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Seasonal characteristics of precipitation in the region of NAO Rozhen, Bulgaria, for the period 2023—2025

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Abstract. The article presents high-resolution observations of winter precipitation in the region surrounding the National Astronomical Observatory (NAO) Rozhen, Bulgaria, at an altitude of 1,730 meters above sea level, during the 2023–2025 period. Utilizing an array of advanced meteorological instruments, including the OTT Pluvio²L, Parsivel² disdrometer, WS100 radar sensor, and SHM31 snow depth sensor, we captured detailed in-situ data on precipitation type, intensity, and duration. The integrated sensor system enabled the classification and quantification of various precipitation events such as snow, rain, drizzle, and hail with minute-level resolution. The study features multiple precipitation-related variables, including total amount, intensity, and precipitation type. Seasonal and daily variations in precipitation behavior were documented, with snow dominating the winter period but often accompanied by mixed-phase events. The dataset supports enhanced understanding of precipitation dynamics in mountainous terrain and offers potential for model calibration, climate profiling, and natural air purification assessments. All data is provided in FAIR-compliant formats to support further research and environmental monitoring efforts.

Key words: Open monitoring network, precipitation, IoT, in-situ monitoring, Bulgaria, Observations, FAIR.

Introduction

Atmospheric pollution from both natural and anthropogenic sources has become an increasingly central issue in environmental and public health discourse. This growing concern is nested within the broader complexity of Earth's ecosystems, where air quality not only impacts human health but also biodiversity, soil integrity, and climate systems. Recent advancements underscore two primary development vectors: (1) the enhancement of predictive modelling techniques and computational infrastructure, and (2) the expansion of high-resolution spatiotemporal monitoring networks. (Bakó et al., 2021).

On the modelling front, there has been a substantial evolution in the use of artificial intelligence (AI), including deep learning, ensemble machine learning, and hybrid neural networks to predict air pollution levels across rural and urban regions. These models are now capable of handling vast and heterogeneous datasets, originating from satellites, low-cost sensors, and traditional monitoring stations, resulting in improved predictive accuracy and greater interpretability. The integration of remote monitoring data into real-time modelling frameworks and the use of geospatial artificial intelligence (GeoAI) has significantly improved temporal and spatial resolution, once a major bottleneck (Wu et al., 2024).

Simultaneously, data acquisition systems have seen tremendous advancement. The installation of smart sensor networks and satellite-based observation systems allows near-continuous tracking of particulate matter ($PM_{2.5}$, PM_{10}), nitrogen dioxide, ozone, and volatile organic compounds. These monitoring infrastructures are increasingly being deployed in underrepresented regions and ecosystems, filling critical data gaps. Long-term monitoring programs are now essential not only for pollution forecasting but also for validating models, understanding climate-ecosystem interactions, and supporting evidence-based regulatory decisions (Ding et al., 2024; Badawy, 2025).

Moreover, the integration of monitoring systems with data on land use patterns and changes in landscape, vegetation and surface conditions is enabling more nuanced analyses of how urbanization, deforestation, and industrial expansion influence air quality. Techniques like GIS-based fuzzy inference systems are emerging as powerful tools for policy evaluation and scenario planning (Zaid & Basu, 2024).

Looking forward, the convergence of AI, satellite remote sensing, and cloud-based computing platforms promises an ecosystem-scale, real-time understanding of air pollution dynamics, from dense urban corridors to remote natural landscapes. These technological and methodological innovations are reshaping environmental science, with implications for health, climate policy, and sustainable urban design.

A major component in air quality modelling lies in accurately representing natural atmospheric cleansing processes that contribute to the removal of pollutants. These processes include wind-driven dispersion, precipitation scavenging (wet deposition), dry deposition on soil and foliage, and atmospheric photochemical reactions. Each of these mechanisms plays a unique role in mitigating pollutant concentrations and varies significantly across spatial and temporal scales. Modern models increasingly leverage high-resolution data on these variables, enabled by advances in remote sensing and atmospheric instrumentation, to simulate and forecast pollutant removal with greater accuracy (Shukla et al., 2023; Liang et al., 2023).

