

Satellite and Ground-Based Lidar Observations of Aerosol Mass Concentrations over Albania

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Abstract

The vertical structure of aerosols plays a crucial role in regulating the radiative budget, influencing cloud formation, and determining surface air quality. Aerosols from continental sources can be transported over intercontinental scales, thereby affecting air quality and climate far from their origin. In this study, we assess the vertical distribution of aerosol mass concentration using long-term satellite-based CALIOP (Cloud–Aerosol Lidar with Orthogonal Polarization) observations (15 years) and one year of ground-based Polly lidar measurements in Tirana, Albania. CALIOP data show that non-dust aerosol mass concentrations in the first 2 km of the atmosphere range between 5 and 20 $\mu\text{g}/\text{m}^3$, decreasing to below 5 $\mu\text{g}/\text{m}^3$ above 2 km. Dust layers are typically observed from the surface up to 5 km, with concentrations varying widely between 5 and 80 $\mu\text{g}/\text{m}^3$ depending on event intensity. Over the 15-year record, aerosol mass concentrations remained relatively stable, except for a notable reduction during the COVID-19 lockdown period. Polly lidar measurements in Tirana reveal higher near-surface values, with mass concentrations reaching up to 60 $\mu\text{g}/\text{m}^3$.

Keywords: aerosol, mass concentrations, long-term observations, remote sensing, dust, anthropogenic pollution

1. INTRODUCTION

Aerosols such as mineral dust, sea spray, biomass burning smoke, fossil fuel combustion, and industrial processes are released into the Earth's atmosphere from various natural and anthropogenic activities (Sonwani et al. 2021). Once emitted, they undergo atmospheric transport that can redistribute particles across large distances, often far from their sources, thereby shaping their spatial and temporal variability as well as their properties and chemical composition. Mineral dust particles, e.g., can be transported over long distances, impacting the climate, environment, and human health at the source and downwind regions (Xiao et al. 2023). Aerosols can be transported on regional to intercontinental scales and vertically up to the stratosphere, and thus they can influence air quality and climate by altering cloud formation and by

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scattering or absorbing solar radiation. Local sources and long-range transported aerosol can affect human health, cloud formation, the climate, and air quality. The vertical structure of aerosols is particularly important, as their distribution with height strongly influences the radiative budget and surface air quality (Parajuli et al. 2020). The aerosol mass concentration is a critical parameter for assessing their abundance and evaluating associated impacts.

Comprehensive observations are essential for characterizing these processes, with both ground-based measurements and satellite observations providing complementary perspectives. Aerosol composition can be measured via satellites, ground-based instruments, in situ surface sampling, or aircraft. Satellite observations cover large areas but have low temporal resolution, while in situ measurements are highly accurate but limited in altitude and coverage. Ground-based remote sensing provides continuous, altitude-resolved measurements with a geometry similar to satellites (Ji et al. 2023). Satellite instruments are particularly valuable in regions with sparse in situ networks like Albania. Albania, situated in the Western Balkans, has a long Adriatic coastline and is characterized by a Mediterranean climate. The country is frequently affected by dust outbreaks originating from the Sahara Desert, as well as by emissions from local and regional wildfires, and occasionally even from distant North American and Canadian wildfires. In addition to traffic and industrial activities, a substantial contribution to aerosol loading arises from residential wood combustion, which is common in the region and particularly evident during winter (Gladiola Malollari et al. 2025).

In Albania, where continuous aerosol monitoring is absent, satellite observations combined with ground-based measurements provide valuable insights into aerosol sources, long-range transport, and seasonal variability, thereby contributing to an improved understanding of their role in regional air quality and climate.

This paper is organized as follows. Section 2 provides a detailed description of the datasets used in this study and the methodology applied to derive aerosol mass concentrations. Section 3 presents the results, followed by the conclusions in Section 4.

2. DATA AND METHODS

In this study, data from a ground-based lidar, called Polly, deployed for one year in Tirana, Albania, are employed. Along with, we make use of CALIOP space-based observations, a 15-year dataset enabled by NASA.

Lidars, ground or space-based, are generally used to investigate the aerosol optical properties of the aerosols. These properties can be investigated starting from the ground up to the troposphere or stratosphere (in case of a ground-based lidar), and from the stratosphere down to the ground (in case of the space-based lidar).

