Evaluating the MONARCH Model with Lidar Data: A Step Toward Improving Global Dust Surface Concentrations

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Introduction

Dust is a major atmospheric aerosol component that significantly impacts air quality, human health, and climate. Accurately forecasting dust concentrations, especially near the surface, is crucial for early warning systems and environmental assessments. Since July 2024, the Multiscale Online Nonhydrostatic AtmospheRe Chemistry (**MONARCH**) model provides **vertical profiles of dust concentrations** through the Barcelona Dust Regional Center (**BDRC**), which acts as part and coordination entity of the Northern Africa, Middle East and Europe (**NAMEE**) node of the WMO Sand and Dust Storm Warning Advisory and Assessment System (**SDS-WAS**). This study presents the **first evaluation** of this new forecast product using lidar measurements from the NASA Micro-Pulse Lidar Network (**MPLNET**). The objective is to assess whether dust vertical profiling can constrain and improve modelled ground concentrations. As a term of comparison, we also used **PM_{10} observations** from the European Environment Information and Observation Network (**Eionet**).

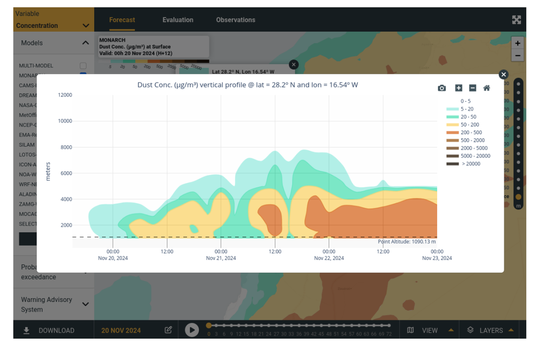


Figure 1: Vertical profile of dust concentration (μg/m^3) forecasted by MONARCH in Tenerife from 20th to 23rd November 2024. Screenshot from https://dust.aemet.es.

Dust Vertical Profiles

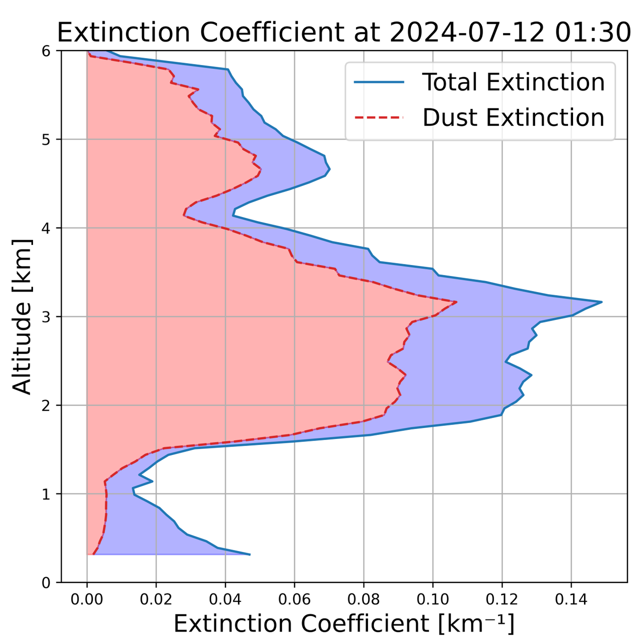


Figure 2: Extinction coefficient and dust extinction coefficient in Tenerife on 14th of July 2024 around 8 AM.

We compared MONARCH model and MPLNET lidar measurements of **dust extinction coefficient vertical profiles** in Tenerife, Barcelona, and El Arenosillo between July 2024 and February 2025. For that purpose, the **POLIPHON** algorithm was used to extract the dust extinction coefficient from the available lidar products. According to Tesche et al. 2009 (doi:10.1029/2009JD011862):

$$\alpha_{\lambda,d}(z) = S_{\lambda,d} * \beta_{\lambda,d}(z)$$

$$\beta_{\lambda,d}(z) = \beta_{\lambda,p}(z)\frac{(\delta_{\lambda,p}(z) - \delta_{\lambda,nd})(1+\delta_{\lambda,nd})}{(\delta_{\lambda,d} - \delta_{\lambda,nd})(1+\delta_{\lambda,p}(z))}$$

where, α and β are the extinction and backscatter coefficients, z is the altitude, λ is the wavelength (532 nm), and the subscripts "d", "nd" and "p" stand for "$dust$", "$non-dust$" and "$particle$" respectively. The assumptions we made were:

- Dust particle linear depolarization ratio, $\delta_{\lambda,d} = 0.31$
- Non-dust particle linear depolarization ratio, $\delta_{\lambda,nd} = 0.05$
- Dust lidar ratio, $S_{\lambda,d} = 54$ sr

Regarding MONARCH we exploited the first 24 hours of **operational forecasts** of dust extinction coefficient at 550 nm and dust PM_{10} concentration (**pm10du**). Figure 3 compares the vertical profiles of dust extinction retrieved from lidar measurements against those simulated with the model in the three sites during dust episodes.

