

An Anemometer Integration in a Low-Cost Air Quality Sensor System: A Real-World Case Study [†]

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Abstract

The field deployment of low-cost air quality sensors systems enables enhanced spatial resolution in air quality monitoring. Although these sensor systems cannot achieve the same accuracy as regulatory monitoring stations, they can attain acceptable levels of confidence and provide *Indicative Measurements* as regulated by *Ambient Air Quality EU Directive*. The integration of an anemometer into a system can provide additional information for the classification of the measurement area, the identification of potential sources of pollutant emissions, and the assessment of the device's operating conditions during measurement. The measurement capabilities of an Airbox, a low-cost air quality sensor system, have been extended through the integration of a DW6410 anemometer (Davis Instruments). The Airbox, designed to transmit data in real-time or near real-time to servers and IoT platforms, was deployed for a duration of 4 months, from October 2021 to February 2022, within the airport area of Grottaglie (Southern Italy). The anemometric measurements and particulate concentration data (PM_{2.5} and PM₁₀, measured by NextPM sensor, Tera Sensor) were integrated and compared to meteorological open data and data from a regulatory regional air quality control network located in the area around the airport.

Keywords: air pollution; anemometry; air quality monitoring; low-cost sensor system; anemometric measurements; particulate matter; air pollutant flux; wireless sensors; Internet of Things

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1. Introduction

Environment and public health are daily exposed to the aggressive action of polluting agents with serious risks, not only for vulnerable people, of the onset of pathologies that can evolve dramatically over time. Air pollution is one of the recognized causes [1] and, following shared regulatory guidelines [2,3]. Many Countries have designed, installed and currently maintain local networks of Air Quality Monitoring Stations (AQMSs) fulfilling rigorous standards to know accurately the concentration levels of pollutants. However, AQMSs are at high cost of management and maintenance, and they are not uniformly and widely distributed spatially.

Low-Cost Sensor Systems (LCSSs) for air quality can supplement regulatory monitoring networks and provide *Indicative Measurements* [3], thereby enhancing the understanding of pollution levels and dispersion. The LCSSs constitute an additional contribution to air pollution monitoring. In fact, they are receiving growing attention [4,5], and an increasing number of studies are evaluating their application [6–9].

The United Nations direct attention to pollution control in general, and air pollution in particular, by explicitly including ‘*Mortality rate attributed to household and ambient air pollution*’ (Indicator 3.9.1) and ‘*Annual mean levels of fine particulate matter (e.g., $PM_{2.5}$ and PM_{10}) in cities (population weighted)*’ (Indicator 11.6.2) among the indicators of the 17 Sustainable Development Goals (SDGs) for 2030 [10].

Moreover, pollution is closely linked to meteorological conditions, with particularly severe implications associated to heat [11], and knowledge of the anemometric conditions at measurement sites provides valuable information both for forecasting systems and for assessing the potential quality of the measurements.

This work presents the field experience of an LCSS developed by ENEA, the Airbox [12–14], in which anemometric measurements supplement particulate matter data ($PM_{2.5}$ and PM_{10}). The Airbox, installed in the airport area of Grottaglie (Southern Italy), approximately 15 km East of Taranto—a city characterized by significant industrial activity (i.e., steel and cement plants, petrochemical refinery—enabled a combined analysis of air pollution and wind-related parameters, providing an integrated view of the environmental conditions at the measurement site.

2. Methods

2.1. The Low-Cost Sensor System for Air Quality Measurements Airbox

The activities presented in this work refer to field measurements performed using the Airbox, a custom-built LCSS based on a Raspberry Pi single-board computer, which, due to its compact size, processing power, and extensive availability of I/O interfaces, enables the connection of various sensor types and the management of their measurement data (Figure 1). In the design of the Airbox, the Raspberry Pi 2 was selected over subsequent Raspberry Pi generations due to its lower power consumption and reduced heat generation. The Airbox allows real-time transmission of measurement data to a remote server via mobile network connection for data remote consultation and functionality checks. Additionally, the data are stored locally on a microSD card to handle potential mobile network interruptions. A compact UPS integrates with the Airbox auxiliary systems to buffer sudden power supply interruptions.

