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Historical and Contemporary Analysis of Climate Change and PM_{10} Air Pollution in Plovdiv

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ABSTRACT

This study examines the interplay between climate change and fine particulate matter (PM_{10}) pollution in Plovdiv, the second-largest urban and industrial centre in Bulgaria. Long-term climate data spanning 1976–2024, together with contemporary air quality records from the Kamenitsa and Trakia automatic monitoring stations for the period 2015–2024, were analysed. The results indicate a marked increase in annual mean temperature of approximately 1.5–2°C over the past five decades, accompanied by greater variability in precipitation, manifested through alternating droughts and short but intense rainfall events. PM_{10} pollution persists as a major environmental challenge, with peak concentrations occurring during the winter months, primarily due to domestic solid-fuel heating and frequent temperature inversions. Exceedances of the EU and WHO daily limit value of 50 µg/m³ are widespread. A strong correlation was observed between meteorological conditions and PM_{10} dynamics: calm conditions and inversions facilitate particle accumulation, whereas precipitation and stronger winds exert a cleansing effect. The study underscores the need for improved monitoring, restrictions on solid-fuel heating, and the adoption of sustainable urban policies to reduce environmental and public health risks.

Keywords: *Climate change, Plovdiv, Fine particulate matter (PM_{10}), Air pollution, Sustainable development*

INTRODUCTION

Climate change and air pollution represent two of the most pressing environmental challenges across Europe. Plovdiv, Bulgaria's second-largest city, is situated in a lowland basin that is particularly susceptible to temperature inversions, which in turn intensify episodes of air pollution. Rapid urbanisation, transport-related emissions, and the widespread use of solid fuels further contribute to frequent exceedances of PM_{10} limit values. This article seeks to provide an integrated assessment of long-term climatic trends and recent PM_{10} pollution dynamics in Plovdiv.

Air pollutants may be classified according to their origin, pathways of entry into the atmosphere, chemical composition, and physical state (Nikolova, 2008).

Among the most significant air pollutants are particulate matter (PM). Fine particulate matter is defined as PM_{10} – particles with an aerodynamic diameter of 10 micrometres or less; $PM_{2.5}$ – particles with a diameter of 2.5 micrometres or less; and ultrafine particles (UFP) – particles with a diameter of 0.1 micrometres (100 nanometres) or less. These particles pose a serious threat to human health, as both their size and composition determine the degree of their impact on the body. Coarser particles are typically retained in the upper respiratory tract, whereas finer particles (below 2.5 µm) have a greater propensity to penetrate deeply into the respiratory system, where they may cause damage to lung tissue. It is well established that long-term exposure to elevated PM concentrations increases the risk of respiratory, cardiovascular, and other diseases (Petrova & Dimitrov, 2025).

According to analyses conducted by the European Environment Agency, a considerable proportion of the urban population in the EU is exposed to concentrations exceeding the established thresholds. Particulate matter (PM_{10}) remains a persistent problem in densely urbanised areas. In 2024, the EU revised its air quality standards to align more closely with the recommendations of the World Health Organization. This revision introduced stricter limit values to be achieved by 2030. For PM_{10}, the previous annual EU limit of 40 µg/m³ was lowered to 20 µg/m³ under Directive 2024/2881, thereby intensifying regulatory pressure in cities such as Plovdiv.

