Pollution Report

Investigating Weather-Driven Variability in Particulate Matter: Implications for Climate and Weather Quality in the Boston Area

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1. Abstract

This study investigates the relationship between weather variability and particulate matter (PM) concentrations in Boston over an 18-day period, providing insights into potential air quality impacts of climate change. Temperature emerged as a primary driver of PM fluctuations, with higher temperatures correlating positively with increased PM levels due to enhanced particle resuspension and secondary formation. Conversely, relative humidity demonstrated a negative correlation with PM concentrations, likely driven by particle aggregation and deposition. Limited precipitation events highlighted wet deposition's role in reducing PM, particularly for larger particles, though insufficient rainfall restricted broader conclusions. Overall, localised emissions and short-term variability tempered significant reductions in PM despite weather changes. These findings underscore the need for longer-term studies and targeted policies promoting cleaner technologies to mitigate the dual challenges of air quality degradation and climate change.

2. Introduction

(a) 2.1. Project Description

Climate projections over the next 10 to 50 years suggest significant changes, with regional impacts shaped by existing climatic conditions. In the Boston area, increases in precipitation events, temperature, and atmospheric water concentration are expected. (US EPA, n.d.-a) (Walsh, n.d.) . Weather and PM concentrations are intrinsically linked through atmospheric chemistry and particle distribution processes. (US Department of Commerce, n.d.). Various meteorological factors, such as temperature, precipitation and wind, influence PM concentrations. (Requia et al., 2019). Understanding the impacts of weather variability on PM levels raises important questions about how these dynamics will evolve alongside climate change. Since PM concentrations are largely localised—except when strong winds transport particles over long distances—studying weather-variability effects on PM in Boston provides a foundation for predicting future PM concentrations under localised climate change scenarios. (US EPA, n.d.-b)

Higher temperatures can exacerbate PM levels by creating stagnant air conditions and promoting particle resuspension from dry ground surfaces. ('The Impact of Humidity and Temperature on Particulate Matter Environmental Fate | Request PDF', n.d.). Conversely, colder weather often leads to frequent temperature inversions, which trap PM near the surface by restricting vertical air movement, increasing PM concentrations. (Instruments, 700). Relative humidity, which describes the water vapour content in the air relative to its saturation point at a given temperature, has a complex relationship with PM concentrations. Literature suggests that humidity can both increase and decrease PM levels. High humidity can cause particles to aggregate through water absorption, reducing airborne PM. However, temperature-induced changes in relative humidity can indirectly affect PM; rising temperatures lower relative humidity, potentially leading to increased PM concentrations. (Jayaratne et al., 2018). Precipitation is well-documented as the most effective mechanism for reducing PM concentrations through wet deposition, where water droplets capture and remove particles from the atmosphere. (Roldán-Henao et al., 2020). This effect is particularly pronounced for larger particle sizes, such as PM2.5 to PM10. (Maboa et al., 2022). Throughout the study period, measurements captured both day and night conditions. Although temperatures typically drop overnight, Boston's clear skies frequently lead to temperature inversions, which can intensify PM concentrations during the diurnal cycle. (*Atmospheric Controllers Of Local Nighttime Temperature*, n.d.)

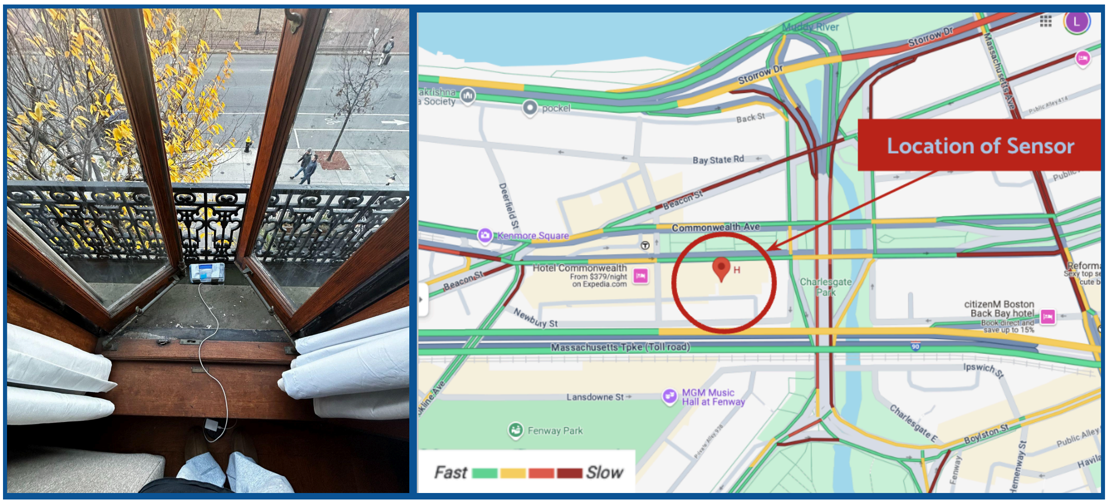
This project examines changes in PM concentrations in response to weather variability over an 18-day period, providing data to address how particulate matter concentrations may evolve over time.