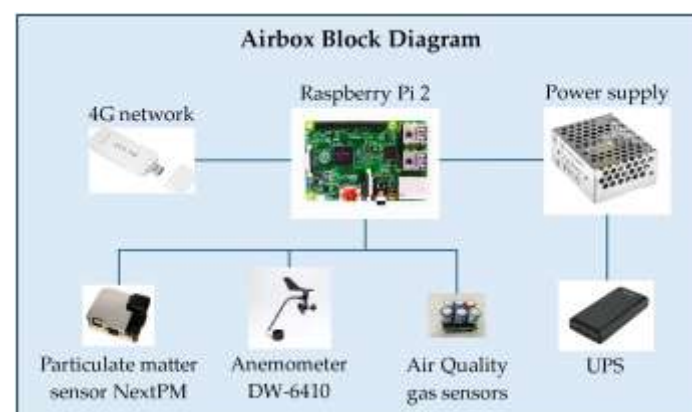


Figure 1. Block diagram of the LCSS Airbox.

The integrated sensors within the Airbox for the objectives of this work consist of a NextPM optical particulate sensor (TERA Sensor, Rousset, France) for PM_{2.5} and PM₁₀ measurements, and a cup anemometer with a wind vane DW-6410 (Davis Instruments, Hayward, CA, USA) for measurements of the horizontal components of wind speed and wind direction. The NextPM optical particulate sensor also provides measurements of PM₁; however, these measurements are not considered in the present work.

Key parameters of the LCSS Airbox are summarized in Table 1.

Table 1. Parameters of the LCSS Airbox.

Airbox	
Control unit	Raspberry Pi 2 (CPU: Quad-core ARM Cortex-A7 @ 900 MHz, RAM: 1 GB LPDDR2)
Connectivity options	4G cellular networks (Ethernet and Wi-Fi are also available)
Supported storage type	MicroSD 32 GB
Operating system	Debian Linux 11 “Bullseye”
Software programming language	Python 3.10
Power consumption	15 W (3 A @ 5 V)
Computational power	129 ÷ 1500 MFLOPS (varies depending on benchmark and workload)
Enclosure dimensions	30 cm (height) × 22 cm (width) × 13 cm (depth)
Enclosure weight	Approx. 1.2 kg (excluding sensors)
Anemometer Integrated into the Airbox	
Model and Manufacturer	DW-6410, Davis Instruments
Wind direction resolution	1°
Wind direction accuracy	±3°
Wind speed resolution	1 mph (rounded to nearest 0.1 m/s)
Wind speed range	0.5 to 89 m/s
Wind speed accuracy	±1 m/s or ±5%, whichever is greater
Anemometer weight	Approx. 1.3 kg
Particulate Matter Sensor Integrated into the Airbox	
Model and Manufacturer	NextPM, TERA Sensor
Targeted pollutants	PM ₁ , PM _{2.5} and PM ₁₀
Particle size detection range	0.3 ÷ 10 µm diameter
Concentration detection range	0 ÷ 1000 µg/m ³ (Arizona dust A1 equivalent)
Sensor weight	45 g

2.2. In-Field Positioning of the Instrumentation

The Airbox was installed in the Taranto-Grottaglie “Marcello Arlotta” airport area, close to the airport control tower (Latitude 40°30'52.7" N, Longitude 17°23'59.3" E), on a balcony at an approximate height of 12 m above ground level. The airport is located near the town of Grottaglie and approximately 15 km from the city of Taranto, which features a large industrial area that negatively impacts air quality in terms of pollution.

The Airbox, together with the anemometer, was mounted on a pole secured to the ground using concrete blocks (Figure 2). The anemometer head was installed at an elevation greater than 3 m above the balcony floor level.

Simultaneously, reference instrumentation for particulate matter, the APM-2 monitor (Comde-Derenda GmbH, Stahnsdorf, Germany), was positioned at approximately 1 m. Both the suction head of reference instrumentation and Airbox inlet were at the same height (approx. 1 m) from the floor.

