ECOLOGIA BALKANICA

2025, Vol. 17, Issue 2 December 2025 pp. 181-189

Continuous integrated monitoring of meteorological conditions and air quality dynamics in the urban core of Plovdiv, Bulgaria

Vesselina Paskaleva, Atanas Terzyiski*, Stoyan Tenev, Nikolay Kochev

Paisii Hilendarski University of Plovdiv, Faculty of Chemistry, Department of Analytical Chemistry and Computer Chemistry, Tsar Assen Str. 24, Plovdiv, 4000, BULGARIA
*Corresponding author: atanas@uni-plovdiv.bg

Abstract. This study provides a comprehensive three-year analysis (2023–2025) of meteorological conditions and air quality parameters in the city of Plovdiv, Bulgaria. The research examines the interactions between temperature, humidity, precipitation, wind characteristics, and fine particulate matter concentrations ($PM_{2.5}$), with the goal of improving the understanding of local atmospheric dynamics and pollution patterns. Recorded temperatures ranged from −7.0°C to 40.4°C. The highest pollution episodes were consistently observed during the coldest months, largely due to intensified household heating combined with reduced atmospheric dispersion under stable winter conditions. Wind speed and direction analyses revealed a significant influence on pollutant dispersion, with lower wind speeds promoting the accumulation of airborne particles, particularly in the city's low-lying zones. Precipitation intensity varied considerably across the study period, with the most intense events reaching up to 94.73 mm/h. These episodes were associated with temporary reductions in airborne particle concentrations due to effective washout processes. Overall, the results demonstrate a strong interdependence between meteorological variability and air pollution dynamics in Plovdiv.

Key words: open monitoring network, meteorology, precipitation, wind, extreme events, IoT.

Introduction

Plovdiv is the second-largest city in Bulgaria. It has long been recognized as one of the most polluted urban centers in the country. Its geographical location in a valley surrounded by hills, combined with dense traffic, industrial activity, and seasonal heating, contributes to persistent air quality challenges. Numerous studies, including recent satellite-based assessments, have highlighted elevated concentrations of particulate matter (PM_{10} and $PM_{2.5}$) and sulfur dioxide (SO_2), underscoring the need for robust environmental monitoring systems (Georgieva et al., 2021; Ivanov et al., 2024; Mitev et al., 2025).

Meteorological conditions play an important role in the dispersion and accumulation of air pollutants. Parameters such as wind speed and direction, temperature, humidity, and precipitation directly influence pollutant transport, chemical transformation, and deposition. For instance, low wind speeds and temperature inversions can trap pollutants near the surface, increasing human exposure, while rainfall events can temporarily reduce airborne particulate concentrations through wet deposition. Understanding these dynamics is essential for improving the accuracy of pollution modeling and forecasting.

Long-term in-situ monitoring remains essential for air quality management. Ground-based stations provide high-resolution temporal data that play a central role in validating satellite observations, calibrating models, and assessing potential health impacts (Dzhambov et al., 2023; Khomenko et al., 2025).

The integration of satellite data has significantly enhanced spatial coverage and enabled the identification of pollution hotspots across urban and rural areas.

Given the complex interplay between meteorology and air pollution, long-term meteorological monitoring is crucial. It not only facilitates the interpretation of air quality trends but also enhances the predictive accuracy of dispersion models. Continuous tracking of atmospheric conditions enables researchers and policymakers to anticipate pollution episodes, implement targeted mitigation strategies, and safeguard public health. In cities like Plovdiv, where pollution levels frequently exceed recommended thresholds, such integrated monitoring systems are not just beneficial but essential.

Materials and methods

Meteorological observations were conducted using professional high-precision stations to ensure accurate and reliable data collection. Specifically, the OTT HydroMet WS501 (Lufft WS501 Smart Weather Sensor | OTT HydroMet, n.d.) sensor was employed for comprehensive meteorological measurements, including wind speed and direction, air temperature, relative humidity, and atmospheric pressure. Precipitation monitoring was performed using the OTT HydroMet WS100 (Lufft WS100 Radar Precipitation Sensor / Smart Disdrometer - OTT Hydromet, n.d.), which provides precise rainfall intensity and accumulation data.

Air quality monitoring focused on particulate matter (PM) concentrations. For this purpose, we utilized in-house designed monitoring stations, which are protected as intellectual property. These custom-built systems allow for continuous measurement of PM_{10} and $PM_{2.5}$ levels, by HPMA 115S0-XXX sensor (International Inc., n.d.), ensuring high-resolution temporal data and compatibility with local environmental conditions. The integration of these stations into the monitoring network provides a robust dataset for analyzing pollution dynamics in relation to meteorological factors.

