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Neighborhood-Level Air Pollution Monitoring and Analysis in Massachusetts

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Abstract. Air pollution is a significant environmental issue with far-reaching consequences for both human health and the planet. It arises from the emission of harmful pollutants, such as particulate matter, ozone, and nitrogen dioxide, into the atmosphere. These pollutants originate from various sources, including vehicles, industrial facilities, and power plants. The impacts of air pollution are wide-ranging, encompassing respiratory infections, cardiovascular disease, cancer, harm to ecosystems, and contributions to climate change. The study of air pollution is a multidisciplinary field that draws upon knowledge from physics, chemistry, biology, and engineering. Understanding the causes and effects of air pollution is crucial for developing effective strategies to mitigate its harmful effects. Physics, in particular, plays a vital role in this field by providing the tools and techniques required to measure and comprehend the behavior of pollutants. By examining air pollution, we gain insights into the factors driving this problem and can devise measures to reduce pollution levels. Moreover, this knowledge empowers individuals and societies to make informed decisions about minimizing exposure to pollutants and formulating policies and regulations that safeguard both human well-being and the environment. In our study conducted in the central Massachusetts region, we investigated the status of air pollution using a combination of Environmental Protection Agency (EPA) monitoring sites and hand-held sensors. While the EPA sites offer long-term monitoring data, hand-held devices' flexible and affordable nature allowed us to explore air quality at the local neighborhood and street levels. By utilizing these tools, we assessed the spatial and temporal variations in air pollution within the city, aiding in the identification of localized hotspots. Such information is valuable for targeting specific areas requiring interventions and further understanding the dynamics of pollution distribution.

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INTRODUCTION

Air pollution is the presence of harmful substances in the air that can have negative health effects. Cities and neighborhoods around the world have seen an increase in air pollution due to emissions, which poses a threat to human health. Air pollutants such as particulate matter (PM) can worsen the condition of preexisting heart and lung diseases. PM is made up of tiny particles that are smaller than a fraction of human hair. These particles can carry surface-absorbed carcinogenic compounds and cause damage to the lungs, even in people without preexisting lung diseases, of which they can exacerbate. Cities like Boston and Worcester have varying pollution levels in different parts of the city. In this project, we used data collected by the Environmental Protection Agency (EPA) monitoring sites as well as hand-held sensors to study air pollution levels in various cities.

EPA has designated six air pollutants as criteria pollutants because of their harmful effects on human health and the environment. These pollutants are carbon monoxide, lead, nitrogen dioxide, ozone, particulate matter, and sulfur dioxide. Particulate matter, the focus of our study, will be elaborated on later on in our report. Sulfur dioxide (SO_2) has both short-term and long-term effects. In the short term, SO_2 can cause burning of the nose, throat, and lungs, difficulty breathing, and harm to the respiratory system. Long-term exposure to SO_2 can lead to changes in lung function, decreased fertility, loss of smell, headache, dizziness, nausea, vomiting, bronchitis, and shortness of breath. Ground-level ozone (O_3) can cause coughing, make the lungs more susceptible to infections, and worsen bronchitis, emphysema, and asthma. (O_3) is formed when pollutants from cars, power plants, and other sources react with sunlight. Nitrogen dioxide

(NO_2) contributes to the levels of PM and O_3. NO_2 can also inflame respiratory diseases, like asthma. Lead exposure can cause damage to the nervous system in children under the age of 17. However, lead can also cause issues in the kidneys, immune systems, reproductive and developmental functions, and cardiovascular organs in people of all ages. Carbon Monoxide (CO) is a colorless, odorless gas that is produced by cars, trucks, and other combustion engines. Carbon Monoxide can cause headaches, increased risk of chest pain for people with heart disease, and decreased oxygen levels in the blood. [1].

LITERATURE SURVEY

Understanding air pollution and air quality is critical to learning how to best protect the environment and the health of the greater population. Air quality is often viewed through the lens of different pollutants that can exist in the air. One of the major pollutants is $PM_{2.5}$, defined as Particulate Matter with a diameter of less than 2.5 micrometers. Due to the characteristics and exposure abundance to humans, $PM_{2.5}$ has been considered to pose a greater danger to human health than Ozone and Carbon Monoxide [2]. These particles can be emitted from several different sources, including emissions from vehicles, biomass burning, combustion from power generation and more [3]. These particles can be inhaled and absorbed into human bodies, and are linked to several negative health outcomes, such as heart and lung disease, diabetes, and issues related to pregnancy and childbirth [1].