LITERATURE REVIEW

In recent decades, research activity on climate change and air pollution in Southeastern Europe has increased significantly. A growing body of literature documents a persistent warming trend across the Balkan Peninsula Heatwaves are becoming increasingly frequent and prolonged (Cheval et al., 2017; Djurdjević et al., 2024), while drought events are also occurring more often. These changes affect the entire region and are accompanied by shifts in precipitation patterns (Drenovski & Stoyanov, 2009, 2010; Velev, 2010; Rachev & Dimitrova, 2016). Urban areas are of particular concern, as local climatic conditions, high population density, and transport-related emissions exacerbate challenges related to the formation of urban heat islands and the deterioration of air quality (Gocheva-Ilieva et al., 2016; Stoimenova et al., 2017; Boras et al., 2025). The European Environment Agency (EEA, 2023) asserts that fine particulate matter (PM_{10} and $PM_{2.5}$) continues to be the most critical pollutant in terms of its human health implications. Recent Bulgarian studies (Nikolova, 2008; Petrova & Todorov, 2025; Ivanov, 2017; Gosteva, 2021) highlight the strong influence of meteorological factors – including wind speed, temperature inversions, and precipitation – on the variability of particulate matter concentrations. Significant attention has also been devoted to the issue of air pollution in Bulgaria's largest cities, including Sofia, Plovdiv, Varna, Stara Zagora, and others (Gocheva-Ilieva et al., 2016; Ivanov, 2017; Health Effects Institute, 2022). In addition, particular attention is paid to particulate matter pollution resulting from the transport of Saharan dust (Evgenieva et al., 2024). The *National Climate Change Adaptation Strategy and Action Plan of the Republic of Bulgaria* (Ministry of Environment and Water, 2019) further emphasises the heightened vulnerability of urban areas to heat waves and air pollution episodes. Collectively, these studies provide a robust scientific foundation for integrated assessments that link long-term climate analyses with contemporary air quality monitoring.

MATERIALS & METHODS

The present study is based on the following data sets: (a) climate data for temperature and precipitation (1976–2024) from NIMH, and PM_{10} data (2015–2024) from the Kamenitza and Trakia monitoring stations. The statistical techniques employed include regression analysis, trend estimation, and correlation analysis between meteorological conditions and pollution levels. The data are compared with the standards set by the EU and the WHO.

The National Institute of Meteorology and Hydrology (NIMH) is the primary source of climate data. Mean monthly values of temperature (1977–2024) and precipitation (1976–2024) from the

Plovdiv station were utilised. To enable comparison and assess long-term trends in the distribution of these climatic elements, processed data were also drawn from the *Climatic Reference Book of the People's Republic of Bulgaria* (1959), the *Precipitation Reference Book* (1962), and the climatic reference volumes on individual elements published in the 1980s (Vols. 1–6).

The Regional Inspectorate of Environment and Water (RIEW) – Plovdiv is responsible for monitoring air quality in the Plovdiv region through the operation of two stations. Data were obtained from the Executive Environment Agency (ExEA) via the Information System for Public Access to Ambient Air Quality. The online Information System for the Public on Ambient Air Quality of the ExEA was also used as a supplementary data source. This platform provides hourly, daily, and annual average values for 13 meteorological indicators and air pollutants. For the purposes of this study, daily mean concentrations of PM_{10} were extracted and processed from two Automatic Monitoring Stations (AMS) covering the period 2015–2024. These stations form part of the *National System for Environmental Monitoring (NSEM)*. Concurrently, data on temperature, wind direction, and wind speed were collated, amounting to approximately 30,000 records.

The AMS "Kamenitsa" is classified as an urban background station. It is located in the central part of the city and is predominantly surrounded by residential buildings, with moderate traffic intensity. The average hourly traffic flow in the area has been estimated at approximately1900 motor vehicles (MV) (Municipality of Plovdiv, 2020).