The monitoring campaign was conducted over period (2023–2025, mid-September), following established meteorological standards. Wind measurements comply with the World Meteorological Organization (WMO) requirements for Class 1 stations, ensuring high accuracy and representativeness.

The collected meteorological and air quality data are considered representative for the city of Plovdiv, as all sensors are installed on the roof of the University of Plovdiv, located near the geographical center of the city. This strategic positioning minimizes local biases and provides a reliable basis for assessing urban-scale pollution dynamics.

Meteorological data were recorded at one-minute intervals, while air quality measurements were updated every five minutes. This high temporal resolution is critical for capturing short-term fluctuations in wind speed, temperature, and pollutant concentrations, which often drive rapid changes in urban air quality. Such detailed data enhances the accuracy of dispersion patterns modeling and improves the reliability of correlations between meteorological conditions and pollution episodes.

The data presented here is analyzed using open-source tools available in the R language (R: The R Project for Statistical Computing, n.d.) using the integrated development environment (IDE) RStudio (RStudio Desktop - Posit, n.d.). Besides the basic functionalities, additional packages like openair (Carslaw & Ropkins, 2012) and lubridate (Spinu et al., 2024) are used. The lubridate package is used for parsing date-time data. All results are conducted using the openair package. This package is specifically developed for the analysis of data in the atmospheric sciences, like analyzing air quality data and air pollution measurement data.

Results

Our study covers the period from 2023 to 2025, focusing on detailed monitoring of ambient air temperature, relative humidity, precipitation intensity, wind characteristics, and particulate matter pollution.

Ambient temperature monitoring

Fig. 1 presents the daily average temperatures recorded throughout the monitored period. The green curve represents the daily mean temperature, while the red and blue curves indicate the highest and lowest recorded temperatures, respectively. These three datasets are compared against the corresponding climatological normal (BulgariaBGR - Climatology (CRU) | Climate Change Knowledge Portal, n.d.), indicated by the yellow line.

Fig. 2 compares the observational years (2023 – solid line, 2024 – dashed line, and 2025 – dotted line) with the mean climatological normal (yellow line). The boundaries of the yellow shaded area represent the maximum and minimum temperature normals.

Each year is represented by three lines: the upper line indicates the maximum measured temperature, the lower line shows the minimum measured temperature, and the middle line represents the mean measured temperature.

We encourage readers to refer to the following source for more detailed temperature analyses: (Supplementary Data: Temperature, n.d.).