Of particular concern is the air quality during winter months, especially in urban environments across Europe, Asia, and North America. These seasonal levels are primarily attributed to increased combustion of fossil fuels for residential heating and power, combined with meteorological phenomena such as temperature inversions that suppress vertical air mixing and trap pollutants near the surface (Wu et al., 2024). Under such conditions, the role of precipitation becomes even more critical. Snow and rain events during winter can significantly reduce concentrations of $PM_{2.5}$, NO_x, and other airborne pollutants through enhanced washout effects and surface deposition.

In this study, we focus specifically on the role of winter precipitation as a key direction for natural air purification. By integrating high-resolution precipitation data with air quality observations, we aim to improve the understanding of wet scavenging dynamics during cold seasons. This focus not only enhances the realism of model outputs but also supports better seasonal policy interventions in urban air management.

Soil erosion is an environmental issue affecting many regions, including Bulgaria. The primary factor contributing to soil erosion is precipitation, encompassing its amount, intensity, and duration. It has the potential to initiate or speed up erosion processes and is an important indicator for the climate characteristics of a particular region (Nikolova et al., 2024).

Precipitation measurement is an important aspect of developing and monitoring a region's climate profile for the members of the United Nations Framework Convention on Climate Change, part of which is Bulgaria. The climate profile of Bulgaria for the period 1988-2016 is prepared per the requirements of the Ministry of Environment and Water and as part of the Seventh National Communication on Climate Change of Bulgaria (Marinova et al., 2017).

Materials and methods

Precipitation and atmospheric monitoring in this study were conducted using a suite of commercial sensors developed by OTT HydroMet (Lufft). The instruments used include the Pluvio²L weighing precipitation gauge, the Parsivel² laser disdrometer, and the WS100 radar-based weather sensor. All devices were installed at a permanent meteorological station at NAO Rozhen (41.695, 24.740) and operated continuously over an extended period (OTT Pluvio² L – Weighing Rain Gauge - OTT Hydromet, n.d.).

The Pluvio²L is a high-resolution weighing-type precipitation gauge designed to accurately measure both liquid and solid precipitation. It operates by continuously weighing the accumulation of precipitation in a collector vessel using a high-precision load cell. This device is widely accepted in hydrometeorological networks and conforms to WMO standards for precipitation measurement. Its measurement range spans from 0 to 3000 mm/h, with a resolution of 0.1 mm, an accuracy of ±0.1 mm or ±1% and a time resolution of 1 minute. The Pluvio² L was mounted at a standard height on a flat terrain at NAO Rozhen.

The Parsivel² is an optical disdrometer that classifies hydrometeors by detecting particles as they pass through a horizontal laser beam. It measures both the size and fall velocity of each particle, enabling real-time determination of precipitation type and drop size distribution (DSD). The particle size range varies from 0.2 to 8 mm for liquid precipitation, and up to 25 mm for other particles. The velocity range extends from 0.2 to 20 m/s with a sampling area of 180 x 30 mm (54 cm²). The device was installed at a height of 5 m above ground level and aligned horizontally to ensure accurate measurements. It classifies both size and velocity into 32 discrete size classes and 32 velocity classes (OTT Parsivel² - Laser Weather Sensor - OTT Hydromet, n.d.).

The WS100 is a compact, maintenance-free 24 GHz Doppler radar sensor that detects precipitation type and intensity based on the Doppler frequency shift caused by hydrometeors. It provides rapid updates of precipitation dynamics, suitable for short-term weather applications. Detectable precipitation types are rain, snow, sleet and hail. It operates within an intensity range of 0.1 to 200 mm/h, detects particle velocities from 0.9 to 15.5 m/s, and measures solid precipitation sizes ranging from 5.1 to 30 mm. The device functions at a frequency of 1 Hz (Lufft WS100 Radar Precipitation Sensor / Smart Disdrometer - OTT Hydromet, n.d.). The WS100 was mounted on a mast at 3 meters above ground level. Data from the WS100 was used primarily to verify onset time and precipitation type, serving as a complement to the detailed microphysical information provided by the Parsivel².