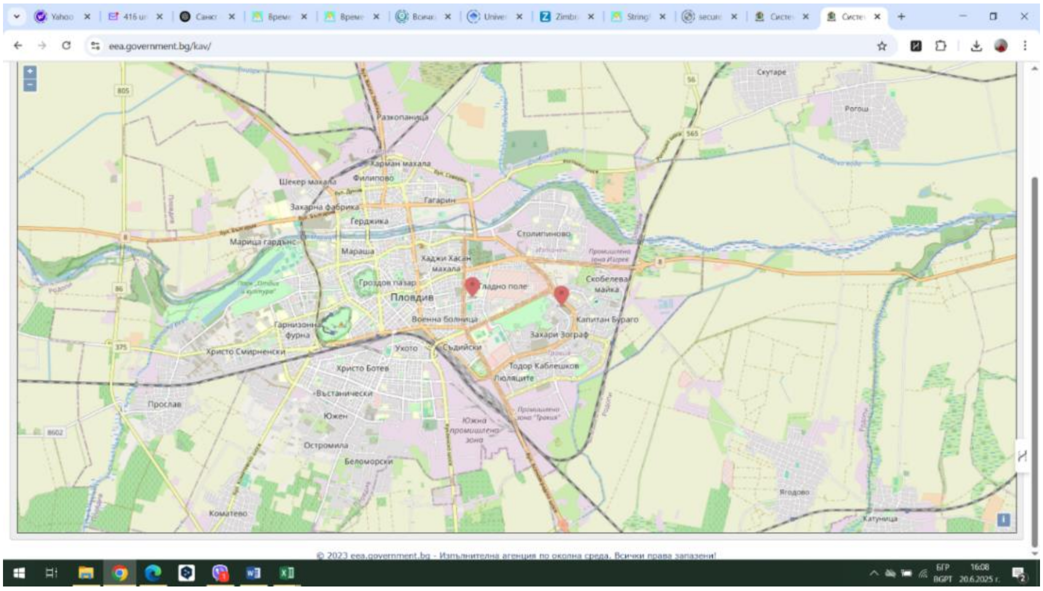

Figure 1. The geographical location of AMS Kamenitsa and AMS Trakia

The "Trakia" AMS is classified as a traffic monitoring site. It provides information on air pollution levels resulting from road traffic in close proximity to a high-traffic roadway. According to the Municipality of Plovdiv (2020), the average hourly traffic intensity near this site is approximately 2100 MV (fig. 1).

In this study, daily mean PM_{10} data were collected and processed from AMS Kamenitsa over a ten-year period (2015–2024), and from AMS Trakia for the period 2016–2024; however, sporadic interruptions in data collection were observed. The dataset was analysed using standard statistical methods, including regression, correlation, and trend analysis. The results are presented in tables and figures.

RESULTS & DISCUSSION

The city of Plovdiv is located within the transitional continental climate zone of Eastern Central Bulgaria. This region encompasses most of the lowlands along the Maritsa and Tundzha rivers and borders the Continental-Mediterranean climatic region to the southeast (Velev, 2010). It represents the most extensive part of the transitional climatic zone. According to Sabev and Stanev (1959), the area is classified as part of the transitional-continental climatic sub region of the European-continental climatic region. In this region, the continental character of the climate is considerably moderated compared to the Danube Plain, as reflected in a lower annual temperature amplitude, primarily due to milder winters.

Temperature trends

As shown in Table 1**,** mean monthly and annual temperatures recorded at the Plovdiv station are presented for four distinct periods. The first period covers 40 years, while the remaining three span 30 years each. Two of these periods correspond to reference climatological normal adopted by the World Meteorological Organization (WMO)**.** Table 2 displays the differences in average temperatures between the initial and the most recent period. A clear warming trend is evident across all months. The most pronounced increase is observed in January, with a rise of 1.9°C, equivalent to 0.29°C per decade. For February, March, and August, the increase is 1.7°C. The smallest change is recorded in November, at 0.3°C. Seasonal analysis indicates that the most substantial warming has occurred in summer, followed by winter, spring, and autumn.

Table 1. Average monthly and annual temperatures in Plovdiv across different time periods

Period	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	**Год.**
1995-2024	1,5	3,9	7,7	12,8	17,9	22,3	24,7	24,4	19,2	13,1	7,7	2,8	13,1
1991-2020	1,1	3,3	7,7	12,7	17,9	22,1	24,4	24,1	19,1	13,2	7,5	2,4	13,0
1961-1990	0,3	2,8	6,8	12,2	17,1	20,9	22,9	22,0	18,4	12,4	7,0	2,4	12,1
1931-1970	-0,4	2,2	6,0	12,2	17,2	20,9	23,2	22,7	18,3	12,6	7,4	2,2	12,0

Table 2. Difference in monthly temperatures in Plovdiv between two periods

Difference, C°	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Annual average
1995-2024 /1931-1970	1,9	1,7	1,7	0,6	0,7	1,4	1,5	1,7	0,9	0,5	0,3	0,6	1,1