2.1 Ground-based lidar observations

The ground-based lidar, Polly, is a portable and autonomous lidar that can operate 24 hours. The lidar has a cabin to protect it from outside agents, and in case of rain, the measurements stop automatically. Through a glass window, a vertically pointed green (532 nm) laser beam is emitted into the atmosphere. A telescope is used to collect the 180° backscattered radiation from aerosols and molecules in the atmosphere (G. Malollari et al. 2025). In this study, we use the Raman method to retrieve the optical properties, like the backscatter coefficient, the extinction coefficient, the depolarization ratio, and the lidar ratio (Ansmann et al. 1992). The extinction coefficient is impacted

by the incomplete overlap between the laser and telescope field of view. We make use of the backscatter coefficient to retrieve the extinction coefficient and the mass concentration down to the ground. The mass concentration is computed by the following equation:

$$M = \beta * S * \rho * c_v \quad (1)$$

Where β is the particle backscatter coefficient in $\text{Mm}^{-1}\text{sr}^{-1}$, S is the lidar ratio in sr, ρ is the density in g cm^{-3} , and the extinction-to-volume conversion c_v in $\text{Mm m}^3 \text{m}^{-3}$.

In the case of dust, we applied these values: 2.6 g cm^{-3} for density, 40 sr for the lidar ratio, and 0.8 for the conversion factor. In the case of the non-dust mass concentration profile, the density is 1.5 g cm^{-3} , the lidar ratio is 50 sr, and 0.3 for c_v . The backscatter coefficient at 532 nm wavelength is directly measured with Polly. The uncertainties, represented by the error bars, are assumed to be in the order of 30% (Ansmann et al. 2021; Chen et al. 2017) and were calculated analytically using the error propagation law.

2.2 Space-based observations

CALIOP (Cloud–Aerosol Lidar with Orthogonal Polarization) is the lidar instrument onboard the CALIPSO satellite, operated by NASA from June 2006 to August 2023, which provides vertically resolved aerosol measurements (Winker et al. 2007; 2009). The measurement dataset is available through the NASA EarthData Search portal (<https://search.earthdata.nasa.gov/search>) at different processing levels, including Level 1, Level 2, and Level 3. Aerosol mass concentrations at multiple altitude ranges are derived from the monthly gridded extinction coefficients provided as a Level 3 product, with a spatial resolution of $5^\circ \times 2^\circ$ (longitude $\times$ latitude) (Winker et al. 2013). Similar to the Polly lidar observations, only nighttime, cloud-free measurements are used in this analysis.

3. RESULTS

Aerosol mass concentrations are presented in Figures 1–3, calculated using Equation 1 and displayed as a function of altitude. Both ground-based Polly lidar observations in Tirana, Albania, and CALIOP satellite measurements are included in the analysis.

3.1 Polly lidar observations

In Figure 1, we present the aerosol mass concentration profiles based on ground-based Polly observations. These measurements, taken in Tirana, were performed during November 2022 and October 2023. The lidar was operating 24 hours.

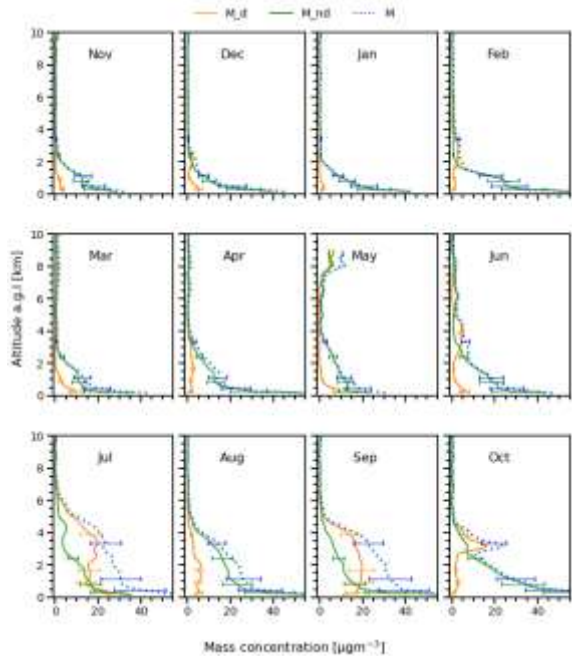


Figure 1: Aerosol mass concentration profiles for dust (orange line), non-dust (green line), and the total (blue dotted line), obtained from Polly observations in Tirana, Albania, during November 2022 and October 2023. The error bars indicate the uncertainties computed as error propagation.