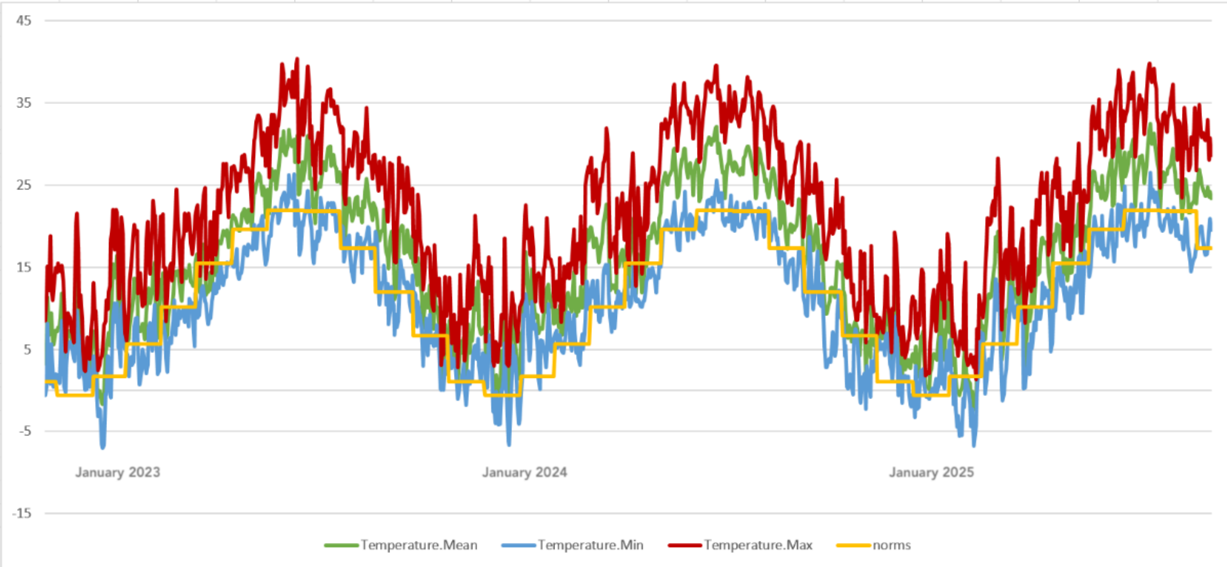

Fig. 1. Temperature variations during the monitoring period

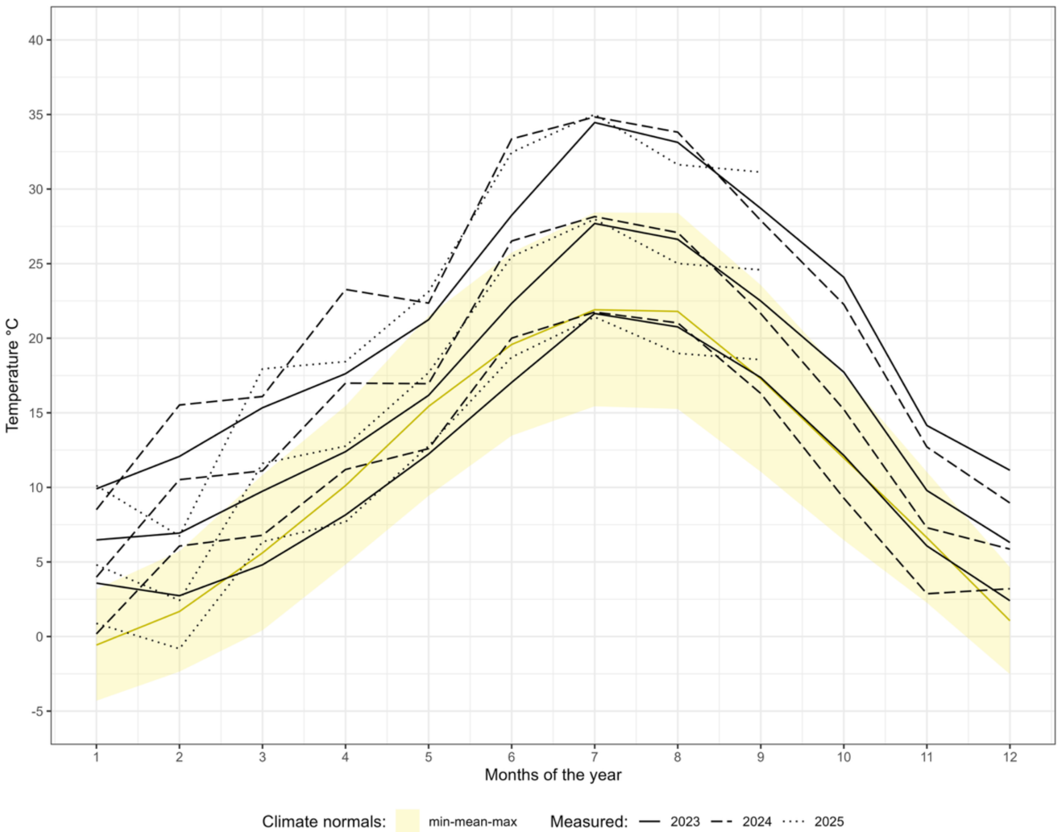

Fig. 2. Temperature comparison and climatological normal.

Relative humidity

Fig. 3 presents the relative humidity for all days of 2024 in a heatmap format. As expected, higher humidity levels are observed from January to May and from November to December. Relative humidity is a critical parameter to monitor, as it influences both the performance of particulate matter sensors and the formation of air pollutants. High humidity can impact sensor performance by altering particle adhesion and scattering characteristics, while it also contributes to secondary aerosol formation and pollutant accumulation under stagnant atmospheric conditions.

Additional data and detailed humidity analyses are available at the following link: (Supplementary Data: Humidity, n.d.). Readers are encouraged to refer to this source for extended datasets, methodological details, and high-resolution temporal records supporting the present findings.