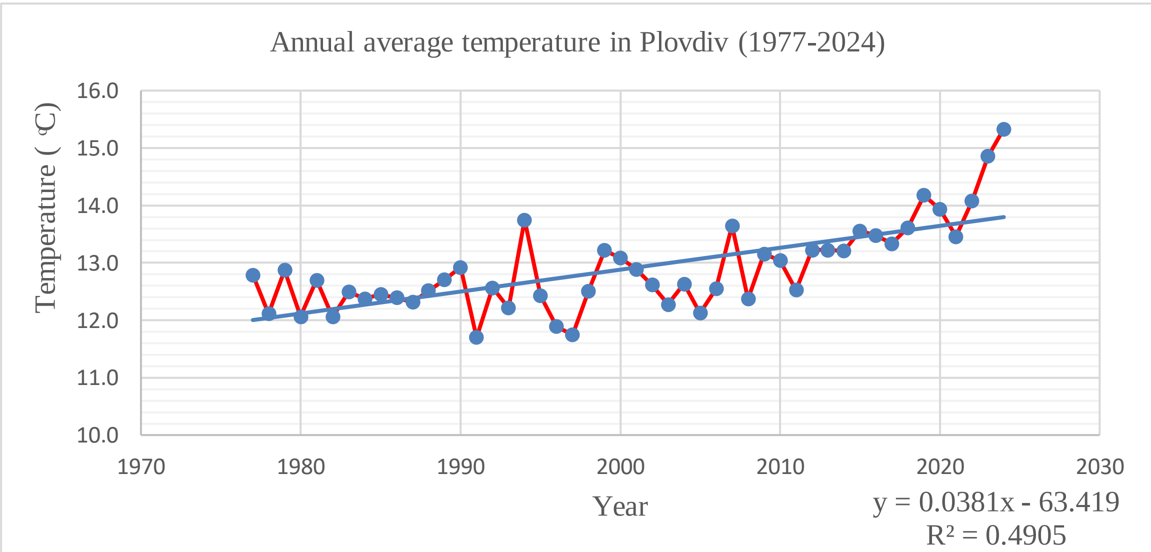

Figure 2. Annual average temperature in Plovdiv (1977–2024).

Figure 2 shows the change in mean annual temperature over the past 48 years. Linear regression was applied to assess the presence of a statistically significant trend. The graph reveals that during the initial decades (1977–2000), temperatures fluctuated around 12–13 °C, with minor variations and no clear trend. From approximately 2000–2005 onwards, a gradual but consistent increase in mean annual temperature is observed. After 2015, this increase becomes more pronounced and accelerated, with recent years (2022–2024) reaching approximately 14.5–15 °C. Overall, the data indicate an upward trend in mean annual temperatures in Plovdiv for the period 1977–2024, with an estimated warming of about 1.5–2 °C. This trend, confirmed through linear regression, corresponds to an average increase of 0.038 °C per year (approximately +1.8 °C over the 47-year period), as indicated by the analysis. Despite the presence of some cooler years, the overall pattern is one of sustained warming.

The graph illustrates a long-term warming trend in Plovdiv's climate, particularly evident since 2000 and accelerating after 2015. Annual temperatures exceed the climatic norms for the period 1961–1990 by more than 1.5–2.0 °C.

The linear regression analysis indicates an average decadal increase of 0.38 °C over the period 1977–2024. The cumulative effect over this 48-year period is approximately +1.8 °C, which aligns with the visual increase observed in the graph. This variability can be attributed to two main factors: a long-term warming trend and short-term fluctuations driven by processes such as urbanisation, atmospheric circulation, and local meteorological conditions.

Precipitation

The annual precipitation totals from 1976 to 2024 demonstrate a high degree of variability, characterised by alternating periods of drought and short-lived extreme rainfall events. No discernible long-term trend has been identified.