Only nighttime measurements are included in this study due to their higher signal-to-noise ratio. Aerosol mass concentrations are retrieved using Equation 1, as described in Section 2.1, and the contributions of dust, non-dust, and total aerosols (sum of both) are shown. The aerosol layer varies seasonally, extending from ~ 2 km in January to 10 km in June. During November through February, the layer remains lowest, around 2–3 km, while in summer it reaches 6–10 km. Ground-level mass concentrations are lowest in November and May ($\sim 30 \mu\text{g m}^{-3}$) and range between $40\text{--}60 \mu\text{g m}^{-3}$ for the rest of the year.

Dust occurs year-round, peaking in July and September at $\sim 20 \mu\text{g m}^{-3}$ from the surface up to 5 km, dominating the aerosol composition in these months. In other months, the non-dust component prevails. A small peak in the non-dust profile between 8 and 10 km in May is attributed to long-range transported aerosols, likely smoke from North American and Canadian wildfires. In June and October, two dust layers are observed: one near the surface and a second extending from 2 to 5 km.

3.2 CALIOP observations

The following plots present the seasonal variability of dust and non-dust aerosol mass concentrations derived from CALIOP observations spanning 2006–2021. Results are shown for three altitude ranges: 0–2 km, 2–5 km, and 5–10 km.

3.2.1 Non-dust aerosol evolution

The seasonal pattern of non-dust aerosol mass concentration, as shown in Figure 2, remains relatively stable throughout the study period, suggesting a continuous influence from permanent sources such as traffic and industrial activities. An exception

is observed in spring, where a decreasing trend in aerosol mass concentration is evident. Overall, concentrations are lower in the last two analyzed years, 2020 and 2021, likely reflecting the impact of COVID-19 lockdown measures.

During autumn, the 0–2 km altitude range exhibits two distinct phases. From 2006 to 2012, an increasing trend is observed, peaking at approximately $25 \mu\text{g m}^{-3}$ in 2012. From 2013 onward, following a sharp decline, concentrations remained relatively stable, fluctuating between 5 and $10 \mu\text{g m}^{-3}$.

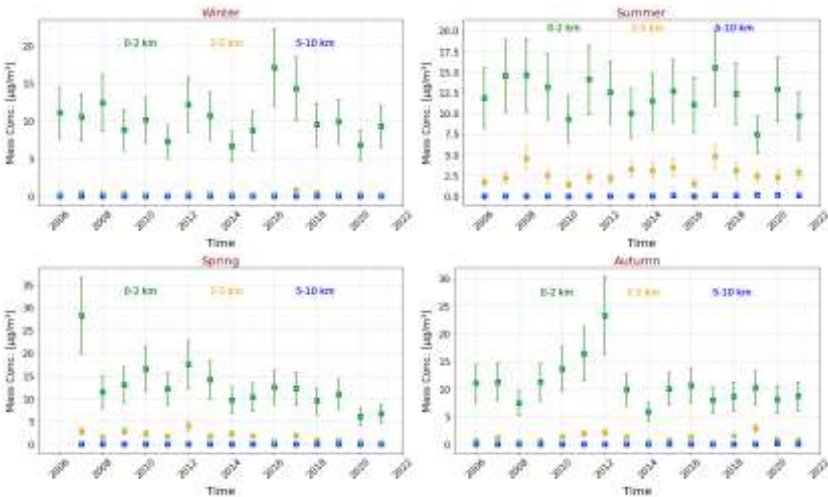


Figure 2: Non-dust aerosol mass concentrations obtained from CALIOP observations for Albania, during June 2006 and December 2021. The error bars represent uncertainties of 30%, estimated through error propagation.