(b) 2.2. PM's affect on health

Particulate Matter (PM) significantly affects both human health and the environment. Different sizes of PM, particularly those smaller than 10 micrometres (µm), are known to have predominantly negative health effects. Particles of this size can penetrate deep into the lungs, with smaller particles entering the bloodstream. Elevated PM concentrations can lead to irregular heartbeats, non-fatal heart attacks, aggravated asthma, and increased lung irritation. (US EPA, 2016a). While national PM levels have generally decreased due to air quality improvement efforts, it remains critical to predict future changes in PM concentrations to better understand and mitigate their potential environmental and health impacts. (US EPA, 2016b).

3. Methods

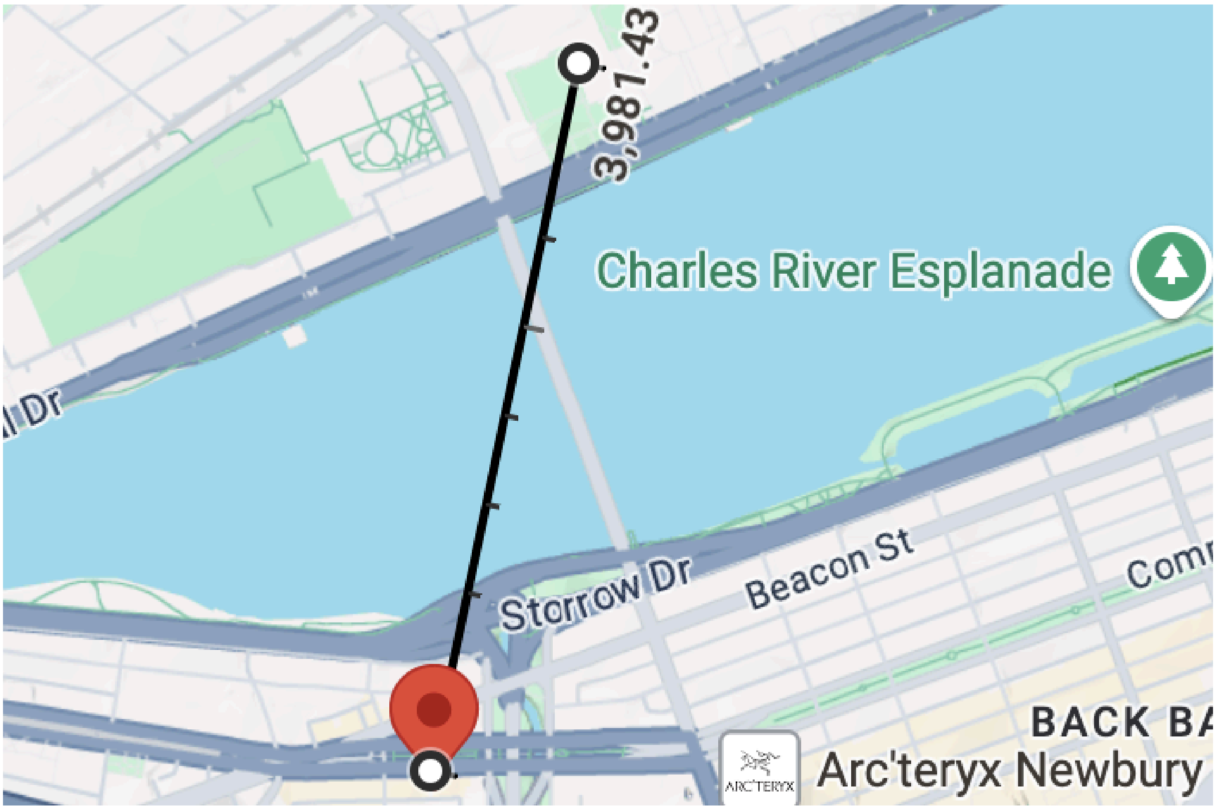
To understand the weather-driven variability of particulate matter (PM) I took measurements for PM_{10}, $PM_{4.0}$, $PM_{2.5}$, $PM_{1.0}$, Temperature, Relative Humidity and Time using an Air Quality Sensor (AQ Sensor) and scraped Precipitation data from the Tempest Weather Station at Building 4. (*Tempest Weather Station at Building 4*, n.d.) The placement of the AQ Sensor was carefully chosen to ensure consistent data collection over an 18-day period, considering factors such as charging availability and proximity to potential pollutant sources. These choices, along with assumptions about the independence of weather variables and the negligible impact of traffic emissions, laid the foundation for the subsequent analysis and the interpretation of figures generated from the data.