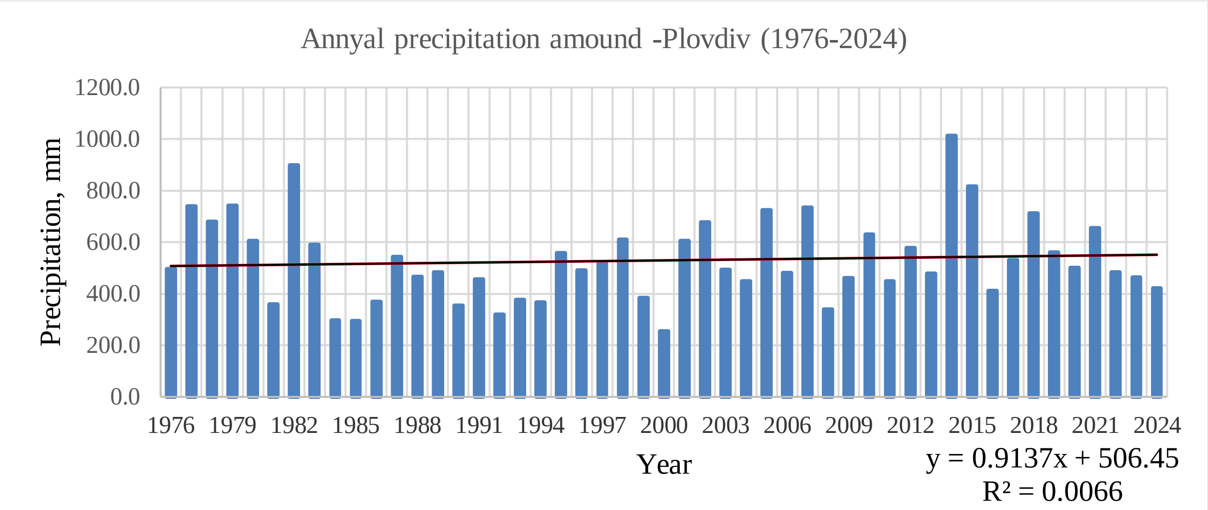

Figure 3. Annual precipitation in Plovdiv (1976–2024)

Precipitation is a climatic element characterised by considerable spatial and temporal variability. Various time periods were analysed, the earliest of which begins in 1896. Although significant fluctuations in annual precipitation totals have been recorded over the years, no long-term trend is evident (Fig. 3).

Precipitation patterns in Plovdiv for the period 1976–2024 exhibits a very weak increasing trend of approximately 0.9 mm per year, which is statistically insignificant (R^2 = 0.0066). Nevertheless, variability is pronounced, with annual totals ranging from below 300 mm to over 900 mm. These results point to increasing irregularity in precipitation distribution rather than a clear long-term trend.

Annual precipitation totals vary considerably, ranging from less than 300 mm in the driest years to over 1000 mm in the wettest. The linear trend demonstrates a marginal positive slope (+0.91 mm/year, or approximately +9 mm/decade), although the coefficient of determination (R^2) is only 0.0066. The Mann–Kendall test was applied to annual precipitation data for Plovdiv (1976–2024). The test statistic did not indicate a statistically significant trend ($p > 0.05$), confirming that variability is primarily driven by interannual fluctuations rather than a long-term directional change. This suggests that, over the long term, no persistent trend in annual precipitation can be observed, with variability largely governed by interannual and decadal climatic oscillations.

Over the past two decades (2000–2024), an increase in precipitation amplitude has been observed, characterised by more frequent dry periods alternating with short-lived but intense rainfall events. This pattern is consistent with broader trends reported in the Mediterranean and Balkan regions, where climate change is driving a shift towards more erratic precipitation regimes.

As illustrated in Table 3, there are noticeable variations in the intra-annual distribution of precipitation. For example, the driest month of the year differs across the analysed periods, with February, March, August, or November appearing as the minimum in different years. It is important to note that the precipitation totals for these driest months differ only slightly – typically by 1–2 mm. Regarding the month with the highest precipitation, it is consistently either May or June, with minimal differences in the recorded values.

Table 2. Mean monthly and annual precipitation totals (mm) at Plovdiv station for different periods

Period	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	**Sum**
1995-2024	44,1	36,1	48,0	42,4	59,8	61,0	50,6	35,9	44,4	47,9	33,7	48,0	**551,8**
1991-2020	39,1	36,2	47,8	41,2	58,9	58,3	51,4	34,4	43,8	48,0	35,7	43,0	**537,6**
1931-1985	42	32	38	45	65	63	49	31	35	43	47	49	**539,0**
1896-1945	39	32	36	42	54	62	47	35	36	40	48	44	**515,0**