The installation point of the Airbox features, to the East, the high-strength steel structure of the control tower, and immediately to the South, a wall that does not obstruct the anemometer.

The measurement campaign was initiated on 5 October 2021, and spanned a duration exceeding 125 calendar days, concluding on 8 February 2022. Access to the instrumentation was restricted during the measurement campaign period according to a predefined schedule, due both to airport access policies and to limitations imposed by the COVID-19 emergency. Consequently, it was not possible to carry out interventions to assess operational anomalies reported by the Airbox control system software outside the previously agreed schedule.

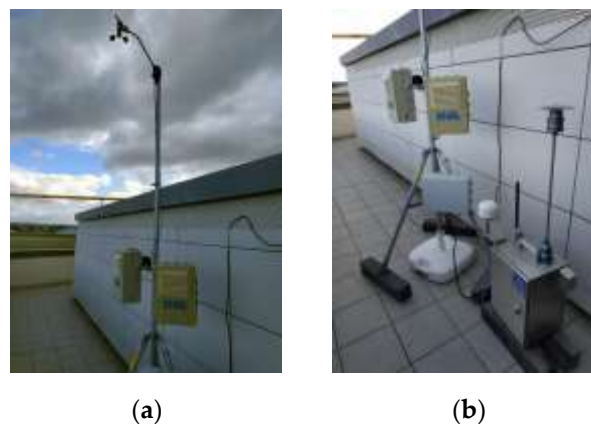


Figure 2. In-field positioning of the Airbox sensors. (a) Airbox sensors and head of the DW-6410 anemometer; (b) Airbox sensors and reference instrumentation for particulate matter measurement.

2.3. Open Data Sources for Comparative Measurement Analysis

In order to establish reference terms for the anemometric measurements, access was made to the open-data provided by Open-Meteo [15], which offers APIs [16] for retrieving historical meteorological data. The Historical Weather API generates historical meteorological data by combining observations from global weather stations, satellite inputs, and advanced numerical models [17–19]. The API reconstructs past weather conditions and provides hourly or daily data on meteorological variables, including wind speed and direction at 10 m above ground level.

The data obtained from Open-Meteo are related to the specific temporal period and the precise coordinates of the instrumentation's deployment.

Open data from 13 of the 14 fixed monitoring stations in the Air Quality Monitoring Network of the Regional Environmental Protection Agency of Apulia, ARPA Puglia [20], located in the area surrounding Grottaglie Airport, were used for comparison with $PM_{2.5}$ and PM_{10} sensor measurements. Characteristics of the ARPA Puglia selected stations are shown in Appendix A.

2.4. Analysis and Comparison of Measurement Data

The Airbox acquired data at a frequency of one record every 10 s. From the raw data, hourly average values were computed for hours containing at least 75% valid raw data, and daily average values were calculated for days with at least 75% valid hourly data.

The aggregated meteorological data provide maximum wind speed values which, in the case of the Airbox, were determined as the highest of the mean wind speed values recorded over the reference period (daily or hourly), calculated using 10-min intervals

(V_{600} , commonly adopted for forecasting purposes [21]) and 2-min intervals (V_{120} , i.e., as used for services for air navigation [22]).

The computation of wind direction averages was carried out following [23].

The daily mean values were compared with open data using Pearson coefficient (r), the coefficient of determination (R^2), the mean absolute difference (MAD), the root mean square difference (RMSD), and they were statistically summarized as a function of wind direction. The definition of the metrics is provided in Appendix B.

To account for the effects of air movements on the transport and dispersion of particulate matter, the calculation of the daily pollutant flux j_m was employed, defined as the product of the hourly mean wind speed $\bar{U}_h$ and the pollutant concentration hourly mean values $\bar{c}_h$:

$$j_m = \frac{24}{N_{vh}} \cdot \sum_{i=1}^{24} \bar{U}_{h,i} \cdot \bar{c}_{h,i} \quad (1)$$

in which the daily values were corrected using a factor accounting for the number of hours N_{vh} in the day with valid hourly averages: this assumption corresponds to assigning the hours with invalid or missing data a contribution equivalent to the mean of the hours with valid data.