(i) Figure 1: Sensor Placement and Traffic in the Boston area

Figure 1: Sensor placed sideways to enable air flow into the device (left), traffic flow at 1700 hours on a weekday around the AQsensor (right).

Balcony doors were shut to prevent interference from indoor air pollutants and a wire connected to the outlet used to ensure the device stayed charged. Traffic emissions were considered negligible as particulate matter measurements inherently account for them, allowing us to focus on comparing the rate of change to weathering effects which is independent of traffic.



(ii) Figure 2: Distance from Tempest Weather Station to Sensor Location (~1.2 km)

The distance from the weather station is close enough to assume similar precipitation trends especially as rainfall increases. This data was used to compare drops in Particulate Matter in the event of rain.

With a large volume of data from the air quality sensor and extreme fluctuations of PM in each size throughout the time series an appropriate smoothing function and averaging function apply to the data to extract prominent values that are comparable to the time scale and weathering changes. First a smoothing function (Equation 1) is used to extract small trends and provides an uncertainty parameter for averaging function (Equation 2) that highlights robust trends in PM levels.

$$P\bar{M}(t) = \frac{1}{5}\sum_{i=0}^{4} PM(t-i) \tag{1}$$

$$\bar{\mathrm{PM}}(T_k) = \frac{1}{N}\sum_{t\in[T_k, T_k+\Delta T)} \mathrm{PM}(t) \tag{2}$$

Equation (1) uses particulate matter concentrations (PM(t)) measured in µg/m^3 as a function of time (t) and applies a moving average over 5 consecutive measurements to reduce noise, highlighting small-scale trends given by ($\bar{PM}$(t)). Equation (2) processes the smoothed PM data by averaging it over fixed intervals (ΔT) set to 6 hours - accounting for potential Temperature Inversions that occur more frequently at night (*Atmospheric Controllers Of Local Nighttime Temperature*, n.d.), producing resampled values ($\bar{PM}(T_k)$) that represent the mean concentration for each time step (T_K). This approach aligns temporal resolution with the time scale of weathering effects, enabling robust analysis of long-term trends while accounting for variability in the original dataset.

After synthesising the data and extracting key trends, PM data is measured against several variables, Temperature, Relative Humidity and Precipitation. These variables were all used to investigate the impacts of weather-variability on particulate matter and assumed to be independent of each other.

This analysis assumes that temperature, humidity, and precipitation independently affect PM concentrations, enabling clear attribution of trends to specific weather parameters. The 18-day timeframe was chosen to capture sufficient variability in weather conditions and their impacts on PM levels while ensuring manageable data consistency and analysis. Traffic-related emissions are treated as negligible over this long-term dataset, focusing on changes in PM levels rather than absolute values influenced by localised pollution.

The air quality sensor data, despite occasional anomalies or "blackout" periods, is addressed through smoothing and averaging functions to maintain reliability. Precipitation data from a monitoring station 1.2 km away is considered representative of the conditions at the sensor's location. Finally, smoothing and averaging processes are assumed to preserve the underlying PM trends, ensuring a robust dataset for comparing PM levels with weathering changes. These assumptions provide consistency and validity for the analysis.