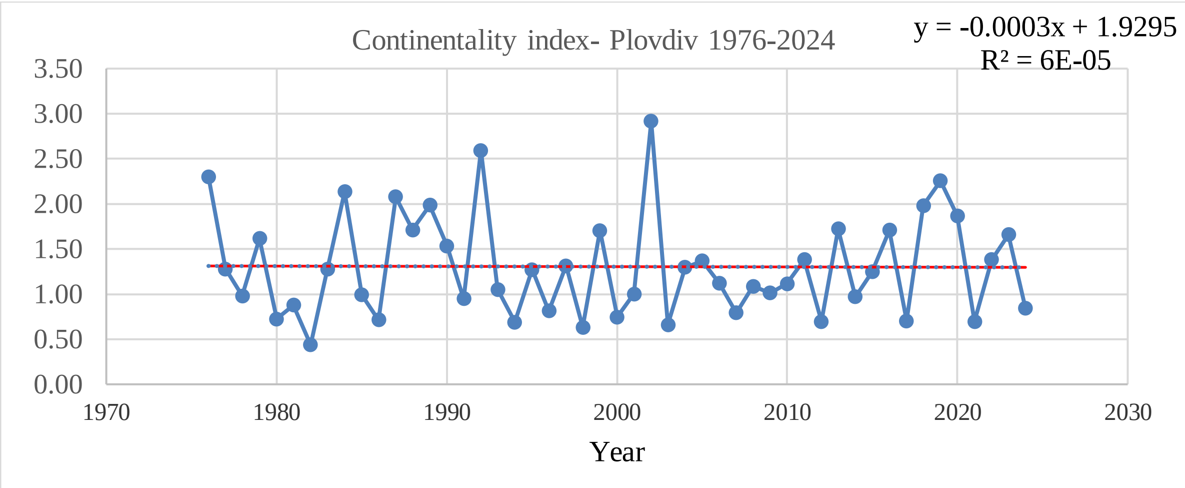

Figure 4. Continentality index based on annual precipitation (1976-2024)

An indicator of prevailing precipitation distribution is the Continentality Index (CI) (Fig. 4), calculated as the ratio of precipitation totals during the spring–summer period to those in the autumn–winter period. This index is used to assess the dominant climatic influence: continental, characterised by a predominance of spring–summer precipitation, or Mediterranean, marked by higher precipitation in autumn and winter. As shown in Fig. 4, the value of *y* (–0.0003) is extremely close to zero, indicating the absence of any discernible long-term trend. Moreover, the coefficient of determination (R^2) confirms that the trend is not statistically significant. Interannual variability is pronounced, precluding the existence of a clear linear tendency. Values range from approximately 0.45 (indicating very wet autumn and winter seasons) to above 3.0 (wet spring and summer periods). These findings highlight the significant influence of specific atmospheric conditions in individual years.

Over the past five decades, there has been no discernible trend towards either a more continental or a more Mediterranean precipitation regime. The distribution of precipitation remains highly variable, predominantly shaped by natural climatic fluctuations rather than by any consistent long-term trend. Years with unusually high or low Continentality Index (CI) values are most likely the result of extreme synoptic conditions, such as very wet summers or winters.

The main conclusion drawn from the analysis is that no stable long-term trend in precipitation amounts can be identified. However, the observed increase in variability amplifies the risk of both droughts and localised flooding. These dynamics have a direct impact on water resources, agriculture, and ecosystems in the Plovdiv region.

PM10 Air Pollution

The mean PM_{10} concentration at the Kamenitsa station is 35.08 µg/m³, while at AMS Trakia it is 43.25 µg/m³. Considerable variations are observed both between years and across months. These are expressed as follows:

High values are recorded during the winter months, with a peak in January, and low values during the warmer half of the year (Fig. 5; Table 4). The months from April to September show similar levels, with the lowest value occurring in May. As seen in Figure 5, the annual course of pollution at the two stations is identical. The lowest concentrations are recorded in May. A gradual increase begins in August–September.