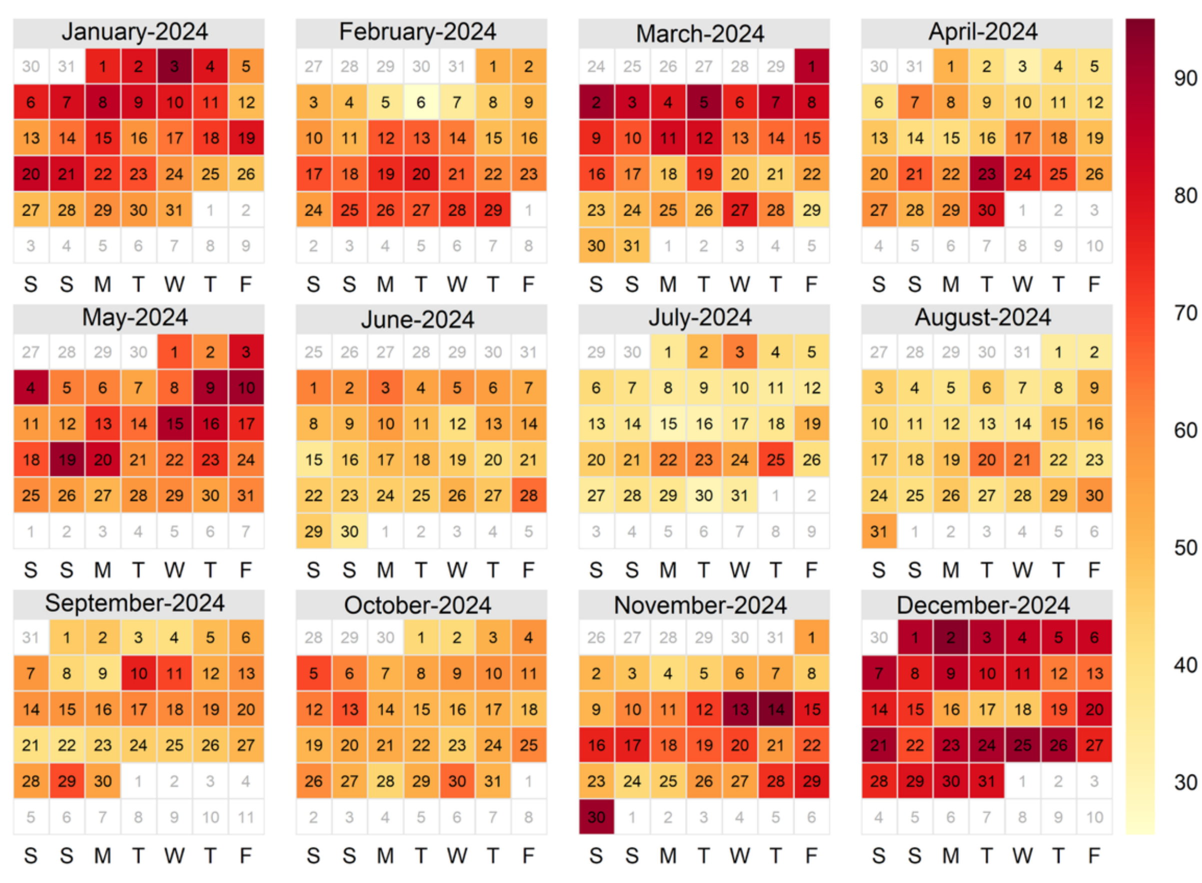

Fig. 3. Daily averaged humidity map for 2024.

Precipitation intensity

In this study, detailed precipitation analyses were conducted using the OTT WS100 weather station, which measures rainfall intensity in millimeters per hour (mm h^{-1}). The following figure illustrates the daily average precipitation intensity, displayed through a color scale ranging from 0 to 1.6 mm/h (shown on the right-hand side). Precipitation amount and intensity are key factors in air quality assessment, as rainfall effectively removes atmospheric pollutants through wet deposition processes, including scavenging of particulate matter and soluble gaseous species.

Additional data on precipitation intensity are available at the following link: (Supplementary Data: Precipitation, n.d.). Readers are encouraged to visit this source for access to extended temporal datasets and comparative analyses that further support the findings discussed in this study.