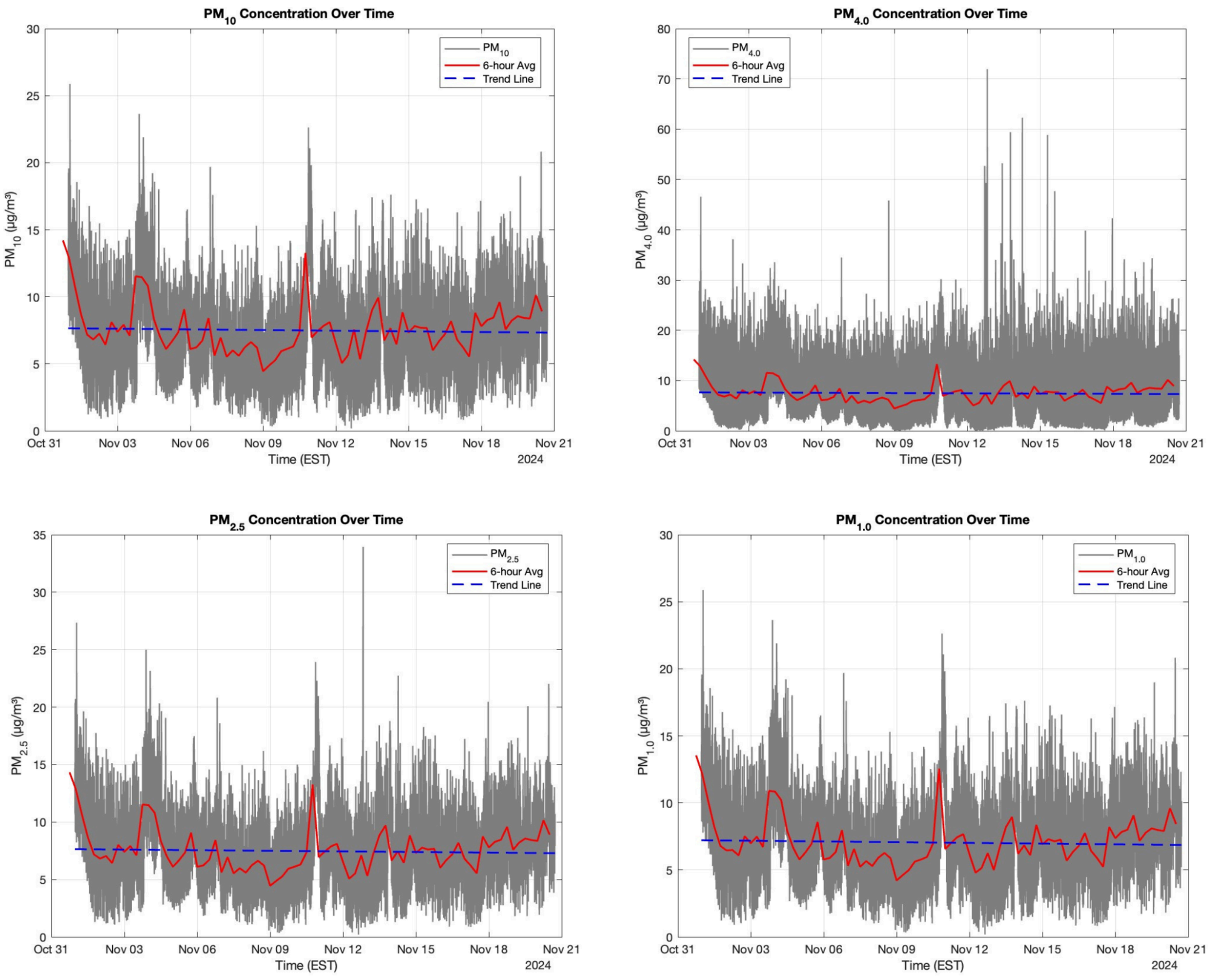
These methods are carried out to investigate how future changes to weather in the boston area will impact concentration of PM in the city and whether it improves (decrease in PM) or if future weather projections exacerbate PM concentrations.