Daily mean values of particulate matter flux were calculated for each wind direction sector.

3. Results

The Airbox enabled validation of daily average measurements for 113 out of 125 operational days, corresponding to 90.4% of the monitoring period: the days for which validated daily data are unavailable correspond almost exclusively to acquisition failures due to power supply interruptions.

As regards anemometric measurements Figure 3 displays the daily wind speed values (top panel) and the maximum wind speed values (bottom panel), where the daily maximum wind speed for the Airbox was determined as the highest recorded value among the non-overlapping 2-min average wind speed intervals V_{200} . The mean wind speed during the measurement period was 2.6 m/s, while the maximum of the sustained wind speed peaks (V_{200}) reached a value of 17.9 m/s. The comparison with Open-Meteo data produced metrics that are summarized in Table 2.

With regard to particulate measurements, the comparison with reference instrumentation indicated [24], for PM_{10} , a good agreement with R^2 values equal to 0.877, whereas for $PM_{2.5}$ the R^2 value was 0.504.

During the 113 days of validated measurements, Figure 4, $PM_{2.5}$ values in 72 days (63.7%) and PM_{10} values in 112 days (99.1%) fell within the ‘Good’ classification level—green color in Figure 4—of the Air Quality Index (AQI) [25], while the remaining days were confined to the ‘Moderate’ level—yellow color—of the AQI.

Table 2. Metrics referring to the comparison between daily mean wind speed from measurements and reference data.

Wind Speed, Daily Parameter	Metrics			
	MAD	RMSD	r	R^2
Mean	3.5 m/s	4.0 m/s	0.674	0.454
V_{120} , Maximum	2.6 m/s	3.2 m/s	0.627	0.393
V_{600} , Maximum	3.1 m/s	4.0 m/s	0.602	0.362

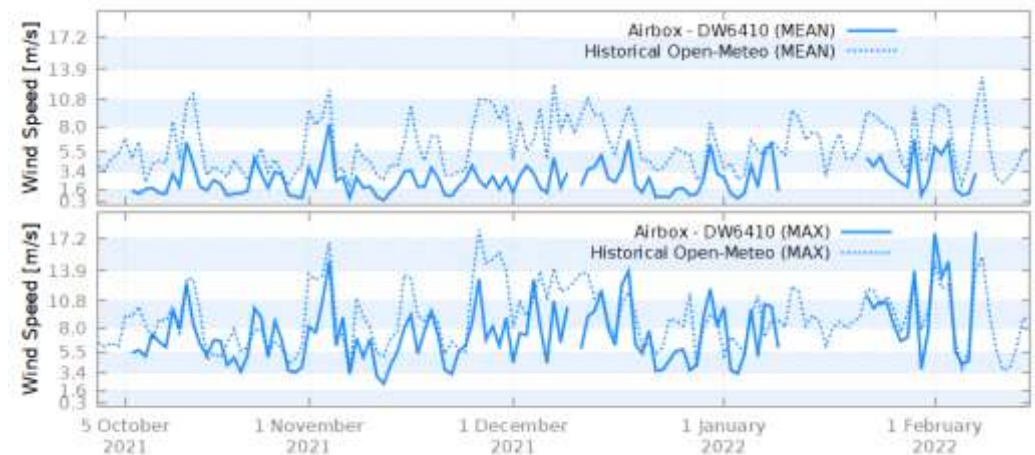


Figure 3. Daily wind speed values (top panel) and maximum wind sustained speed V_{200} values (bottom panel); horizontal shaded areas differentiate the wind speed classes in accordance with the Beaufort scale definition [21].