The OTT SHM31 (Snow Depth Sensor SHM31, OTT HydroMet, n.d.) is a non-contact, optoelectronic snow depth sensor designed to monitor snow accumulation and surface height changes with high precision. Utilizing laser pulse time-of-flight technology, the sensor ensures accurate and maintenance-free operation even in harsh alpine or polar conditions. The device was mounted 4 meters above the ground on a rigid mount to ensure precise vertical alignment. The measurement site was carefully selected to minimise external interferences such as drifting snow, vegetation, or shadowing by nearby objects. Before deployment, the surface directly below the sensor was levelled and cleared to ensure a consistent and reliable measurement baseline. It has an accuracy of ± (5 mm + 0.06%) under ideal conditions, with a resolution of 1 mm. The measurement is based on time-of-flight (ToF) laser ranging, using near-infrared (NIR), eye-safe (Class 2 laser). The SHM31 continuously measures the distance to the snow surface and determines snow depth by comparing it with the pre-calibrated reference distance to the bare ground. Its performance is unaffected by precipitation, fog, or ambient light, making it particularly suited for unattended, year-round snow monitoring.

Pluvio²L Parsivel² WS100 SHM31

Fig. 1. Monitoring devices set up at NAO Rozhen.

Raw distance measurements from the SHM31 were automatically converted into snow depth values based on the reference ground level established during installation. A data transmitter (logger) was used to store and synchronize SHM31 measurements with other hydrometeorological sensors, including Pluvio²L, Parsivel² and WS100.

Results

The collected data for the 2023–2025 period was analysed with a focus on the typical precipitation season. In this study, we offer a brief analysis of precipitation only for December 2024 and March 2025. For us, these months represent a rich and diverse observational material, which is a good illustration of the capabilities of individual measuring instruments and equipment. We have not included in the text a detailed statistical analysis and results for all months of operation of the equipment, due to the technical limitation of the number of pages for publication. The following plots highlight two key aspects of December 2024 (Fig. 2): the total daily accumulated precipitation (left plot) and the distribution of precipitation types (right plot). As shown, snow is the dominant form of precipitation throughout the month, though rain, drizzle, and hail also occurred on several days. Notably, there are some days with no recorded precipitation. Days without precipitation are 9, which is 29% of the days in December 2024.

On March 30, 2025, a total of 16 distinct precipitation events were recorded between 01:35:01 and 23:58:01 GMT+2. The shortest event lasted just a few minutes, while the longest persisted over two hours, as illustrated in Fig. 3.

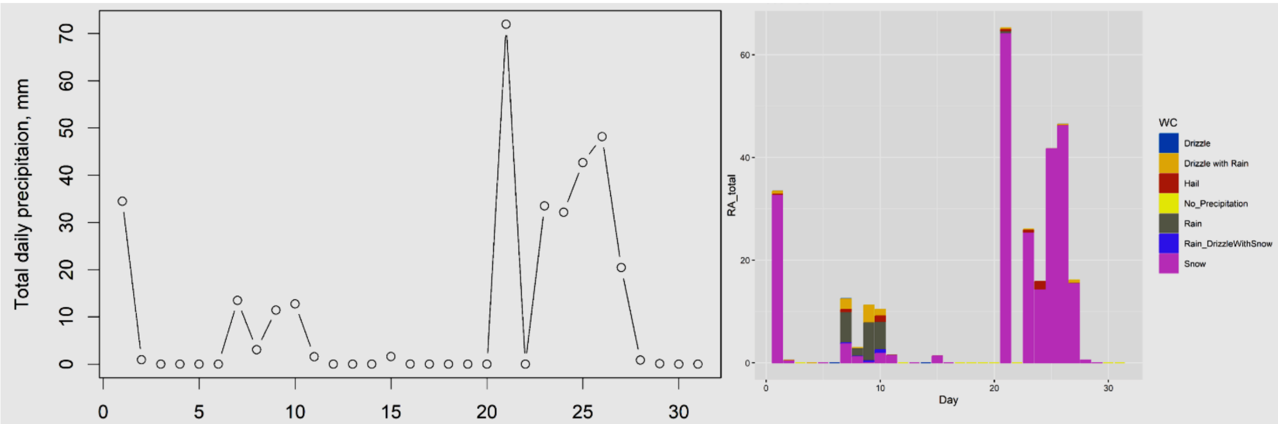

Fig. 2. Total daily precipitation and type distribution for December 2024.

