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Reliability Evaluation of CAMS Air Quality Products in the Context of Different Land Uses: The Example of Cyprus †

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Abstract

Cyprus is located between Europe, Asia and Africa, and its location is vulnerable to dust transport from the Sahara Desert, wildfire smoke particles from surrounding regions, and other anthropogenic emissions caused by several factors, mostly due to business activities on harbor areas. Moreover, the country suffers from heavy traffic conditions caused by the limited public transportation system in Cyprus. Therefore, taking into consideration the country's geographic location, heavy commercial activities, and lack of good public transportation system, Cyprus is exposed to dust episodes and high anthropogenic emissions associated with multiple health and environmental issues. Therefore, continuous and qualitative air quality monitoring is essential. The Department of Labor Inspection of Cyprus (DLI) has established an air quality monitoring network that consists of 11 stations at strategic geographic locations covering rural, residential, traffic and industrial zones. This network measures the following pollutants: nitrogen oxide, nitrogen dioxide, sulfur dioxide, ozone, carbon monoxide, particulate matter 2.5, and particulate matter 10. This case study compares and evaluates the agreement between Copernicus Atmosphere Monitoring Service (CAMS) air quality products and ground-truth data from the DLI air quality network. The study period spans from January to December 2024. This study focuses on the following three pollutants: particulate matter 2.5, particulate matter 10, and ozone, using Ensemble Median, EMEP, and CHIMERE near-real-time model data provided by CAMS. A data analysis was performed to identify the agreement and the error rate between those two datasets (i.e., ground-truth air quality data and CAMS air quality data). In addition, this study assesses the reliability of assimilated datasets from CAMS across rural, residential, traffic and industrial zones. The results showcase how CAMS near-real-time analysis data can supplement air quality monitoring in locations without the availability of ground-truth data.

Keywords: health; atmosphere; air pollution; emissions; air quality

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1. Introduction

Air pollution is widely recognized as one of the most significant environmental risks to human health and ecosystems. According to the World Health Organization (WHO), exposure to ambient (outdoor) air pollution causes approximately 7 million premature deaths annually [1]. Among the most critical pollutants are particulate matter (PM10 and PM2.5) and ozone (O_3), which have been linked to respiratory diseases, cardiovascular disorders, and increased hospital admissions [1,2]. In the Eastern Mediterranean and the Middle East region, including Cyprus, the burden of air pollution is further intensified by unique geographical and meteorological factors [3]. Cyprus is frequently affected by transboundary transport of mineral dust originating from the Sahara Desert and the Middle East. These episodes can significantly elevate PM concentrations, sometimes exceeding the EU limit values [4,5].

Furthermore, urban traffic emissions, industrial activities, and seasonal wildfires contribute to local pollution loads [6]. The semi-arid climate facilitates resuspension of dust from soils and roads, particularly during summer and autumn [7]. This combination of long-range transported and local emissions makes air quality management in Cyprus especially challenging. Accurate, timely information on pollutant concentrations is vital for (i) issuing health advisories, (ii) supporting regulatory compliance, and (iii) designing mitigation measures [8].

Given the sparse spatial coverage of ground-based monitoring stations, there is a growing interest in integrating model-based and satellite-derived air quality products to improve situational awareness and early warning capabilities. Traditionally, air quality monitoring has relied on ground-based measurement networks operated by national or regional authorities. These stations use reference-grade instruments to continuously measure concentrations of regulated pollutants such as PM10, PM2.5, ozone (O_3), nitrogen dioxide (NO_2), and carbon monoxide (CO). While these observations are considered the gold standard for regulatory compliance and public health protection, they have important limitations, including sparse spatial coverage—particularly in rural or remote areas—high operational and maintenance costs, and delays in data availability, which can hinder timely health advisories.

To overcome these constraints, the past two decades have seen rapid advances in satellite remote sensing, chemical transport modeling, and data assimilation techniques. These technologies enable the generation of spatially continuous estimates of atmospheric composition at high temporal resolution. One of the most important initiatives in this field is the open-access Copernicus Atmosphere Monitoring Service (CAMS) EAC4, implemented by the European Centre for Medium-Range Weather Forecasts (ECMWF). CAMS Atmosphere Data Store (https://ads.atmosphere.copernicus.eu/, accessed 5 July 2025) delivers global forecasts of atmospheric composition up to five days ahead and reanalysis datasets that combine satellite observations, ground measurements, and advanced models to produce consistent, high-quality estimates of historical air pollution levels, as well as near-real-time analyses that support applications ranging from scientific research to environmental policymaking [9].