Table 3. Monthly mean concentrations of PM_{10} (2015–2024)

Stations	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Year.
AMS Kamenitsa	54,95	48,55	34,21	26,49	22,63	24,28	24,46	26,2	28,78	35,46	44,97	49,94	35,08
AMS Trakia	64,95	60,31	42,37	32,3	29,5	30	30	31,64	33,59	44,75	57,41	61,27	43,25

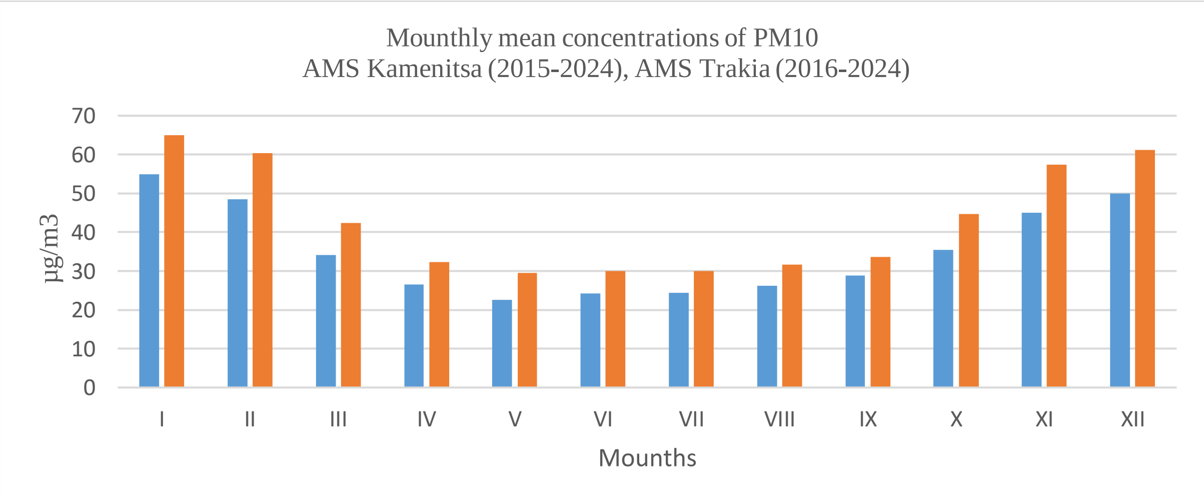

Figure 5. Monthly mean concentrations of PM_{10}– AMS Kamenitsa (blue) and AMS Trakia (red)

A direct relationship between meteorological conditions and particulate matter pollution, as well as other air pollutants, has been established (Gosteva, 2021). Very low average wind speeds have been recorded at the monitoring stations: 0.61 m/s at AMS Kamenitsa and 0.80 m/s at AMS Trakia. This can be attributed to the fact that wind speed is measured not at the standard height of 10 meters, but at approximately 2 meters above ground level, where speeds are significantly lower. An additional contributing factor is the dense urban development; as reduced wind speed is a characteristic feature of the urban climate.

Wind direction remains almost constant throughout the months and seasons, influenced by local conditions such as street orientation and the presence of buildings. At the Kamenitsa station, the prevailing wind direction is WSW (238°), while at the Trakia station it is SSE (152°).

A clear correlation has been observed between wind speed and pollution levels. Figure 6 illustrates this relationship for February 2017 at AMS Trakia. The Pearson correlation coefficient between PM_{10} concentration and wind speed is r = –0.63, indicating a moderately strong negative relationship. At the highest PM_{10} concentrations (200–330 µg/m³), wind speeds are very low (0.39–0.64 m/s), whereas at higher wind speeds (above 2 m/s), PM_{10} values are considerably lower (e.g., 32–66 µg/m³).