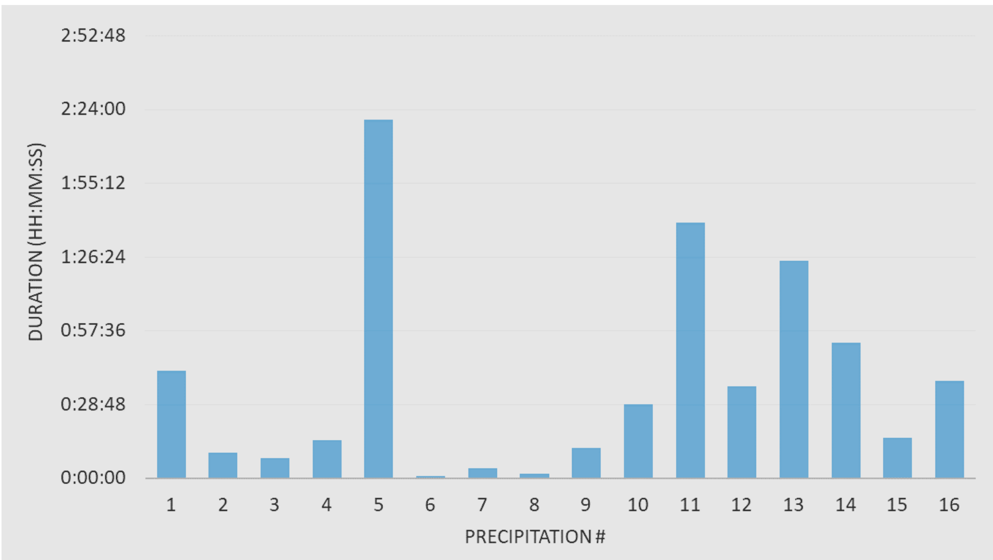

Fig. 3. Precipitation event count and their durations on 30 March, 2025.

Precipitation event #1 lasted 42 minutes and comprised various forms of precipitation: a total 0.04 mm of drizzle, 0.82 mm of mixed drizzle and rain, 1.06 mm of rain alone, 1.40 mm of snow, and 0.21 mm of hail.

The following Fig. 4 presents the spectral distribution of particle diameter versus velocity, as recorded by Parsivel[2] instrument during this precipitation event.