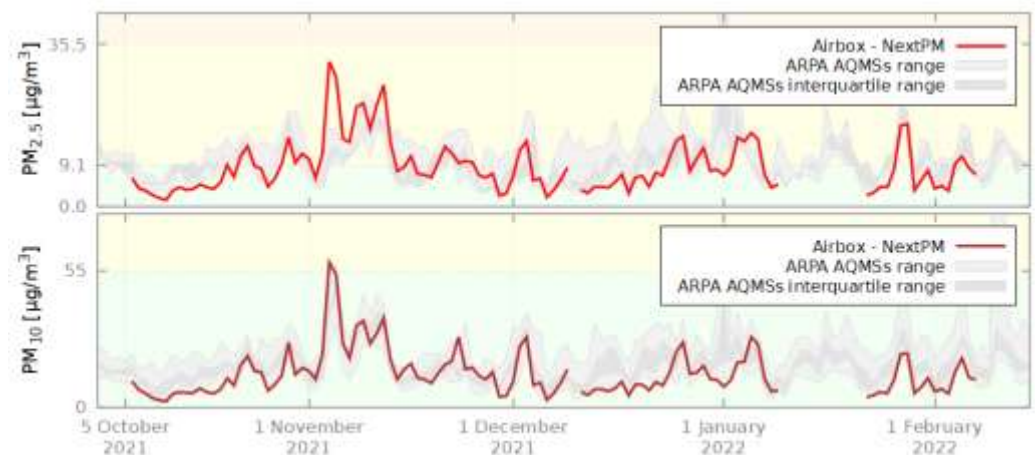


Figure 4. Daily concentration values of PM_{2.5} (top panel) and PM₁₀ (bottom panel); the shaded grey bands indicate the range of variation between the minimum and maximum values, and interquartile range, recorded by the regulatory stations of the ARPA Puglia AQMSs (4 stations for PM₁₀ and 13 stations for PM_{2.5}); background colors indicate the AQI classification levels according to [25].

The mean concentrations during the measurement period were $8.7 \mu\text{g}/\text{m}^3$ for PM_{2.5} and $13 \mu\text{g}/\text{m}^3$ for PM₁₀, while the maximum daily concentrations reached values of $31.7 \mu\text{g}/\text{m}^3$ for PM_{2.5} and $58 \mu\text{g}/\text{m}^3$ for PM₁₀.

The final time series presented, shown in Figure 5, displays the calculated data of particulate fluxes. The profiles of the two particulate classifications exhibit variations of differing magnitudes, compared to those shown in Figure 4, due to the scaling factor associated with the intensity of air movements. In particular, a distinct peak is observed—being the only one to exceed the graph scale—on 4 November 2021. On this day, the combination of relatively elevated concentrations and above-average wind speeds resulted in a calculated flux peak of $263.1 \mu\text{g}/\text{m}^2/\text{s}$ for PM_{2.5} and $483.1 \mu\text{g}/\text{m}^2/\text{s}$ for PM₁₀. This value is considerably higher than the averages over the measurement period, calculated as $21.5 \mu\text{g}/\text{m}^2/\text{s}$ and $34.7 \mu\text{g}/\text{m}^2/\text{s}$, and could reasonably be classified as an outlier in the context of different types of analyses.

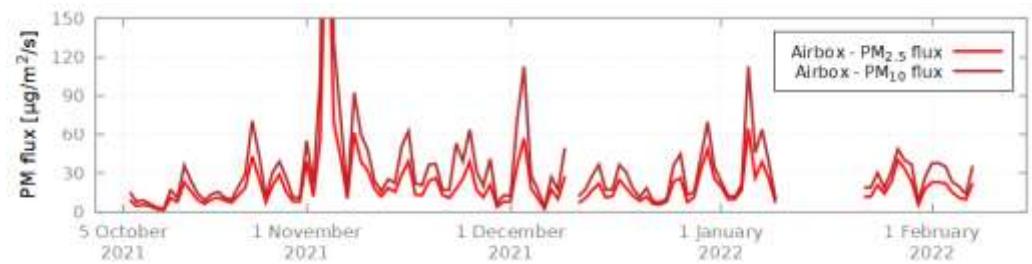


Figure 5. Daily mean values of PM_{2.5} and PM₁₀ particulate matter fluxes.