A key CAMS product family is the CAMS Global Reanalysis (EAC4), which integrates multiple data sources, including satellite sensors such as MODIS, IASI, and OMI, in situ observations from monitoring networks, and the Integrated Forecasting System (IFS) with chemistry modules. These datasets have been validated against ground-based measurements and shown to provide reliable large-scale estimates of pollutant concentrations [9]. Furthermore, the CAMS Atmosphere Data Store (ADS) offers free, open access to reanalysis and forecast data, along with download tools, APIs, and interactive viewers and Jupyter notebooks that facilitate analysis by experts and non-experts alike.

Integrating CAMS products with national monitoring networks has the potential to enhance spatial coverage, support the identification of transboundary pollution episodes, and complement local observations for regulatory compliance, public information, and health protection [10,11].

Despite the advances in atmospheric modeling and satellite-derived datasets, the adoption of CAMS products for operational air quality management in Cyprus remains limited. One of the main reasons for this limited uptake is the lack of systematic validation of CAMS outputs against in situ observations under local conditions. As the island is characterized by diverse land use types, ranging from densely populated urban areas to industrial zones and rural backgrounds, it is critical to understand how well CAMS estimates represent actual measurements in each setting.

The primary aim of this study is to evaluate the reliability and agreement of CAMS air quality products with observations from the national air quality monitoring network operated by the Department of Labor Inspection (DLI) in Cyprus. By focusing on different land-use categories and key pollutants such as PM10, PM2.5, and O_3, the study seeks to provide evidence on the suitability of CAMS data for supporting air quality assessment, public health protection, and regulatory reporting at the national level.

To address this aim, the study pursues the following specific objectives: First, it integrates CAMS model-based data with ground-based observations for a defined study period, creating a consistent dataset for comparative analysis. Second, it conducts a time-series exploration of pollutant concentrations across selected monitoring stations representing urban traffic, industrial, and rural environments. Third, it assesses the statistical relationships and performance metrics—such as correlation coefficients, root mean square error, mean absolute error, and bias—to quantify the agreement between CAMS estimates and official measurements. Finally, it discusses the implications of the findings for the potential operational use of CAMS products in Cyprus and identifies areas where further calibration or adjustment may be needed.

The remainder of this paper is structured as follows. Section 2 presents related work and relevant studies that have evaluated CAMS products and other air quality models against observational datasets. Section 3 describes the study area, data sources, and methodological approach, including the statistical techniques used for performance assessment. Section 4 provides the results of comparative analysis across pollutants and land use types. Finally, Section 5 presents the discussion and conclusions, offering recommendations for future work and potential strategies to enhance the integration of CAMS data into air quality management practices in Cyprus.

2. Related Works

This section reviews relevant studies that validate and utilize the Copernicus Atmosphere Monitoring Service (CAMS), such as Ensemble Median, CHIMERE, and EMEP, particularly through comparison with ground-based measurements.

Several studies have focused on the comprehensive evaluation of regional air quality models and CAMS products across various geographical domains. CAMS data have been utilized even in areas with limited monitoring stations, and have been shown in multiple studies. Research in Colombia was conducted using CAMS data together with MODIS Aerosol Optical Depth (AOD) to estimate PM10 and PM2.5 levels, finding strong correlations with ground measurements [12,13]. These studies from different locations demonstrate the overall effectiveness of CAMS for particulate matter monitoring.

In Europe and the Eastern Mediterranean, numerous assessments have evaluated the performance of CAMS products, generally reporting moderate to strong agreement between CAMS estimates and ground station data for particulate matter concentrations in urban environments [14]. Furthermore, studies specifically examining CAMS-based pollutant data in the Eastern Mediterranean region and Turkey have highlighted significant spatial and seasonal variations in model reliability, with some reporting acceptable performance in less industrialized areas, despite underestimating PM2.5 in high-pollution zones [15,16]. Moreover, another study [17] has shown similar findings where CAMS reanalysis products have shown a weak correlation in China. These regional findings point out the necessity of regional model assessment and validation, such as the one presented here for Cyprus, given the unique atmospheric dynamics of the Eastern Mediterranean.

Kaffashzadeh et al. [18] developed a unified framework for evaluating regional air quality models, including CHIMERE v2023r1 and EMEP rv4.34 , across Europe using in situ measurements. This approach emphasizes the importance of standardized validation methodologies, which directly informed the design of the present study. Collectively, these studies demonstrate that while CAMS provides valuable large-scale air quality estimates, regional assessments remain essential to characterize model performance in specific environments and support their integration into local air quality management. The present work contributes to this effort by evaluating CAMS products in Cyprus, an area influenced by unique atmospheric dynamics and transboundary pollution processes.