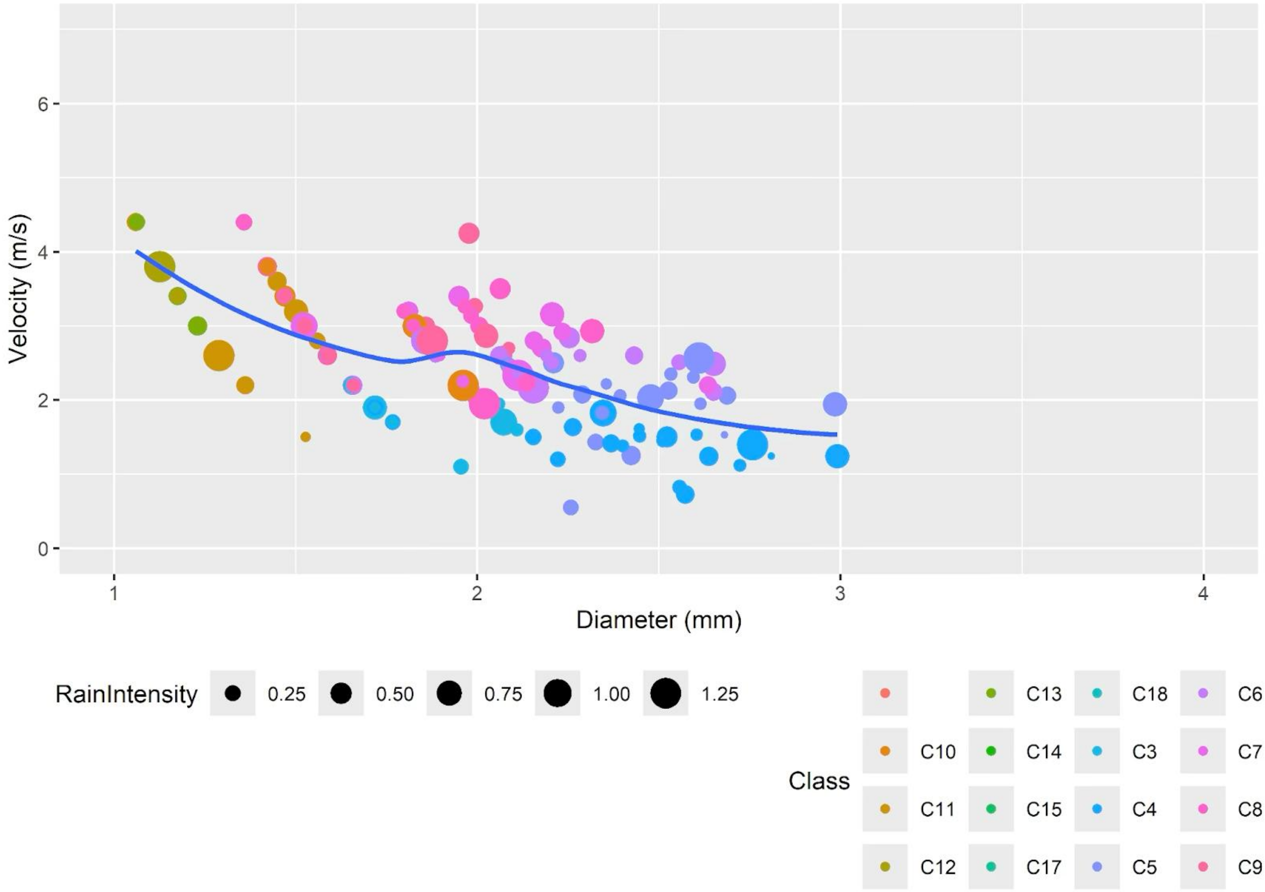

Fig. 4. Particle diameter vs. velocity distribution for precipitation event #1 (on Figure 3).

Larger dots represent higher rain intensity, corresponding to increased precipitation rates measured during the event. The colour coding denotes particle classification, differentiating between precipitation types such as drizzle, rain, snow, and hail based on their physical characteristics. This combined visualization provides detailed insight into both the intensity and micro-physical composition of the precipitation, facilitating a comprehensive analysis of the event's dynamics.

Further analyses and a more extensive dataset are provided in our supplementary materials (Https://Meter.Ac/Precipitaion2025/, n.d.). These resources offer detailed information that could not be included in this paper due to space limitations and are designed to support additional analyses tailored to diverse user needs. The supplementary materials adhere to the FAIR principles (Findable, Accessible, Interoperable, and Reusable), ensuring that the data can be easily discovered, seamlessly integrated, and reused in future research activities.

Discussion

Our observations indicate that the precipitation type, intensity and overall behavior may vary seasonally and monthly. The following plot (Fig. 5) represents the daily precipitation patterns for March 2024. The squares represent the hour of the day and their color - the total amount of precipitation. Fig. 6 illustrates the dynamics of the accumulated snow coverage in meters for two winter seasons, 2023/2024 (blue graph) and 2024/2025 (orange graph).