In winter, most aerosols are confined within the planetary boundary layer, with concentrations almost entirely below 2 km. By contrast, during the other seasons, the aerosol layer extends higher into the atmosphere, reaching the free troposphere. At 2–5 km altitude, aerosol concentrations are negligible in winter, while small amounts appear in spring and autumn. In summer, however, aerosol layers regularly extend up to 5 km throughout the 15 years, although their concentrations remain lower than those observed in the 0–2 km range. Besides permanent contributions from local sources, regional and continental transport of pollution aerosols plays a significant role, with wildfire smoke episodes—occurring sporadically in summer—also contributing.

At 5–10 km altitude, where aerosols are strongly influenced by long-range intercontinental transport, their contribution is negligible on average. Although events such as wildfires in North America and Canada can occasionally inject aerosols into this layer, their impact is not visible in the long-term mean due to averaging over the 15-year dataset.

3.2.2 Dust Evolution

Mineral dust considerably enhances aerosol mass concentrations. As shown in the summer plot, average concentrations can reach up to $80 \mu\text{g m}^{-3}$ during dust outbreaks. The dust layer typically extends up to 5 km, with additional contributions occasionally observed between 5 and 10 km. The dust season appears to span from spring through

autumn; however, dust intrusions are also recorded in winter. For instance, during the winters of 2008 and 2015, dust mass concentrations in the lower troposphere (0–2 km) reached 28 and 38 $\mu\text{g m}^{-3}$, respectively.

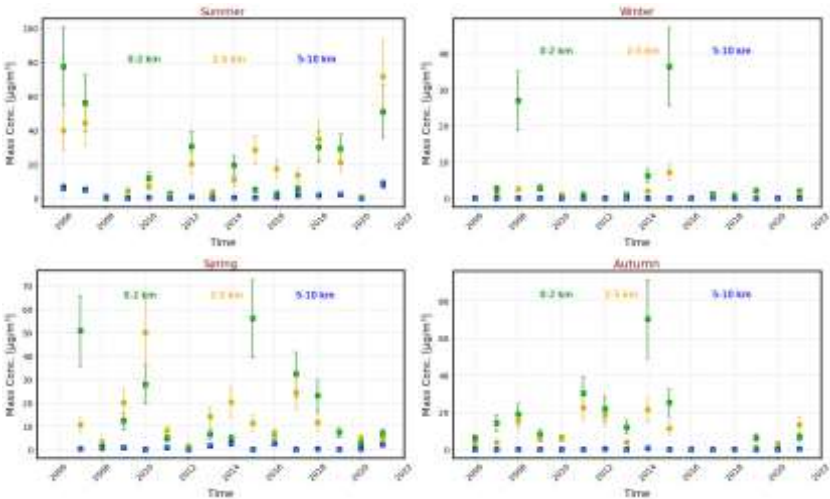


Figure 3: Dust mass concentrations obtained from CALIOP observations for Albania, during June 2006 and December 2021. The error bars represent uncertainties of 30%, estimated through error propagation.

In the summer, spring, and autumn plots, some years appear to show no dust presence. However, this may reflect the limitations of satellite measurements rather than the complete absence of dust events. CALIPSO, with a repeat cycle of 16 days, provides relatively low temporal coverage. As a result, short-lived or spatially localized dust intrusions may be missed, leading to underrepresentation in the seasonal averages.

4. CONCLUSIONS

This study provides a comprehensive assessment of aerosol mass concentrations over Albania and the surrounding region using long-term CALIOP satellite observations and one year of Polly lidar measurements in Tirana. Compared to the regional background, Tirana exhibits notably higher near-surface concentrations, reflecting its role as the most urbanized and densely populated area in Albania. The long-term CALIOP observations indicate no significant trend in aerosol mass concentrations, with relatively stable levels across different altitude ranges. Non-dust aerosols are primarily confined to the lowest 2 km, whereas dust layers show greater vertical variability, frequently extending up to 5 km. Ground-based measurements in Tirana confirm elevated aerosol loads near the surface throughout the year, with seasonal differences in vertical distribution: during winter, the main aerosol layer remains below 2 km, while in other seasons it can extend to 5–10 km. These findings underline the importance of integrating satellite and ground-based observations to capture both regional and urban aerosol characteristics and to better understand their seasonal and vertical variability.

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