4. Results

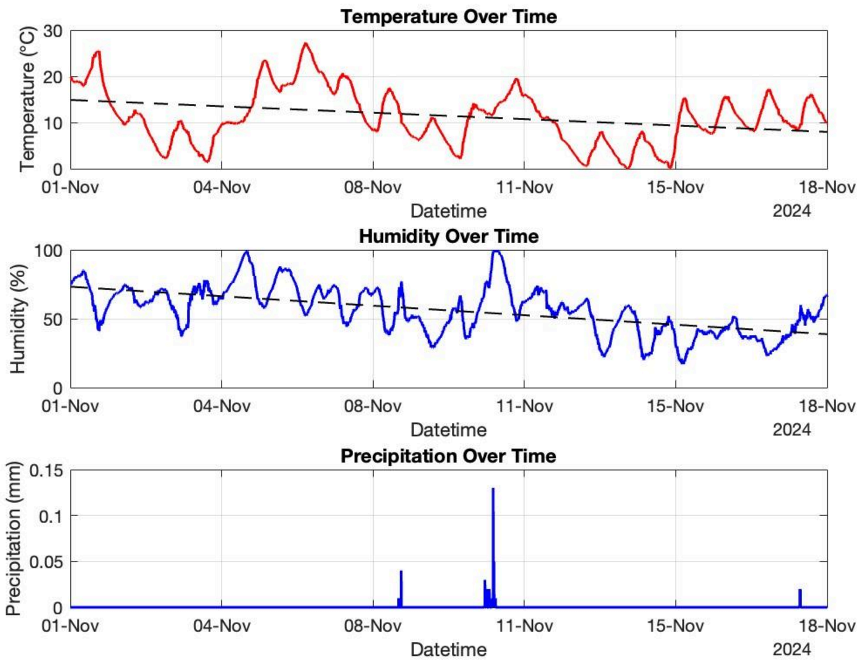
The following section summarises the results of the data analysis from the AQsensor as well as the Weather Station at Building 4. It is important to note PM concentrations are depicted left to right starting from PM_{10} and decreasing in size for all figures. Time is given by dates to consciously consider the impacts of the diurnal cycle and account for any discrepancies with frequent temperature inversions; the graph lines on the x axis signify the time starting from 00:00 on the day given. Additionally, the smoothed data is provided in grey listed as PM_x and the averaged data is depicted by the red line in each graph for readability.

4.1. Overall Particulate Matter (μg/m³) Change Over Time (T)

With the changing weather conditions the literature states that PM may decrease with decreased temperatures, humidity and increased precipitation periods which occur more frequently in the winter and spring. Conversely, PM matter may increase with additional use of vehicles and heating in "bad weather".



(iii) Figure 3. PM_x Concentration Change (μg/m³) over Time (t)