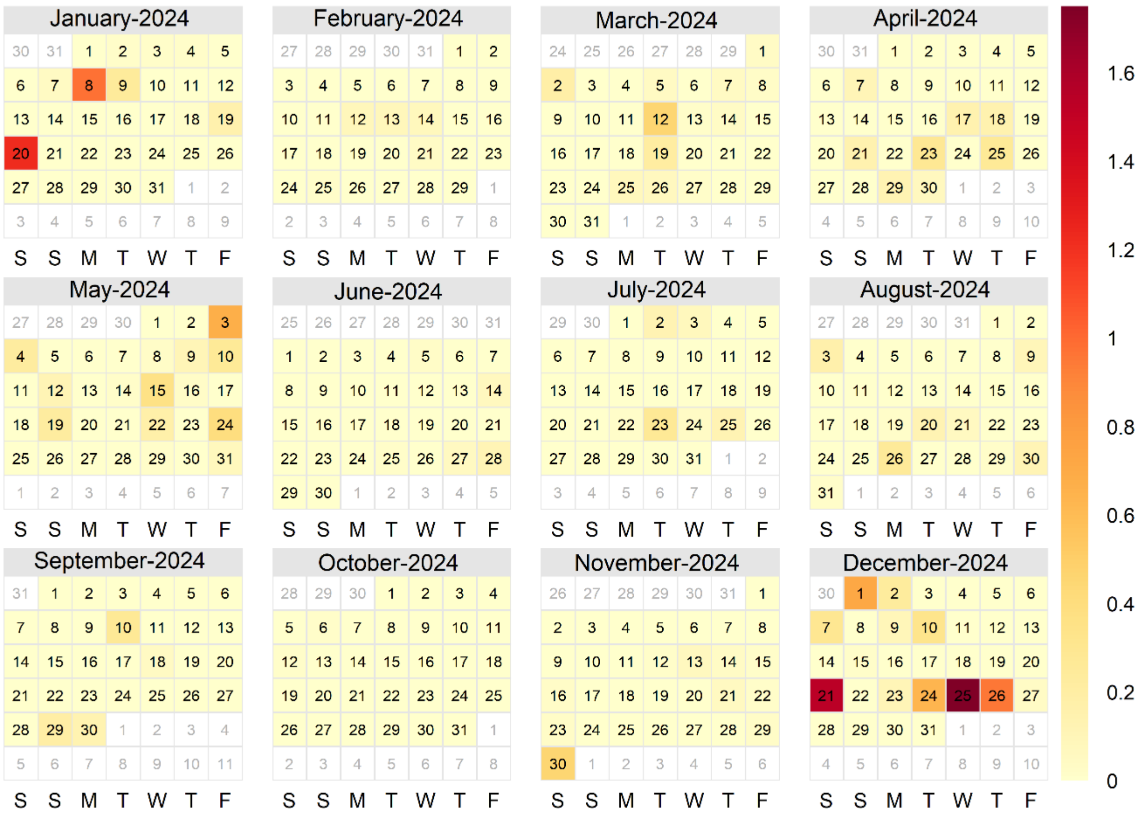

Fig. 4. Daily averaged precipitation intensity in mm/h for 2024.

Wind characteristics

Wind characteristics are a key determining of air quality, as they govern the transport, dispersion, and dilution of atmospheric pollutants. Wind speed influences the rate of pollutant dispersion and mixing within the boundary layer, while wind direction determines the pathways through which emissions are transported from their sources to receptor areas. Calm wind conditions often lead to pollutant accumulation and the formation of smog or haze episodes, whereas strong or turbulent winds enhance dispersion and improve air quality conditions.

Detailed analyses of wind behavior were conducted using a wind rose representation, as shown in Fig. 5. The wind rose illustrates monthly statistics and mean wind vectors, providing insights into dominant wind directions, frequency distributions, and their seasonal variability.

Detailed analyses are provided in the supplementary materials section, available at (Supplementary Data: Wind, n.d.). Readers are encouraged to consult these materials for a more comprehensive understanding of wind behavior in Plovdiv throughout the three-year monitoring period. The supplementary content includes extended datasets, monthly and seasonal wind rose diagrams, and statistical evaluations that further elucidate the spatial and temporal variability of local wind dynamics.

