km along track, corresponding to a sampling volume of roughly 1.8 km in the along-track direction and 1.5 km across track. The A-Train constellation was in a Sun-synchronous orbit with equator crossings at approximately 01:30 and 13:30 local time.

In this study we use the following CloudSat data (both ascending and descending overpasses): the 2B-GEOPROF (R05) cloud mask and radar reflectivity products (Mace et al., 2006; Marchand et al., 2008), the 2B-CLDCLASS-LIDAR (R05) cloud type, cloud top and cloud base products [8] and the 2B-CWC-RO (R05) liquid and ice water path products (Austin et al., 2009). We use only reflectivities associated with a “CPR_cloud_mask” value ≥ 30 indicating high confidence in the retrieval.

The Earth Clouds, Aerosols and Radiation Explorer (EarthCARE) mission [9] carries a Cloud Profiling Radar (CPR) operating at 94 GHz (W-band), designed to provide vertically resolved observations of clouds and precipitation with enhanced sensitivity compared to CloudSat. More specifically, the EarthCARE CPR has higher sensitivity (5–6 dB more sensitive), better vertical sampling (100 versus 240 m), higher along-track resolution (500 versus 1100 m) and a smaller instantaneous field of view (IFOV, 800 versus 1400 m) and includes Doppler velocity measurements and improved detection in the lowest atmosphere levels [10].

This study utilizes the EarthCARE A-LAY and A-TC products for the aerosol layering and typing and the ACM-COM product [11] for cloud statistics, with one year of measurements analyzed for the period from October 2024 to October 2025.

3. Results and Discussion

Representative examples of the analyzed aerosol properties over the Eastern Mediterranean are shown in the Figures below. Figure 2 shows the seasonal vertical distribution of aerosol types (expressed as the number of detected aerosol types per height level) over the Eastern Mediterranean, derived from the LIVAS database. Figure 3 presents the corresponding seasonal vertical distribution of aerosol types retrieved from nearly one year of observations of the EarthCARE mission over the same region.

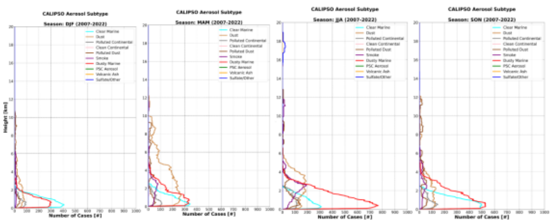

Figure 2. Seasonal mean vertical distribution of aerosol types, expressed as the number of detected aerosol types per altitude level, over the Eastern Mediterranean, based on data from the LIVAS database for 2007-2022.

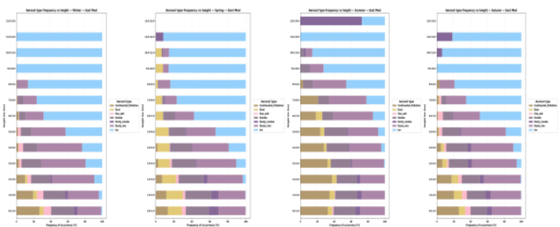

Figure 3. Seasonal mean vertical distribution of aerosol types retrieved from the one year of observations by the EarthCARE mission over the Eastern Mediterranean during 2024-2025.

The direct comparison between the climatological lidar-based estimates and the recent spaceborne measurements are in good agreement.

From the LIVAS climatology, it seems that dust and dust mixtures exhibit the highest frequency of occurrence up to 10 km during spring, while dusty marine aerosols are more prominent in autumn, with their highest concentrations confined to lower altitudes. During spring and autumn periods, dust mixtures, dust, and smoke aerosols show maximum frequency of occurrence across all altitude levels also from the EarthCARE 1-year observations. In autumn, dust mixtures dominate compared to pure dust cases. Additionally, a high occurrence of ice clouds (i.e., mixed-phase or cirrus clouds) is observed, particularly in spring, suggesting the efficient ice-nucleating (IN) ability of dust and smoke particles.

Examples of the analyzed cloud properties are the liquid and ice water paths shown in the Figures below. Figure 4 shows the monthly variations of liquid (blue) and ice (orange) water columns derived from ten years of CloudSat observations (2007-2017), while Figure 5 presents the liquid (purple) and ice (green) water columns derived from 1 year of EarthCARE observations (2024-2025).

Monthly variations from the decade CloudSat observations show that ice and liquid water column values are generally higher over land than over sea in the central and eastern Mediterranean during the summer period. Overall, the highest water column values occur over the western Mediterranean in January, February, and March.

Higher values of both liquid and ice water paths, by approximately one order of magnitude, are observed in the one-year EarthCARE mission dataset, particularly over the Western and Central Mediterranean regions. These differences may be attributed to the specific meteorological conditions prevailing during the analyzed year or to the different sampling of the two space-borne radars (sampling at different local times). Nevertheless, no firm conclusions can be drawn about the continuity of cloud properties from the EarthCARE mission dataset. In the next step, additional EarthCARE measurements will be used to assess the consistency of liquid and ice water patterns over the Mediterranean region.

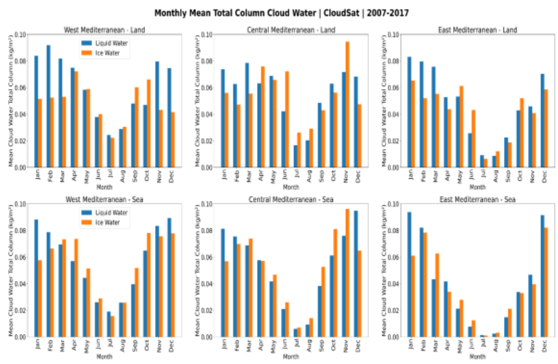

Figure 4. Mean total column cloud liquid and ice water per month, for West Med (left), Central Med (central) and East Med (left), above Land (up) and Sea (down) for the period 2007 - 2017 based on the 2B-CWC-RO CloudSat product.

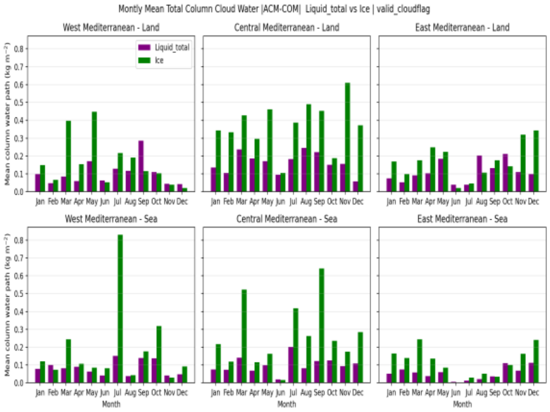

Figure 5. Mean total column cloud liquid and ice water per month, for West Med (left), Central Med (central) and East Med (left), above Land (up) and Sea (down) for the period 2024 - 2025 based on the ACM-COM EarthCARE product.

4. Acknowledgements

This research was funded by the PANGEA4CalVal project (Grant Agreement 101079201) funded by the European Union, and the CERTAINTY project (Grant Agreement 101137680) funded by the Horizon Europe program. Part of this work was supported by the COST Action EARLICOST (CA24135), supported by COST (European Cooperation in Science and Technology).

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