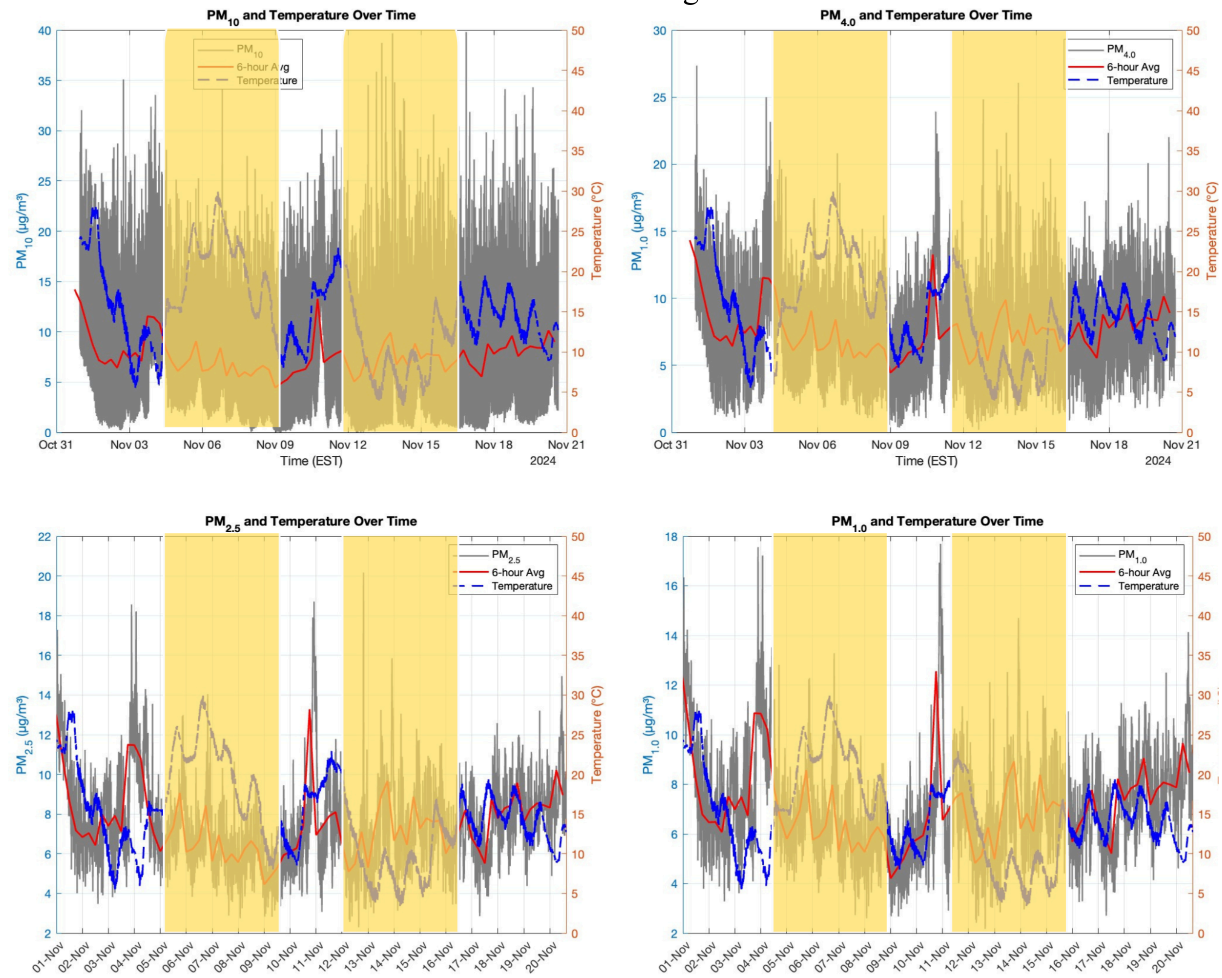


(iv) Figure 4: Meteorological Data over Time

Particulate matter (PM) concentrations (Fig. 3) showed slight decreases across all size categories over the 18-day period. PM10 decreased by 0.0164 µg/m³ per day, PM4.0 by 0.0166 µg/m³ per day, PM2.5 by 0.0176 µg/m³ per day, and PM1.0 by 0.0178 µg/m³ per day. In contrast, humidity and temperature (Fig. 4) exhibited significant decreases throughout November, but the changes in PM levels remained marginal across all size fractions.

4.2. Temperature and PM_x against time

Temperature (℃) and PM_x (µg/m³) are measured overtime to confirm the relationship between the two as the weather gets colder.