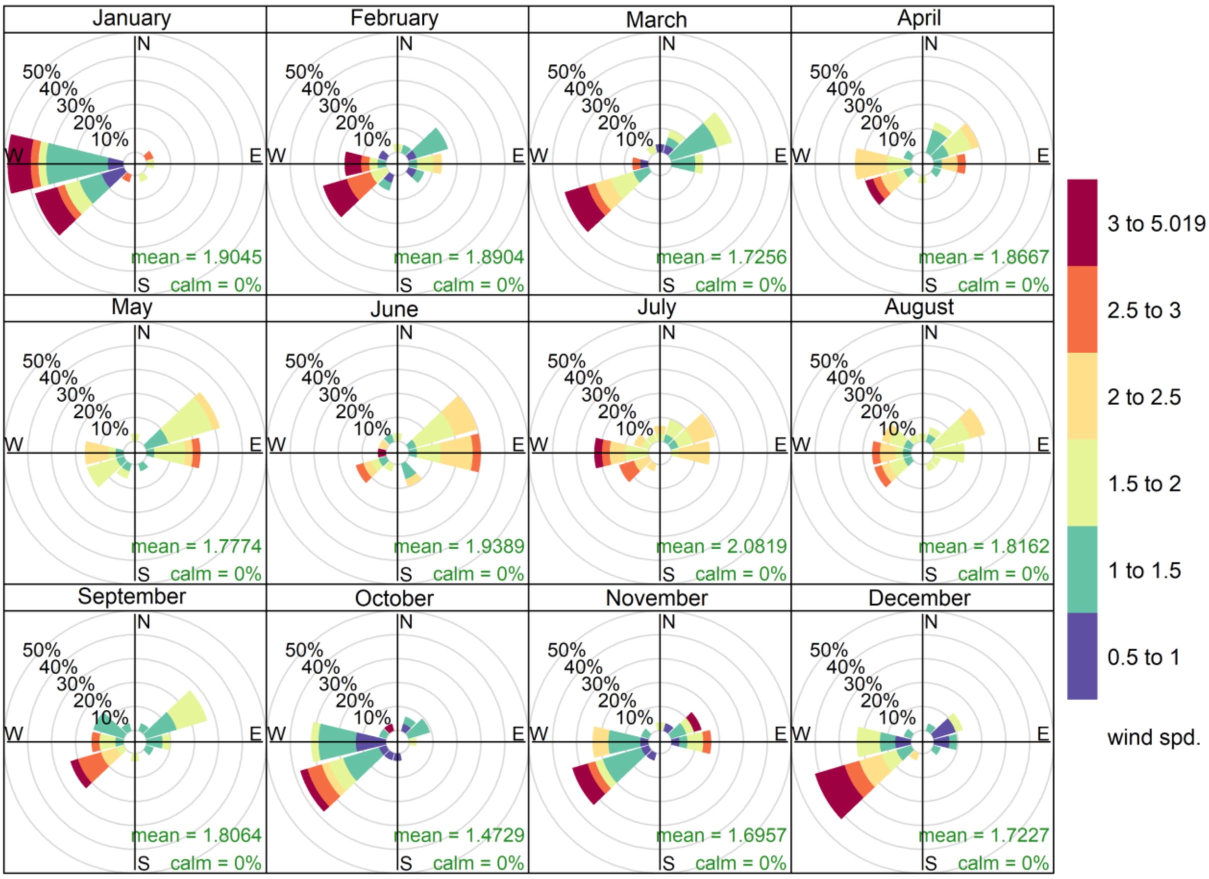

Fig. 5. Wind rose representation for 2024.

Particulate matter pollution

During the three-year monitoring period, a continuous record of fine particulate matter ($PM_{2.5}$) concentrations was collected. The next figure illustrates the daily $PM_{2.5}$ levels observed throughout 2024. As shown, the most severe pollution episodes occurred during the winter months, with daily mean concentrations occasionally exceeding 60 μg m^{-3}.

Such elevated $PM_{2.5}$ levels are of considerable health concern. Exposure to fine particulate matter is strongly associated with adverse cardiovascular and respiratory outcomes, including asthma exacerbation, chronic obstructive pulmonary disease (COPD), and increased risk of ischemic heart disease. Prolonged exposure, particularly during cold, stagnant atmospheric conditions, can aggravate existing medical conditions and contribute to excess mortality in vulnerable populations such as the elderly, children, and individuals with pre-existing health issues. The observed winter peaks likely correspond to increased domestic heating activities and reduced atmospheric dispersion, both common drivers of seasonal air pollution in urban environments.

In this study, we conducted an extensive analysis of the correlation between wind characteristics and $PM_{2.5}$ concentrations. Readers are encouraged to consult the supplementary materials available at (Supplementary Data: Pm2.5, n.d.) for additional figures and data. These materials provide detailed graphical representations illustrating how wind speed and direction influence the dispersion and accumulation of particulate matter across different seasons. The supplementary analyses further demonstrate the significance of atmospheric circulation patterns in modulating local air quality dynamics in Plovdiv.