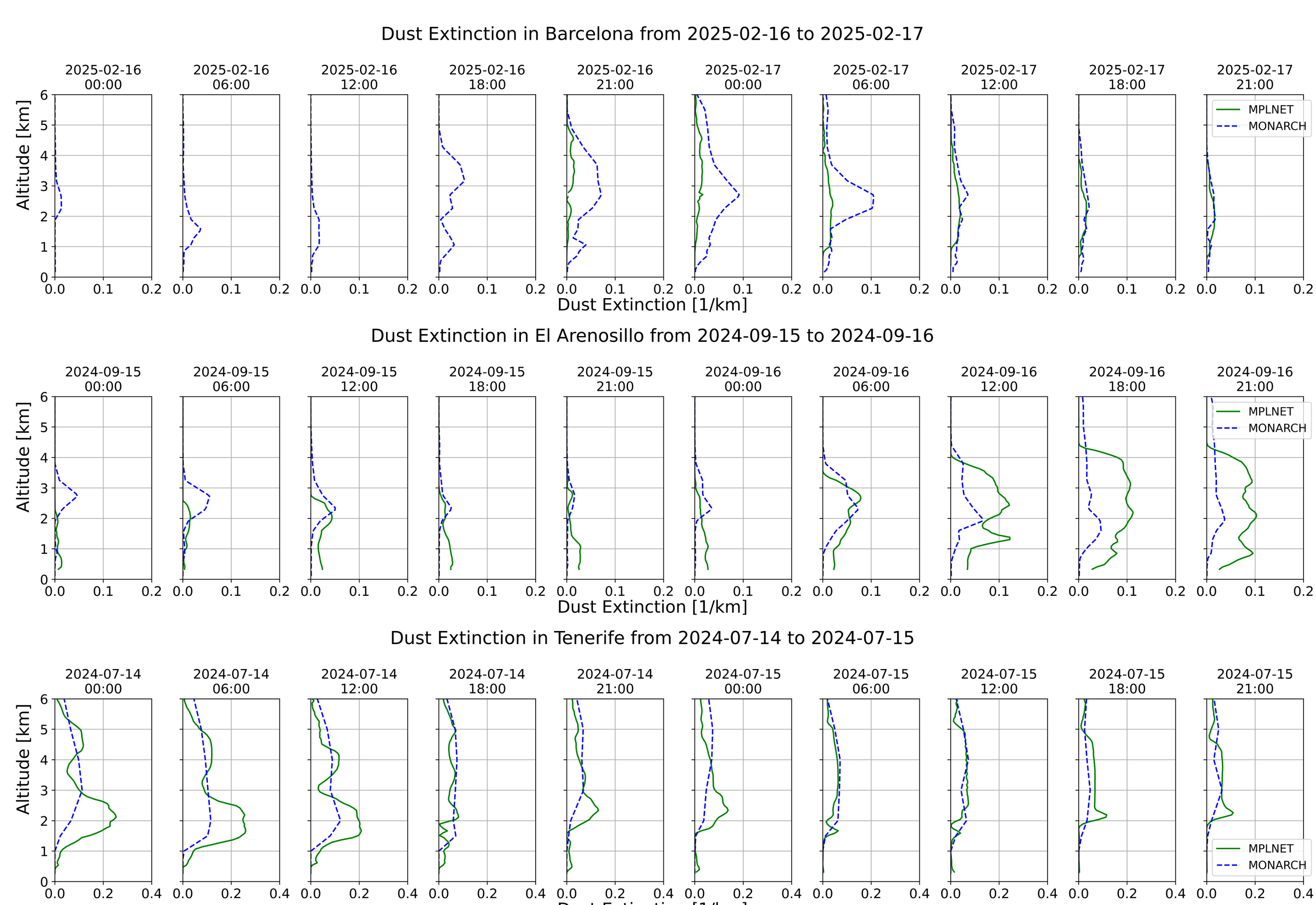
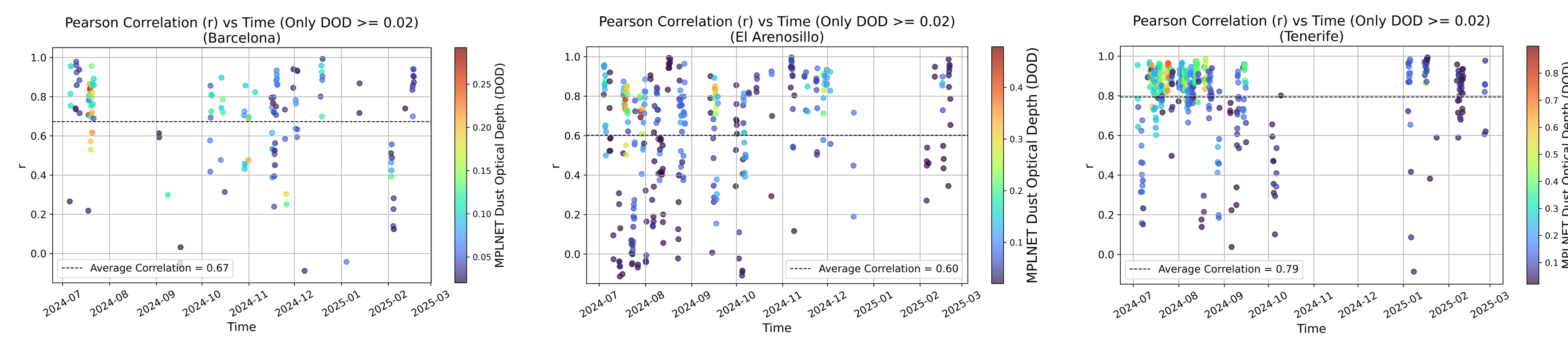