A summary of the statistics related to the time series is provided in the Appendix C.

The statistical classification based on wind direction sectors is summarized in Figure 6, and the aggregated values show prevailing components of the wind direction during the period that do not significantly deviate from the airport runway alignment, 17/35 according to the QFU convention (used in aviation for standardized runway identification and alignment), i.e., 170/350 degrees clockwise from north.

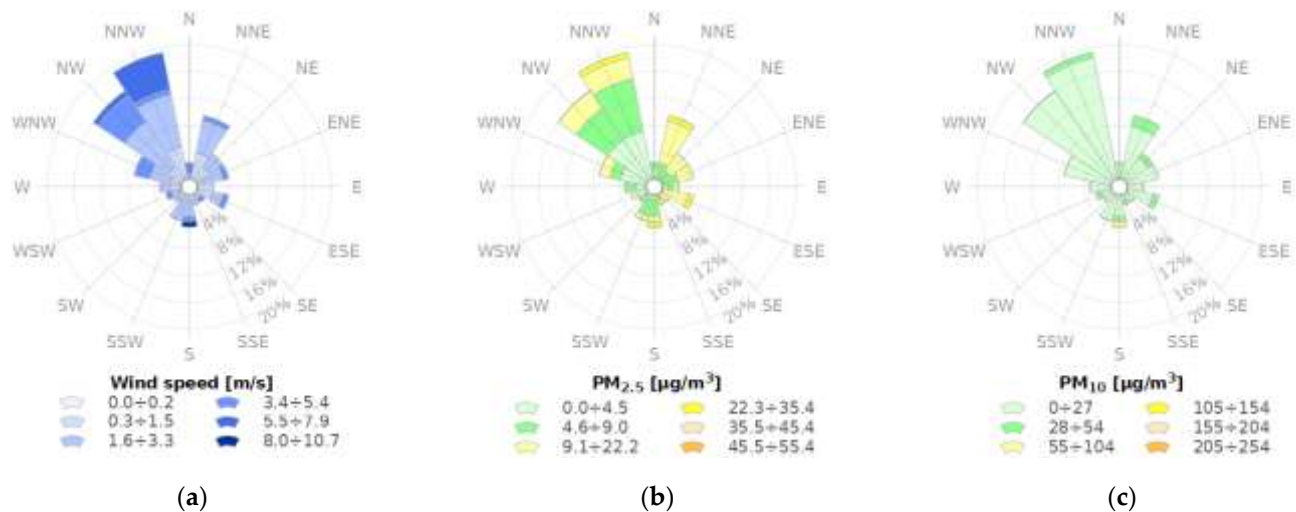


Figure 6. Wind rose plot of daily average values measured by the Airbox for wind speed (a), PM_{2.5} concentration (b), and PM₁₀ concentration (c). In panel (a), different color shades correspond to the Beaufort wind speed classes [21] whereas, in panels (b,c), distinct colors represent categories of the Air Quality Index (AQI) [25].

For each sector, average values of wind speed and concentrations were calculated, as shown in Figure 7, along with the particulate flux derived from Equation (1). In this case as well, the previously identified day, 4 November 2021, marked by a peak in particulate matter flux, has a significant influence on the statistics for the wind source sector, as can also be observed in panel (c) of Figure 7.