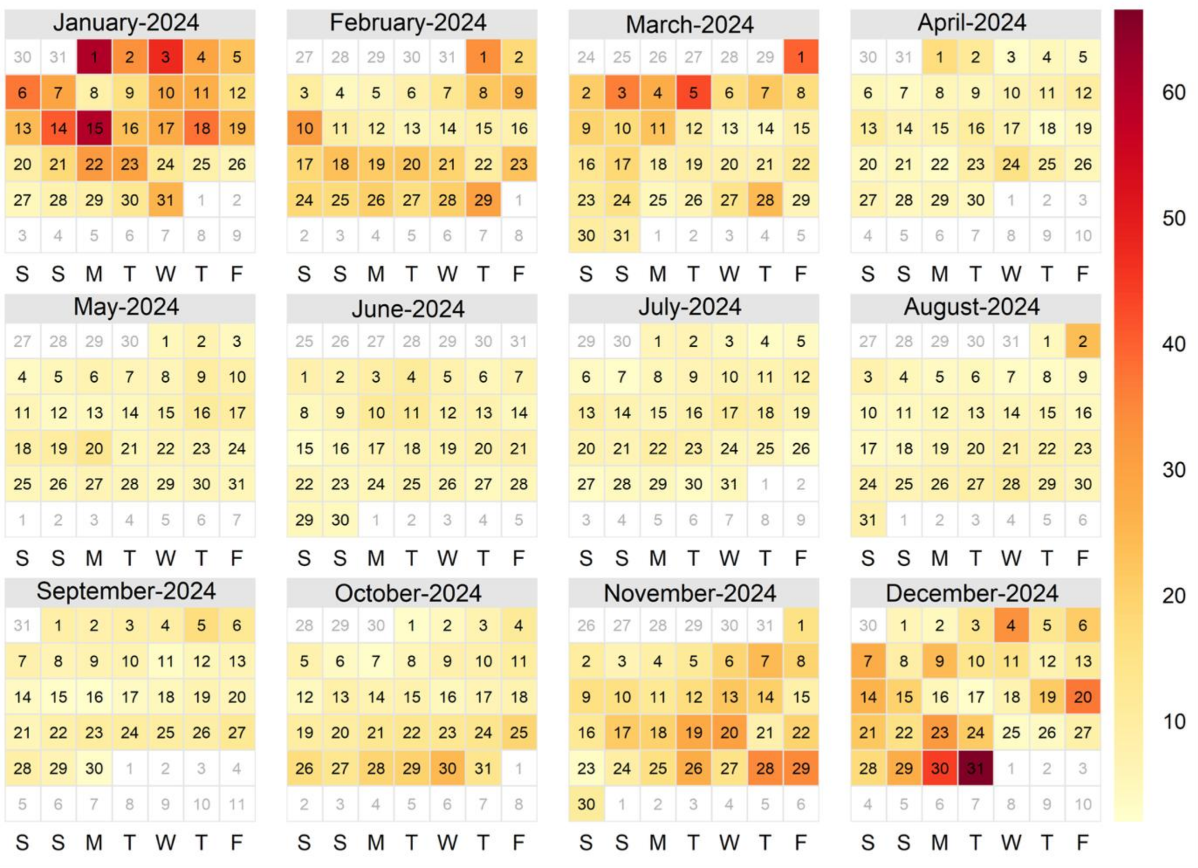

Fig. 6. Particulate matter monitoring for 2024.

Discussion

In this study, meteorological data for the city of Plovdiv were, for the first time, systematically compared with particulate matter ($PM_{2.5}$) concentrations as indicators of air pollution. As expected, the highest pollution levels were recorded during the coldest days of the year, likely attributable to the increased use of solid fuels such as wood in household stoves and heating appliances. Conversely, the study also highlights the occurrence of the highest air temperatures during summer heatwaves, which can have significant implications for both environmental conditions and human health.

Prolonged exposure to high temperatures can lead to heat-related illnesses, including heat exhaustion, dehydration, and heat stroke. Elevated temperatures also exacerbate chronic cardiovascular and respiratory diseases by placing additional strain on the body's thermoregulatory system. Moreover, heat accelerates photochemical reactions in the atmosphere, contributing to the formation of ground-level ozone and secondary pollutants, which further degrade air quality and compound health risks, particularly for sensitive populations such as children, the elderly, and individuals with pre-existing health conditions. However, on the other hand, we did not observe a significant temperature rise for the monitoring period.

Wind speed and direction were also analyzed in detail, along with combined factors involving wind and $PM_{2.5}$ concentrations. These analyses provide a comprehensive dataset that characterizes the meteorological and pollution dynamics over the monitoring period, offering valuable insights into the interactions between weather conditions and urban air quality in Plovdiv.

Conclusions

Over the three-year monitoring period (2023–2025), several key meteorological parameters were continuously observed and analyzed. The recorded temperature extremes for each year were as follows: −6.8°C and 39.8°C for 2023, −6.7°C and 39.5°C for 2024, and −7.0°C and 40.4°C for 2025.

These results indicate consistent interannual variability, with both the lowest and highest temperature values remaining within a narrow range over the study period.

The maximum wind speeds observed during the same period reached 15.1 m/s in 2023, 14.6 m/s in 2024, and 18.7 m/s in 2025, reflecting moderate to strong wind events capable of influencing the dispersion and transport of atmospheric pollutants. Meanwhile, the most intense precipitation events were recorded at 53.22 mm/h (2023), 94.73 mm/h (2024), and 79.71 mm/h (2025), demonstrating substantial temporal variability in rainfall intensity.

Overall, these results provide a valuable meteorological baseline for understanding local climate behavior and its interaction with air quality in Plovdiv. The dataset could serve as an important reference for future studies on atmospheric processes, pollutant dynamics, and the potential impacts of climate variability on urban environments.