Figure 3: Comparison between MPLNET and MONARCH dust extinction coefficient for two days every six hours in the three sites.

Model Comparison

Figure 3 showcases examples of good agreement between profiles (e.g., the Tenerife panel) and cases where the model is overpredicting (Barcelona) or underpredicting (El Arenosillo) a dust plume.

A summary of the degree of similarity between modelled and observed vertical structures is shown in Figure 4, quantified by the **Pearson correlation coefficient (r)** between profiles, for all coincident measurements in the period of study. Average values of r are above 0.6 in the three sites, with better scores in cases of large dust loading (measured by the dust optical depth, DOD).



Figures 4: Time evolution of the Pearson correlation between MPLNET dust extinction and MONARCH dust extinction.

The **average altitude** of the dust extinction coefficient was computed at each timestep as $\sum \alpha_i z_i / \sum \alpha_i$ (where α represents the dust extinction, z the altitude level, and i the i−th layer), and it is shown in Figure 5. There is an overall agreement between MONARCH and MPLNET values in the three sites. For cases where the measured dust optical depth is larger than 0.02, moderate to strong correlation values were found (Table 1).

Table 1: Pearson correlation (r) and number of samples (in parenthesis) between dust profiles of MPLNET and MONARCH.

Barcelona	El Arenosillo	Tenerife
$r = 0.61$ (136)	$r = 0.52$ (318)	$r = 0.84$ (375)