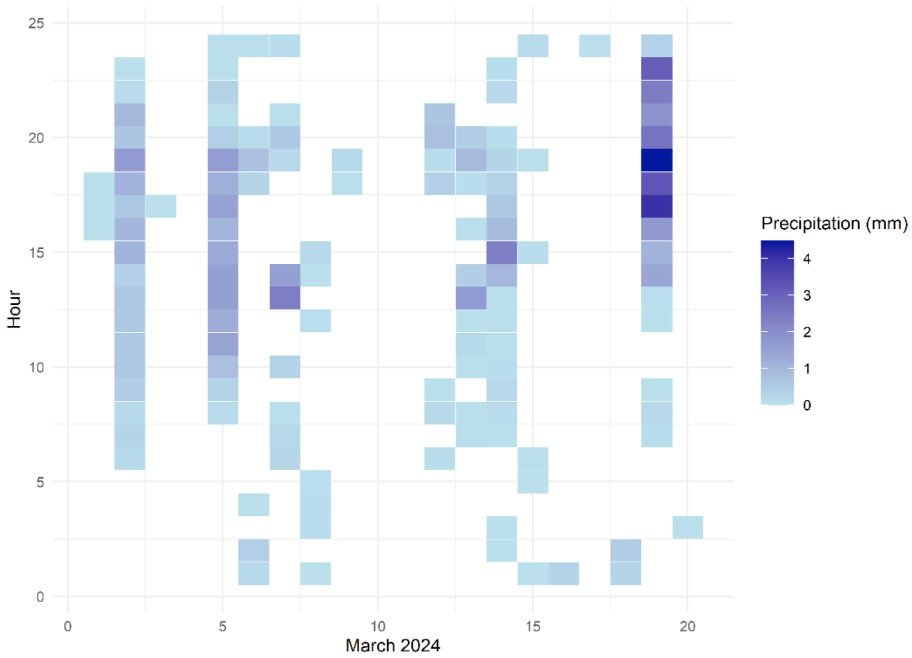

Fig. 5. Daily and hourly precipitation characteristics in March 2024.

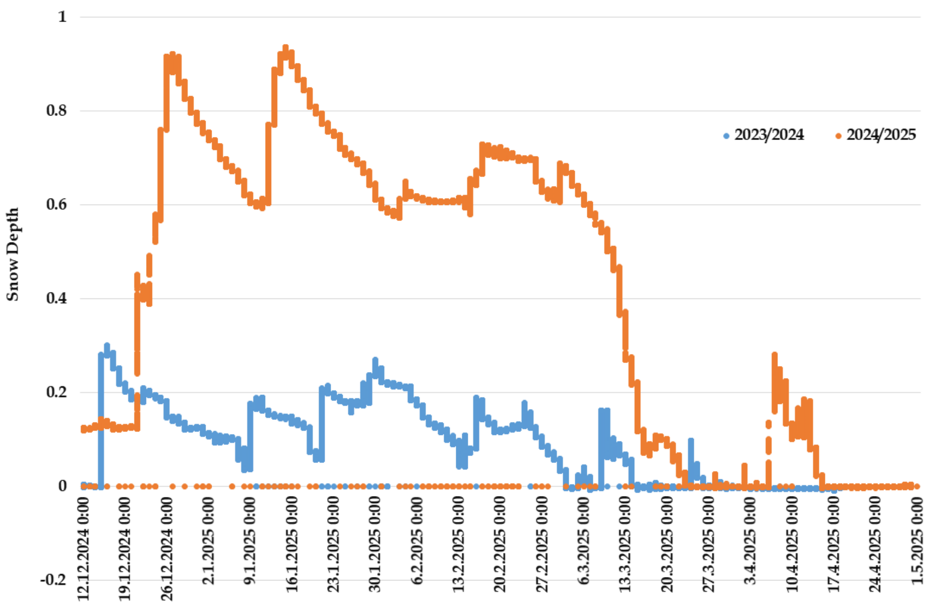

Fig. 6. Snow depth comparison for two winter seasons.

Our multi-instrument observational campaign over the 2023–2025 period provides a unique high-resolution dataset of winter precipitation in the Rhodope Mountains. We can summarise the findings as follows:

1. Snow was the prevailing precipitation type during winter months, although mixed events including rain, drizzle, and hail were also observed, often within a single day.

2. Precipitation patterns exhibited significant diurnal variability. For example, March 30, 2025, featured 16 discrete precipitation events, with durations ranging from minutes to hours, highlighting the need for fine-grained temporal resolution in hydrometeorological models.

3. Efficiency via instrumentation complementarity: the use of multiple sensor technologies (weighing gauge, laser disdrometer, radar, and

snow depth sensor) enabled robust cross-validation and enhanced classification of precipitation types and intensities.

4. FAIR data and Support for Climate Policy and Modelling: the findings emphasize the relevance of detailed precipitation monitoring for better understanding natural pollutant washout processes and improving the realism of air quality and hydrological models, especially in high-altitude, snow-dominated regions.

This study serves as a foundation for ongoing monitoring and modelling initiatives aimed at supporting environmental policy and forecasting systems under changing climatic conditions.

Conclusions

The presented results aim to demonstrate the feasibility of comparing measurements from different measuring instruments. Additionally, we showcase the implementation of a project that enables the long-term accumulation of high-quality statistical monitoring of annual precipitation, with high-frequency measurements. The observational data are organized into an open-access digital database. These data can be used both for statistical analysis and in various models of interconnected atmospheric and meteorological phenomena.

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