All collected data adhere to the FAIR principles—Findable, Accessible, Interoperable, and Reusable. By following FAIR principles, the dataset access contributes to broader scientific collaboration and policy development.

Acknowledgements

This study is financed by the European Union-NextGenerationEU, through the National Recovery and Resilience Plan of the Republic of Bulgaria, project No. BG-RRP-2.004-0001-C01.

References

BulgariaBGR - Climatology (CRU) | Climate Change Knowledge Portal. (n.d.). Retrieved October 08, 2025, from https://climateknowledgeportal.worldbank.org/

Carslaw, D.C., & Ropkins, K. (2012). openair — An R package for air quality data analysis. *Environmental Modelling & Software*, 27–28, 52–61. doi: 10.1016/J.ENVSOFT.2011.09.008

Dzhambov, A.M., Dimitrova, V., Germanova, N., Burov, A., Brezov, D., Hlebarov, I., & Dimitrova, R. (2023). Joint associations and pathways from greenspace, traffic-related air pollution, and noise to poor self-rated general health: A population-based study in Sofia, Bulgaria. *Environmental Research*, 231, 116087. doi: 10.1016/J.ENVRES.2023.116087

Georgieva, E., Syrakov, D., Atanassov, D., Spassova, T., Dimitrova, M., Prodanova, M., Veleva, B., Kirova, H., Neykova, N., Neykova, R., Hristova, E., & Petrov, A. (2021). Use of Satellite Data for Air Pollution Modeling in Bulgaria. *Earth (Switzerland)*, 2(3), 586–604. doi: 10.3390/EARTH2030034/S1

International Inc., H. (n.d.). HPM Series Particulate Matter Sensors Datasheet. Available at: https://prod-edam.honeywell.com/

Ivanov, A., Gocheva-Ilieva, S., & Stoimenova-Minova, M. (2024). Exploring SO_2 air pollution in Plovdiv through multivariate adaptive regression splines: A case study. *Journal of Physics: Conference Series*, 2910, 012017. doi: 10.1088/1742-6596/2910/1/012017

Khomenko, S., Burov, A., Dzhambov, A. M., de Hoogh, K., Helbich, M., Mijling, B., Hlebarov, I., Popov, I., Dimitrova, D., Dimitrova, R., Markevych, I., Germanova, N., Brezov, D., Iungman, T., Montana, F., Chen, X., Gehring, U., Khreis, H., Mueller, N., Zapata-Diomedi, B, Zhang, J., & Nieuwenhuijsen, M. (2025). Health burden and inequities of urban environmental stressors in Sofia, Bulgaria. *Environmental Research*, 279(Pt 1), 121782. doi: 10.1016/j.envres.2025.121782

Lufft WS100 Radar Precipitation Sensor / Smart Disdrometer - OTT Hydromet. (n.d.). Retrieved October 08, 2025, from https://www.ott.com/

Lufft WS501 Smart Weather Sensor | OTT HydroMet. (n.d.). Retrieved October 08, 2025, from https://www.otthydromet.com/

Mitev, T., Tchalakov, I., Keskinova, D., & Parapanov, P. (2025). Air quality control in Plovdiv, Bulgaria: the citizens' awareness. Results from a pilot quantitative study. *Ecologia Balkanica*, 17(1), 225–229. doi: 10.69085/eb20251225

R: The R Project for Statistical Computing. (n.d.). Retrieved October 09, 2025, from https://www.r-project.org/

RStudio Desktop - Posit. (n.d.). Retrieved October 09, 2025, from https://posit.co/

Spinu, V., Grolemund, G., & Wickham, H. (2024). *Make Dealing with Dates a Little Easier [R package lubridate version 1.9.4]*. CRAN: Contributed Packages. doi: 10.32614/CRAN.PACKAGE.LUBRIDATE

Appendix

Supplementary data: humidity. (n.d.). Retrieved October 08, 2025, from https://meter.ac/eb/paskaleva_2025/#humidity

Supplementary data: pm2.5. (n.d.). Retrieved October 08, 2025, from https://meter.ac/eb/paskaleva_2025/#pm25

Supplementary data: precipitation. (n.d.). Retrieved October 08, 2025, from https://meter.ac/eb/paskaleva_2025/#precipitation

Supplementary data: temperature. (n.d.). Retrieved October 08, 2025, from https://meter.ac/eb/paskaleva_2025/#temperature

Supplementary data: wind. (n.d.). Retrieved October 08, 2025, from https://meter.ac/eb/paskaleva_2025/#wind

Received: 18.10.2025
Accepted: 01.12.2025