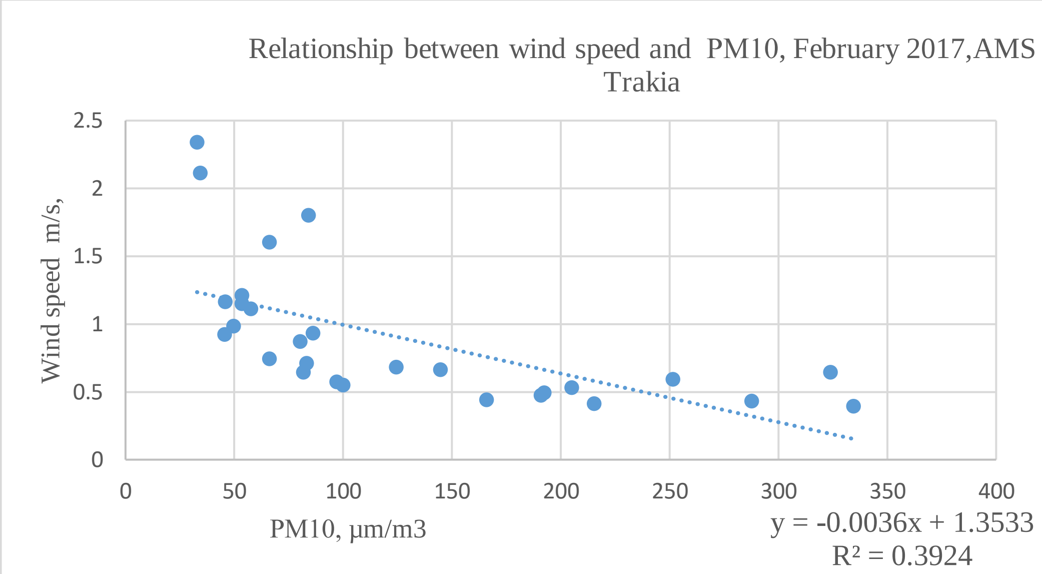

Figure 6. Relationship between wind speed and PM_{10} concentrations in February 2027, AMS Trakia

In the obtained regression analysis, where X = PM_{10} and Y = wind speed (WS), the equation reflects how changes in PM_{10} concentrations correspond to variations in wind speed. The slope is relatively small (–0.0036), as it represents the rate of change in WS per unit increase in PM_{10} concentration.

A clear warming trend is evident, as indicated by the upward trajectory of the trend line. The linear trend is +0.038 °C per year, corresponding to approximately +1.8 °C over 47 years. The coefficient of determination is R^2 = 0.49, suggesting that nearly 50% of the variance is explained by the linear trend, indicating a statistically meaningful relationship.

Since 2015, the rate of warming has accelerated, with average annual temperatures exceeding 14–15 °C in the last three years. Plovdiv is undergoing climate warming, increasingly evident over the past two decades. This trend aligns with broader patterns observed across Bulgaria and South-eastern Europe. Rising temperatures increase the likelihood of more frequent and prolonged heatwaves, with serious implications for public health and urban resilience. The most recent years are among the warmest recorded for the analysed period.

Precipitation data reveal substantial inter-seasonal and inter-annual variability, with some years receiving less than 300 mm, and others exceeding 900–1,000 mm. This highlights a growing irregularity in the precipitation regime, which is more critical than the presence or absence of a long-term trend.

Rather than a clear directional shift, the pattern reflects an alternation of dry and wet years, consistent with the broader climatic instability in southern Bulgaria, influenced by the cyclical nature of Mediterranean cyclones and drought events. In the context of climate change, the increase in extremes – years that are either very dry or very wet – is more important than changes in the average trend.

CONCLUSION

1. The climate of Plovdiv has warmed substantially (+1.5 to 2 °C) since the 1970s. This is reflected in a clear and statistically significant upward trend in temperature.
2. Precipitation patterns are unstable, alternating between dry periods and heavy rainfall. Annual totals and seasonal distribution do not exhibit a consistent long-term trend, with variability largely driven by natural atmospheric processes.
3. There is a clear divergence between temperature and precipitation trends: while temperatures continue to rise, precipitation remains within the range of natural fluctuations. This may affect the region's water balance and contribute to more frequent droughts and heatwaves.
4. PM_{10} pollution remains a serious environmental issue, particularly during winter. In several years, annual average concentrations exceeded the regulatory limit of 40 µg/m³, pointing to a persistent air quality problem. During the winter months (December to February), PM_{10} levels often rise sharply, frequently surpassing the daily limit of 50 µg/m³. The main cause is domestic heating with solid fuels, combined with adverse meteorological conditions such as temperature inversions and low wind speeds. In contrast, concentrations during the summer months are relatively low, confirming the strong seasonal character of the pollution.
5. Meteorological factors – especially wind speed, precipitation, and inversions – have a marked effect on PM_{10} levels. A clear negative correlation is observed between wind speed and particulate matter concentrations, with weaker winds favouring the accumulation of pollutants.
6. Addressing this issue requires integrated measures, including cleaner heating technologies, sustainable transport solutions, and improved air quality monitoring.

This study highlights the need for an integrated approach to climate and air quality in support of sustainable urban planning in Bulgaria.

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