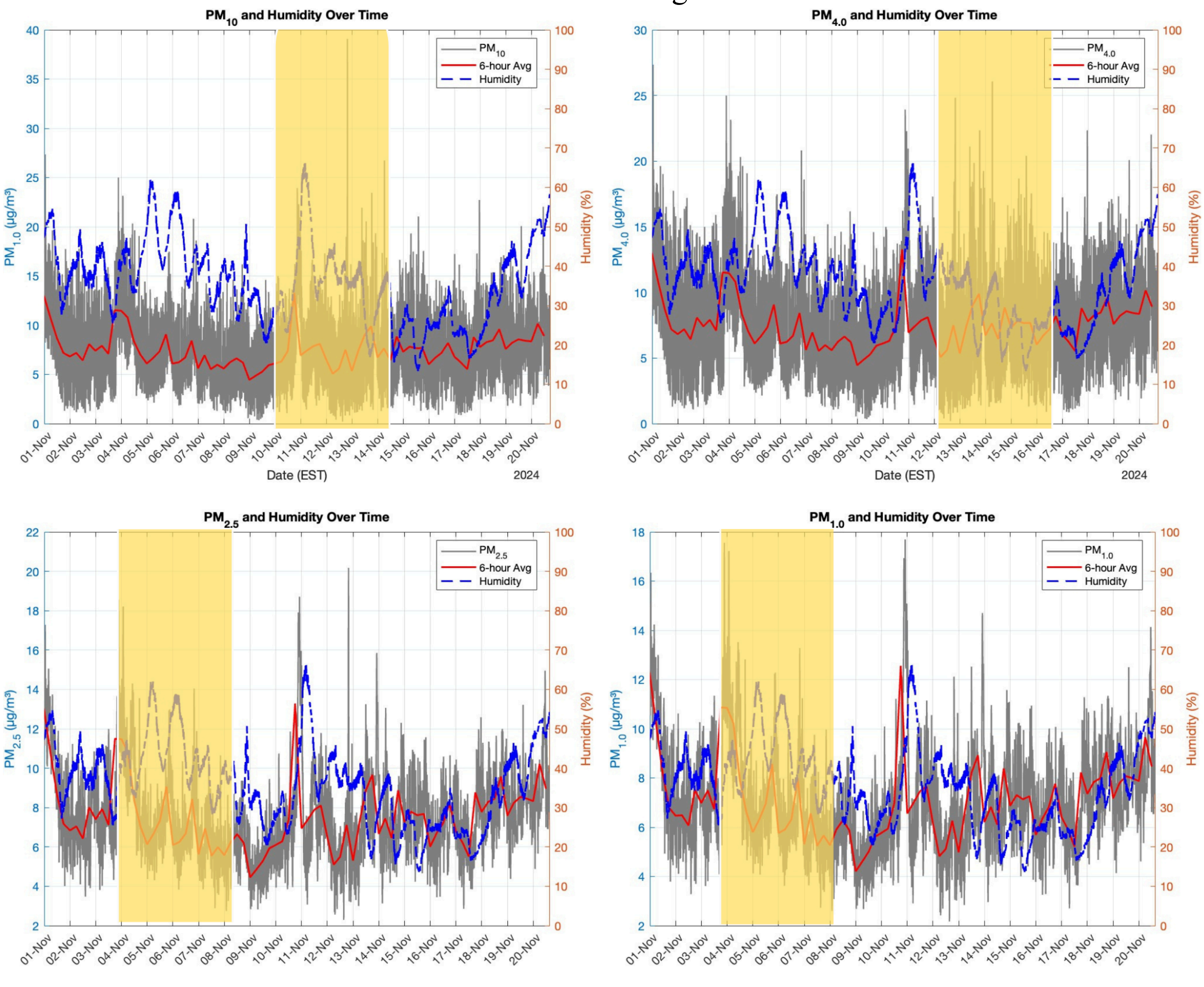


(v) Figure 5. Temperature and PM_x against time

The analysis reveals a strong correlation between temperature and particulate matter (PM) concentrations across all size fractions. When temperature increases, PM levels also rise, and similarly, decreases in temperature are associated with lower PM concentrations. This relationship is evident throughout the time series, with key events highlighted in yellow indicating periods where this correlation is particularly strong and consistent across PM_{10}, $PM_{4.0}$, $PM_{2.5}$, and $PM_{1.0}$. These events demonstrate the sensitivity of PM concentrations to temperature fluctuations over the study period.

4.3. Humidity and PM_x against time

Humidity (mm) and PM_x (µg/m³) are measured overtime to confirm the relationship between the two as the weather gets colder.

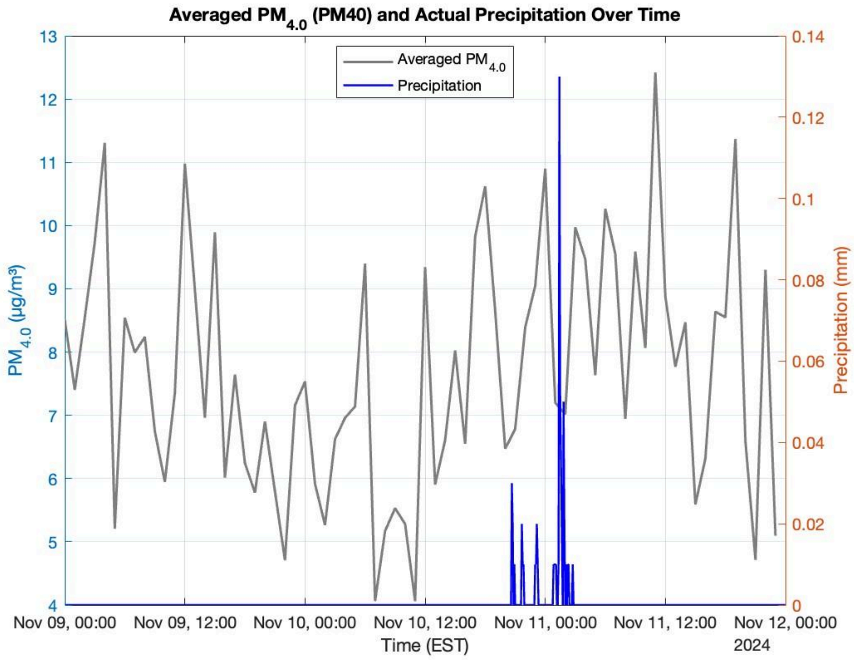


(vi) Figure 6. Humidity and PM_x against time

The analysis shows a negative correlation between humidity and particulate matter (PM) concentrations across all size fractions. As humidity increases, PM levels decrease, and conversely, as humidity decreases, PM levels increase. This relationship is observed throughout the time series, with key events highlighted in yellow indicating periods where this negative correlation is consistent across PM10, PM4.0, PM2.5, and PM1.0.