3. Materials and Methods

3.1. Air Quality In Situ Network

Cyprus is an island located in the eastern Mediterranean Sea and is part of the wider area of the Eastern Mediterranean, Middle East, and North Africa region [19]. The island's air quality is often affected by severe dust events, transportation emissions, and traveling particles of wildfire smoke from neighboring countries, among others. For better monitoring, the Department of Labor Inspection (DLI) of Cyprus has established an air quality network with in situ sensors for surface emissions and particulate matter measurements at strategic locations to represent different land use areas, as shown in Figure 1. The network consists of 9 stations. More specifically, there are five sensors installed near or at areas with high-traffic movement (denoted as traffic stations) within major city centers: two at industrial areas, one station near a residential area, and one reference station in a rural area. The stations measure hourly concentrations of PM2.5, PM10, and O_3.

Figure 1. Air quality in situ network of the Department of Labor Inspection of Cyprus. Yellow dots represent the locations of the air quality sensors. Labels give the names and the land use types where sensors are installed.

3.2. Copernicus Atmosphere Monitoring Service

CAMS offers, on a daily basis, data for air quality forecasts, air quality analyses, and for certain periods, annual time-series reanalyses. Moreover, reanalysis products are based on different models. In this study, a dataset of air quality variables from CAMS was constructed. The dataset consists of air quality reanalysis data spanning the whole year of 2024 for PM2.5, PM10, and O_3 from the three models (i.e., Ensemble Median, EMEP, and CHIMERE). Model outputs were extracted at a spatial resolution of $0.1^\circ \times 0.1^\circ$, corresponding to each station's coordinates.

3.3. Data Analysis

For this research work, data preprocessing includes time alignment and aggregation of hourly observations into daily averages to ensure comparability. In addition, various techniques were used to identify the relationships between ground-truth air quality observations and CAMS reanalysis products. Pearson correlation coefficients are calculated to quantify the linear agreement between the two datasets. Scatter plots are created to visualize the relationship between CAMS estimates and DLI measurements. Time-series plots are generated to illustrate temporal trends over the study period. All analyses are performed using the pandas 2.2.2 and scipy 1.13.1 Python packages, for Python version 3.12.7.

4. Results

To evaluate the performance and reliability of the near-real-time models—Ensemble Median, EMEP, and CHIMERE, provided by the Copernicus Atmosphere Monitoring Service (CAMS)—a comparative data analysis was conducted against in situ measurements from the Department of Labor and Inspection (DLI) air quality monitoring network. This comparison focuses on three key pollutants: ozone (O_3), PM2.5, and PM10. These were assessed across rural, residential, traffic, and industrial environments in Cyprus during the year 2024. The analysis included a correlation table, scatter plots, and time-series plots to illustrate the level of agreement between model-derived estimates and observed data.

Table 1 summarizes the Pearson correlation coefficients for each pollutant and station. For PM10, Ensemble Median correlations ranged from 0.69 to 0.81 across all sites, indicating moderate to strong agreement. EMEP exhibited comparable performance, with slightly lower correlations in some sites, while CHIMERE generally showed weaker correlations, particularly in traffic-dominated areas. For PM2.5, Ensemble Median achieved correlations between 0.68 and 0.83, again demonstrating consistent reliability relative to EMEP and outperforming CHIMERE. Ozone correlations were notably high overall, with Ensemble Median exceeding 0.90 in Nicosia residential and traffic stations and achieving values above 0.80 in most other locations.

Figure 2 presents time-series plots comparing daily PM2.5 concentrations from CAMS Ensemble Median against DLI ground-based measurements during 2024. The top subplot shows data from the Limassol Traffic Station, while the bottom subplot corresponds to the Paphos Traffic Station. These examples were selected to illustrate contrasting seasonal and pollution dynamics in two urban areas with different traffic densities and meteorological patterns. In Limassol, the Ensemble Median model captured the main temporal trends and peak concentrations during high pollution periods in April and November, though it tended to slightly underestimate some episodic maxima. In Paphos, the agreement between the datasets was stronger during summer, with greater discrepancies during winter, likely reflecting differences in local meteorology and boundary conditions.

Table 1. Pearson correlation coefficients for pollutant PM10 between CAMS Models and DLI air quality monitoring network across Cyprus.