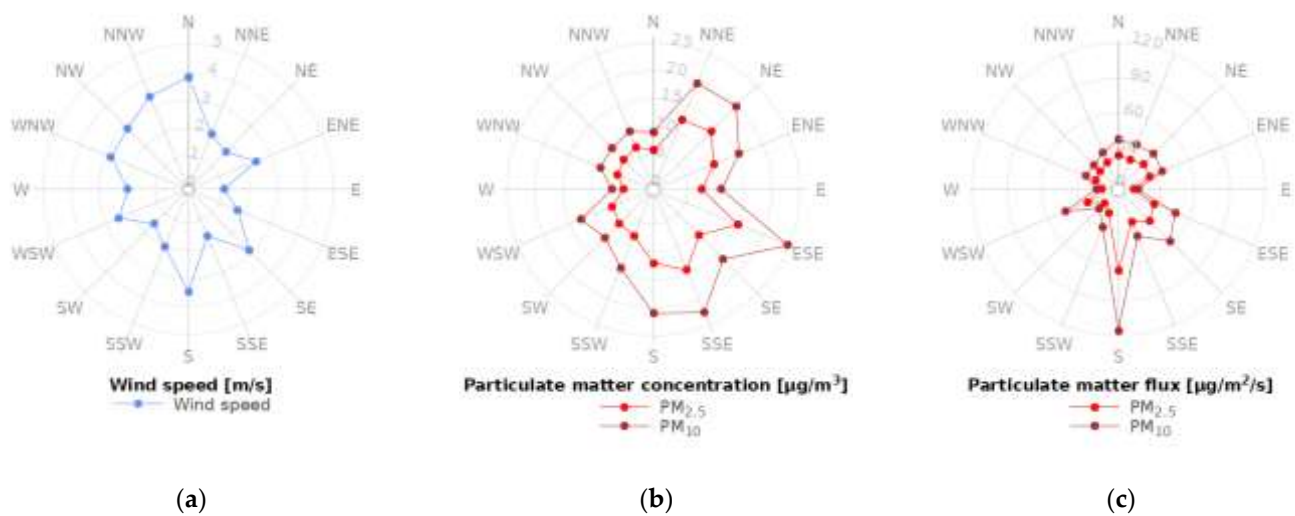


Figure 7. Polar plot of daily average values measured by the Airbox for wind speed (a), particulate matter concentration (b), and particulate matter flux (c) calculated accordingly to Equation (1).

4. Discussion and Conclusions

The integration of an anemometer into the LCSS Airbox has enabled a more comprehensive assessment of environmental conditions, and the wind speed measurements have shown good agreement when compared with Open-Meteo historical reanalysis data.

A discrepancy was to be expected, given that the measurement point was not optimally positioned from an anemometric standpoint, being located on the edge of a building and exposed to turbulence caused by nearby structures. This is, however, a condition commonly encountered in urban and semi-urban environments, which characterizes many environmental measurements.

The combination of anemometric data and pollutant measurements highlights the importance of an integrated perspective, as even moderate concentration levels, when coupled with significant wind speeds, can result in substantial pollutant fluxes.

While in some cases air movements can dilute pollutant concentrations, in other situations they may exacerbate conditions, for instance, during desert dust advection events [13]. Not least, sustained wind speeds can affect the quality and reliability of measurements, particularly in the case of low-cost systems, due both to sensor characteristics and system architecture.

The measurement campaign with the Airbox demonstrated the importance of combined measurements in identifying factors that may interfere with data quality and in providing a more comprehensive understanding of environmental conditions.

The Airbox has demonstrated the capability to communicate in real-time with dedicated servers and is well-suited for integration into the IoT ecosystem for information sharing.

Future work aims to enhance the combined analysis of measurements and the dissemination of their summaries through approaches that facilitate understanding for non-expert individuals.

Author Contributions: Conceptualization, V.P.; data curation, V.P. and M.P. (Mario Prato); formal analysis, V.P.; funding acquisition, M.P. (Michele Penza); investigation, V.P. and M.P. (Mario Prato); methodology, V.P.; project administration, V.P. and M.P. (Michele Penza); resources, V.P. and M.P. (Mario Prato); software, V.P. and M.P. (Mario Prato); supervision, V.P. and M.P. (Michele Penza); validation, V.P.; visualization, V.P.; writing—original draft preparation, V.P. and M.P. (Michele

Penza); writing—review and editing, V.P., M.P. (Mario Prato), and M.P. (Michele Penza). All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement:

Data Availability Statement: Data is available on request from the authors. Open data from ARPA Puglia is available online: <http://old.arpa.puglia.it/web/guest/qariainq2> (in Italian) (accessed on 12 August 2025). Historical weather open data from Open-Meteo is available online: <https://open-meteo.com/en/docs/historical-weather-api> (accessed on 12 August 2025).