4.4. Precipitation and $PM_{4.0}$ against time

As there is little precipitation over the course of the 18 day period, available data for comparison is limited. Literature describes that precipitation has the greatest reducing effects for larger PM sizes such as PM_{10} and $PM_{4.0}$.



(vii) Figure 7. $PM_{4.0}$ and Precipitation (mm)

Figure 7 presents a focused view of a precipitation event that occurred between 10th and 11th November, the largest rainfall event during the study period. This incident highlights the most direct impact of significant precipitation on PM concentrations, with two notable spikes at 0.4 mm and 0.13 mm of rainfall corresponding to decreases in PM4.0 levels.

5. Discussion

The results of this study highlight the complex relationship between weather variability and particulate matter (PM) concentrations. The analysis of temperature and rainfall against PM concentrations over time aligns with findings from existing literature, confirming established trends. Additionally, the examination of relative humidity against PM concentrations in the Boston area supports the conclusion that increasing humidity decreases PM levels.

5.1. Temperature Impacts

Temperature emerged as a significant driver of PM fluctuations, showing a strong positive correlation across all particle size categories. Higher temperatures were associated with increased PM levels, likely due to enhanced resuspension of particles from dry ground surfaces and the promotion of secondary particle formation. These findings underscore the role of temperature in exacerbating air quality challenges, particularly during warm and dry periods (Inhalable Particulate Matter and Health (PM2.5 and PM10) | California Air Resources Board, n.d.).

5.2. Humidity Impacts

Humidity, in contrast, demonstrated a negative correlation with PM concentrations. Increased humidity was linked to reductions in PM levels, potentially due to particle aggregation or deposition facilitated by higher atmospheric moisture (Peng et al., 2019). However, this effect was less pronounced compared to the impact of temperature. A nuanced dynamic between temperature and humidity was observed, where rising temperatures can lower relative humidity, counteracting the moisture's beneficial effects on PM reduction. Literature suggests that this correlation is predominantly driven by water concentration rather than relative humidity alone, as two different temperatures can yield identical relative humidity values but vastly different water concentrations. Water concentration appears to be a more effective parameter for capturing the effects of atmospheric moisture on PM aggregation.

5.3. Precipitation's Impact

Although precipitation during the study period was limited, it showed a clear ability to reduce PM concentrations, particularly for larger particles like PM10 and PM4.0. The largest precipitation event, occurring between November 10th and 11th, highlighted significant reductions in PM levels through wet deposition, where raindrops captured and removed airborne particles (Roldán-Henao et al., 2020). However, the scarcity of rainfall events during the 18-day period limited the ability to generalise this impact or establish trends for smaller particle sizes (PM1.0 and PM2.5), which may require heavier rainfall for effective removal.

5.4. Other Influencing Factors

Despite slight overall declines in PM concentrations during the study, these reductions were marginal compared to the substantial decreases in temperature and humidity. This suggests that localised emissions and other environmental factors, such as increased vehicle use and heating during colder weather, may buffer or even amplify the effects of weather variability on PM levels. Furthermore, the short duration of the study constrained the ability to observe seasonal patterns or longer-term interactions between weather variables and PM concentrations.

6. Conclusions

This study highlights the relationship between weather variability and particulate matter (PM) concentrations, providing valuable insights into how climate change may influence air quality in Boston. Rising temperatures are likely to increase PM levels through enhanced particle resuspension and secondary particle formation. In contrast, higher relative humidity reduces PM concentrations by promoting aggregation and deposition.

Although nighttime PM spikes are not analysed within this scope, variations in boundary layer height can help detect anomalies in the data. The use of an 18-day dataset allows for the identification of consistent trends. Increased precipitation intensity could enhance PM removal through wet deposition, particularly for larger particles; however, fewer rainfall events may limit this effect.

These findings underscore the need for further research to understand the complex interactions between climate change and PM dynamics in urban areas. General changes in PM concentrations (PMx) are limited and inconclusive in determining the direct effects of temperature and humidity changes over time. A longer timescale should be reviewed to extract appropriate data for seasonal variations.

Finally, sufficient research into these effects is critical for informing future decisions on PM regulation. This knowledge also promotes the adoption of cleaner technologies, such as electric vehicles and sustainable heating systems, to mitigate the impacts of increased PM concentrations in the context of climate change.

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