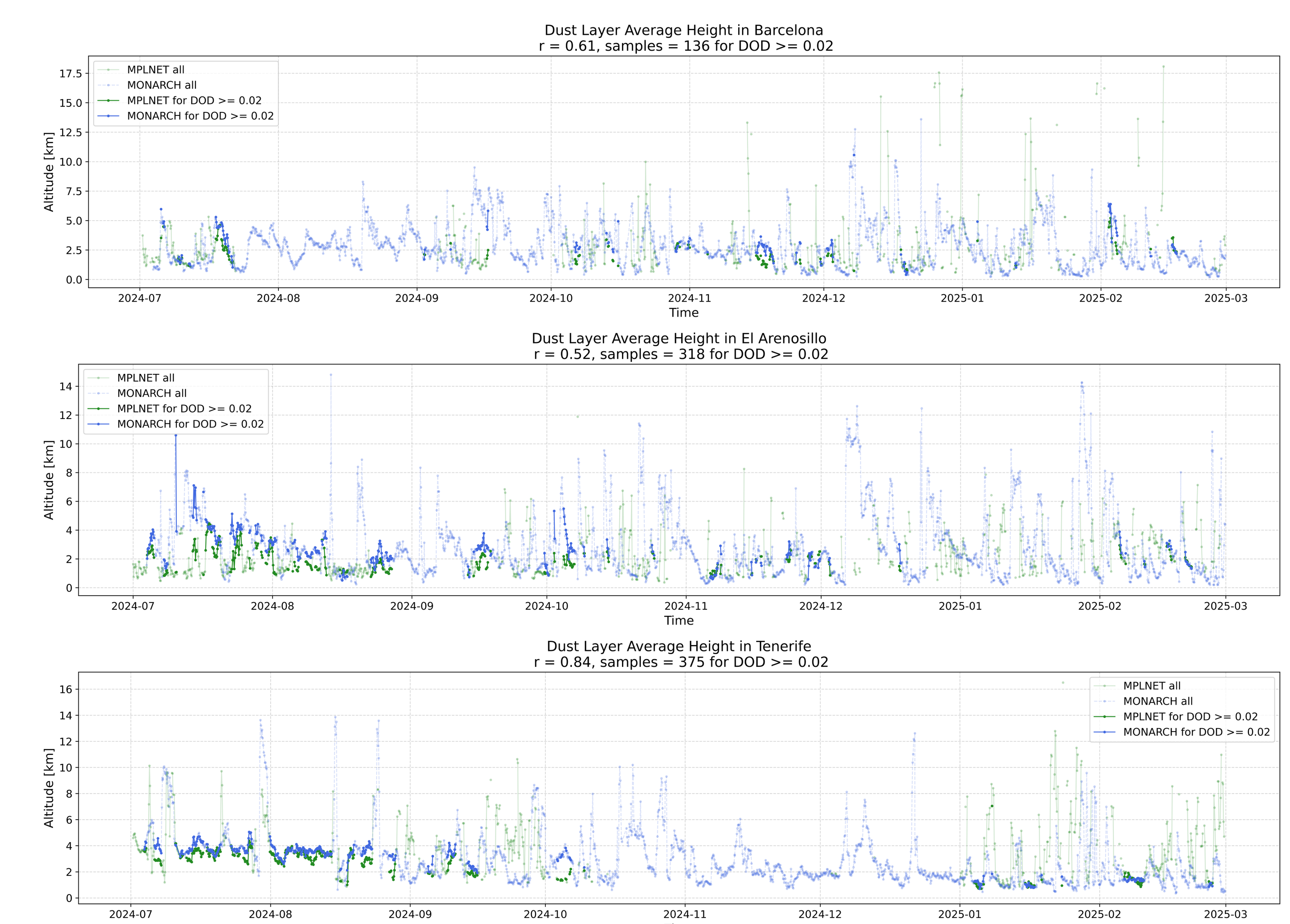


Figure 5: Time variation of the average altitude of dust for MONARCH simulations and MPLNET measurements.

Although MONARCH often agrees with the lidar in terms of vertical structure and dust transport, it does not consistently reproduce **surface concentrations**. As seen in the time series in Figure 6, the model may both overestimate and underestimate PM_{10} levels. This can be due to measurements of other types of aerosols than dust in the PM observations, misrepresentation of dust dynamics, emission or optics in the model, or representativeness issues, among other reasons.

A first step to assess the potential of lidar data in improving model ground concentrations, we analyzed the relationship between MPLNET-derived dust extinction near the surface and observed PM_{10}. Specifically, we averaged extinction values over **three layers** (100–300 m, 400–600 m, and 700–900 m), and compared each with **PM_{10} observations**.

These results (Table 2) suggest that lidar data in the low atmosphere correlates better with observed PM_{10} than the model's output, supporting its use as a correction reference for $pm10du$.

Table 2: Pearson correlation (r) and number of collocated samples (in parentheses) between PM_{10} observations and MPLNET dust extinction per layer and between PM_{10} observations and MONARCH dust-only PM_{10} concentration ($pm10du$) at the three study sites.

	Barcelona	El Arenosillo	Tenerife
MONARCH pm10du	$r = 0.30$ (574)	$r = 0.23$ (800)	$r = 0.49$ (821)
MPLNET 100–300 m	$r = 0.56$ (574)	$r = 0.59$ (800)	$r = 0.83$ (821)
MPLNET 400–600 m	$r = 0.57$ (574)	$r = 0.56$ (800)	$r = 0.83$ (821)
MPLNET 700–900 m	$r = 0.48$ (574)	$r = 0.53$ (800)	$r = 0.81$ (821)