Station	Pollutant	Ensemble Median	EMEP	CHIMERE
Ayia Marina Xyliatou	PM2.5	0.83	0.79	0.67
	PM10	0.81	0.75	0.59
	O_3	0.94	0.85	0.61
Larnaca Traffic Station	PM2.5	0.74	0.70	0.59
	PM10	0.74	0.71	0.55
	O_3	0.81	0.72	0.53
Limassol Traffic Station	PM2.5	0.69	0.68	0.54
	PM10	0.76	0.71	0.53
	O_3	0.83	0.73	0.50
Mari Industrial Station	O_3	0.69	0.62	0.54
Nicosia Residential Station	O_3	0.95	0.89	0.77
Nicosia Traffic Station	PM2.5	0.74	0.73	0.64
	PM10	0.69	0.64	0.55
	O_3	0.94	0.86	0.79
Paphos Traffic Station	PM2.5	0.74	0.76	0.64
	PM10	0.77	0.78	0.50
	O_3	0.78	0.70	0.57
Paralimni Traffic Station	PM2.5	0.68	0.63	0.52
	PM10	0.69	0.66	0.46
	O_3	0.81	0.70	0.60
Zygi Industrial Station	PM2.5	0.81	0.80	0.66
	PM10	0.81	0.80	0.60
	O_3	0.82	0.73	0.57

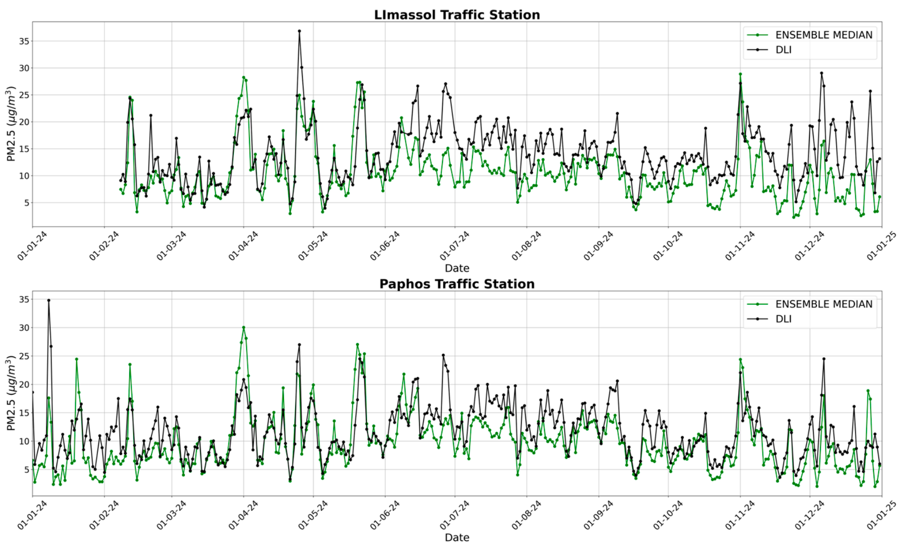

Figure 2. Time-series plots with PM2.5 values derived from model Ensemble Median with DLI for Limassol and Paphos traffic station data in 2024.

5. Discussion and Conclusions

The findings of this study demonstrate that the CAMS Ensemble Median model provided reliable estimates of O_3, PM2.5, and PM10 concentrations throughout 2024 in Cyprus, covering diverse land-use categories. As shown in Table 1, O_3 estimates exhibited particularly strong correlations with ground truth data, achieving Pearson coefficients exceeding 0.9 in the Nicosia residential station, and above 0.80 in most other locations. This strong performance underscores the model's suitability for representing the temporal and spatial variability of O_3, which is critical for public health risk assessment and regulatory compliance reporting.

Both the Ensemble Median and EMEP models performed consistently well in estimating PM2.5 and PM10 concentrations, as evidenced by the correlation results (Table 1). The time-series examples in Figure 2 illustrate how the Ensemble Median model effectively reproduced the temporal variability of PM2.5 in traffic-affected urban areas. While the model tended to underestimate peak concentrations in some high-pollution episodes, overall agreement remained strong across seasons and locations. In industrial zones, such as Zygi, model outputs also aligned closely with observed measurements, reinforcing the potential value of CAMS products in a range of settings.

Although CHIMERE generally demonstrated lower correlation coefficients, especially for PM10, its inclusion within the ensemble framework contributed to a more comprehensive assessment of model uncertainties. These observed differences across models, pollutants, and environments emphasize the importance of site-specific validation studies before adopting CAMS data operationally.

Overall, the results indicate that CAMS models—particularly Ensemble Median—represent a promising resource to supplement existing monitoring networks and support air quality management in Cyprus. The consistency of model performance across varied environments suggests they can provide credible data for routine assessments, public communication, and scenario analysis aimed at reducing air pollution exposure.

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Data Availability Statement: Reanalysis and forecast data used in this study are available from Copernicus Atmosphere Monitoring Service by Atmosphere Data Store Application Programming Interface (https://ads.atmosphere.copernicus.eu/, accessed on 10 July 2025) and in situ datasets by request to the Department of Labour Inspection of Cyprus (https://www.airquality.dli.mlsi.gov.cy/, accessed on 10 July 2025) and/or through the national data portal of the Republic of Cyprus (https://data.gov.cy/, accessed on 10 July 2025).

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