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Appendix A

Table A1. Characteristics of the ARPA Puglia air quality monitoring stations in the region surrounding Grottaglie Airport during the measurement campaign.

Station	Line-of-Sight Distance [km]	Azimuth * [°]	Relative Geographical Location in Relation to the Airport	Type	Pollutants of Interest for This Work **	
					PM ₁₀	PM _{2.5}
Grottaglie	3.3	38.0	NE	Urban Background	+	-
Ceglie Messapica	17.7	32.5	NNE	Urban Background	+	+
Francavilla Fontana	16.0	84.0	E	Urban Traffic	-	-
Taranto–Talsano	15.1	220.5	SW	Urban Background	+	-
Taranto–San Vito	17.9	235.5	SW	Urban Background	+	-
Taranto–Alto Adige	13.0	242.5	WSW	Urban Traffic	+	+
Taranto–Machiavelli	15.0	259.0	W	Industrial	+	+
Taranto–Archimede	14.3	261.0	W	Industrial	+	+
Taranto–CISI	12.4	273.0	W	Industrial	+	+
Statte–Ponte Wind	19.2	274.0	W	Industrial	+	-
Statte–Sorgenti	17.4	288.0	WNW	Industrial	+	-
Massafra	25.5	290.0	WNW	Industrial	+	-
Martina Franca	21.5	344.5	NNW	Urban Traffic	+	-
Cisternino	25.4	3.0	N	Urban Background	+	-

* Angular distance from North, measured clockwise. ** Symbols list: ‘+’ Data available; ‘-’ Data not available.

Appendix B

This section provides the definitions of the metrics employed in this study, where y_i denotes the series of measurements, z_i denotes the reference data used for comparison and $\bar{y}$ and $\bar{z}$ are their respective mean values.

Mean Absolute Difference (MAD):

$$\text{MAD} = \frac{1}{n} \cdot \sum_{i=1}^n |y_i - z_i| \quad (\text{A1})$$

Root Mean Square Difference (RMSD):

$$\text{RMSD} = \sqrt{\sum_{i=1}^n (y_i - z_i)^2 / n} \quad (\text{A2})$$

Pearson Correlation Coefficient (r):

$$r = \frac{\sum_{i=1}^n (y_i - \bar{y})(z_i - \bar{z})}{\sqrt{\sum_{i=1}^n (y_i - \bar{y})^2 \cdot \sum_{i=1}^n (z_i - \bar{z})^2}} \quad (\text{A3})$$

Coefficient of Determination (R^2):

$$R^2 = 1 - \frac{\sum_{i=1}^n (y_i - z_i)^2}{\sum_{i=1}^n (y_i - \bar{y})^2} \quad (\text{A4})$$

Appendix C

Table A2. Statistics on the daily values of the parameters measured or calculated during the four-month measurement campaign conducted with the LCSS Airbox at Grottaglie Airport.

Daily Parameter	Mean	Minimum	1st Quartile	Median	3rd Quartile	Maximum
Wind speed [m/s]	2.6	0.4	1.3	2.2	3.4	8.3
Sustained speed V_{200} [m/s]	7.6	2.3	5.2	6.9	9.7	17.9
Sustained speed V_{600} [m/s]	6.6	1.6	4.4	6.2	8.5	15.5
PM _{2.5} [$\mu\text{g}/\text{m}^3$]	8.7	1.4	4.3	7.0	11.0	31.7
PM ₁₀ [$\mu\text{g}/\text{m}^3$]	13	2	7	11	17	58
PM _{2.5} flux [$\mu\text{g}/\text{m}^2/\text{s}$]	21.5	1.6	9.8	16.1	25.4	263.1
PM ₁₀ flux [$\mu\text{g}/\text{m}^2/\text{s}$]	34.7	2.7	14.2	23.4	38.4	483.1

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