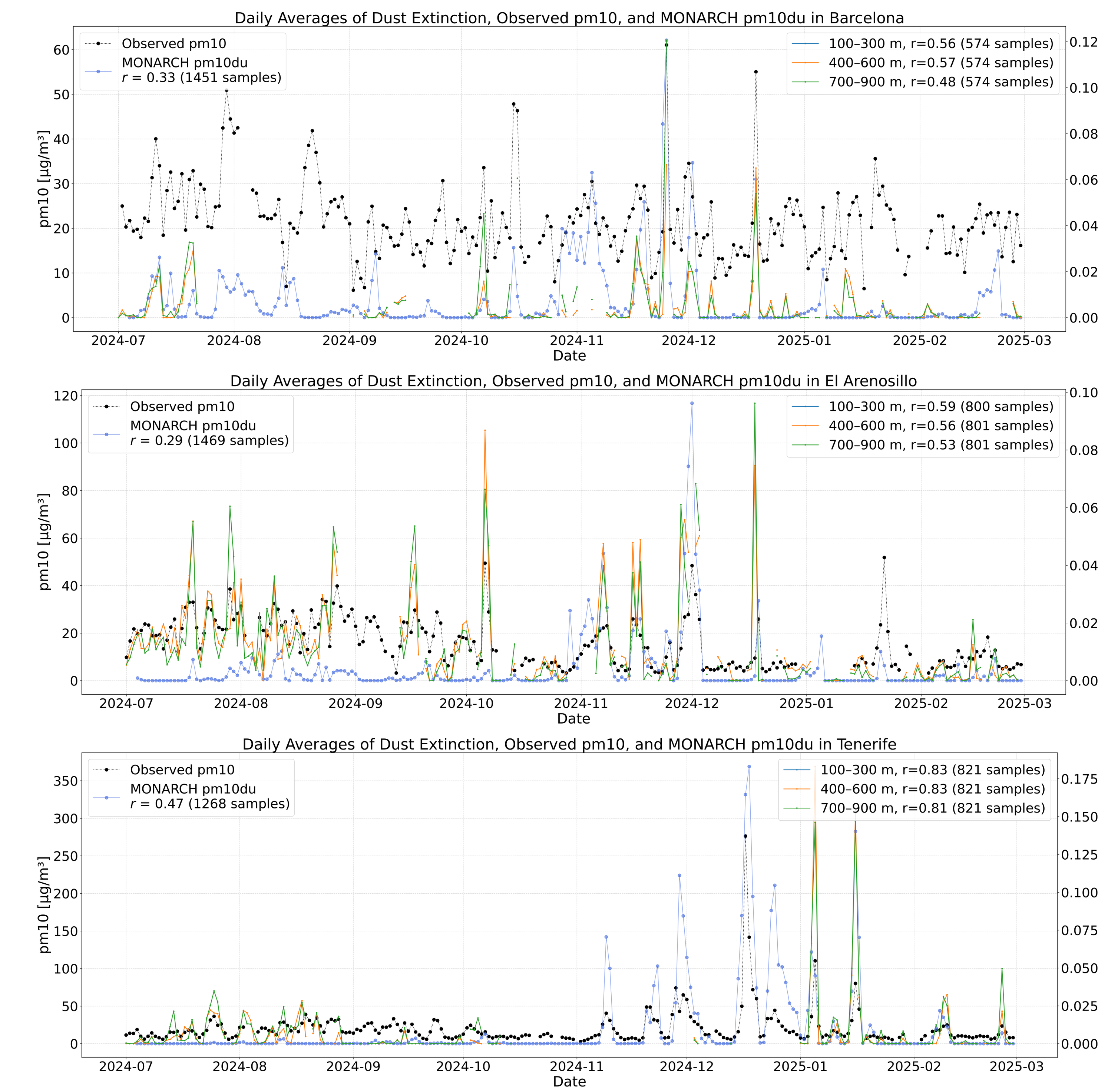


Figure 6: Time series of PM_{10} observations, MONARCH dust-only PM_{10} concentration, MPLNET derived dust extinction coefficient at three different layers (100–300 m, 400–600 m, and 700–900 m) in the three sites.

Conclusions and Future Perspectives

We evaluated SDS-WAS MONARCH operational forecasts of vertical dust profiles against MPLNET lidar and surface PM_{10} measurements. MONARCH reproduces the vertical structure of dust plumes with good agreement to MPLNET lidar, as shown by relatively strong correlations in dust layer altitudes ($r = 0.52$–0.84) during dust episodes (DOD ≥ 0.02). However, correlations between MONARCH $pm10du$ and observations are modest ($r = 0.23$–0.49), and often lower than those obtained using MPLNET-derived extinction in the lowest 100–900 m ($r = 0.48$–0.83). We conclude that the modelled vertical shape of dust appears not to be the main source of error in forecasting dust ground concentrations.

These results highlight the potential of lidar extinction profiles, particularly near the surface, to improve modeled dust ground concentrations through correction or assimilation approaches.

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