Several studies have been conducted linking negative health outcomes in a population to exposure to $PM_{2.5}$. A study on Medicare receivers in Massachusetts found that long-term $PM_{2.5}$ exposure was associated with an increased risk of mortality [4]. Another study that looked at hospitalization rates for medicare receivers found that $PM_{2.5}$ concentrations had a positive association with hospitalizations, especially for cardiovascular and respiratory issues [5]. Another Massachusetts-based study found connections between $PM_{2.5}$ concentrations, local traffic pollution, and birth defects in infants [6]. A New England study on medicare receivers being hospitalized for $PM_{2.5}$-related cardiovascular diseases saw increases of 2 to 5 percent for hospitalization rates for every increase of 10 µg/m^3 of $PM_{2.5}$ [7]. In NYC and its surrounding metro area, models found that annual averages were above the EPA long-term standard. Along with this, $PM_{2.5}$ was associated positively with Asthma attacks, heart failure, and myocardial infections [8].

There exists inequality in how $PM_{2.5}$ concentrations are spread out among the population. Multiple studies have found certain population subgroups are more likely to live in areas with worse $PM_{2.5}$ levels than others. A Massachusetts study found that groups such as non-Hispanic blacks and those with an income under $20,000 USD had the highest average exposure to $PM_{2.5}$ and Nitrogen Oxide concentrations [9]. A study looking at EPA data across the country along with demographic data found that the non-Hispanic black, Hispanic, impoverished, and under 5-year-old populations all were most likely to reside in counties with worse air quality [10]. This inequality can even extend to the distribution of health impacts. In New England, it was found that female, black, and diabetic seniors were all at a higher risk of hospitalization for certain cardiovascular conditions as a result of $PM_{2.5}$ pollution [7]. Inequality in air quality exposure can be seen to exist along racial, economic, and age lines and can result in negative health outcomes from air pollution being more likely for certain populations over others.

In the United States, monitoring of $PM_{2.5}$ has been carried out on a national scale by the EPA, with the agency possessing thousands of monitors across the country collecting daily data on concentration levels of pollution. Since 1999, the standards for air quality have been set by the agency as being under 12 µg/m^3 annually, and under 35 µg/m^3 daily. However, problems exist with the distribution of monitors, and with the agency's current defined standards. Despite the large number of sensors set up across the country, their distribution is often not suitable for getting a full understanding of air pollution everywhere, with some locations being better covered than others. In a study into air pollution data access, it was found that of the 3000 counties in the United States, only 500 of them were found to have a sufficient amount of air quality data that would work for their study into the air quality for counties. The EPA's protocol of setting up monitors mainly in denser, urban areas results in those living in more rural areas lacking sufficient air quality monitoring data [10]. Even in urban areas, the distribution of sensors has been found to be inadequate for representing the population or allowing for an understanding of air pollution on smaller scales. In a study into air pollution variance on a neighborhood level using EPA monitoring stations in the Tampa, Florida area, it was found that the sparsity and spread-out nature of the monitors made it not feasible to conduct small-scale analysis. It was also noted how neighborhoods with a high minority population and low income were not located near stations, while higher income, white areas were more likely to be covered by the stations [11]. The inequality in air pollution spreads to how well some groups or neighborhoods can understand their local air quality.

The current standards for ambient air quality set by the EPA are worth reconsideration, for several reasons, including evolving scientific understanding of air pollutants' impacts, advancements in measurement techniques, and changing environmental and public health contexts [12, 13]. Since the establishment of the current standards of under 12 μg/m^3 annually and under 35μg/m^3 daily in 1999, Studies have come out that indicate a need for more stringent requirements. Negative health outcomes rates have been found to be significant, even at amounts that are considered suitable. Wei's study on Massachusetts Medicare receivers found that $PM_{2.5}$ exposure was related to more deaths per increase of 1 μg/m^3 than other pollutant types, even at levels under the long-term standard [4]. A study by the American Thoracic Society presents new standards of 8 μg/m^3 long term and 25 μg/m^3 short term, finding that the new standards would result in the avoidance of thousands of preventable deaths if implemented [14]. As a result of these and other developments, the EPA has proposed changing the annual standards to 9.0 or 10.0 μg/m^3.

Possibly one of the strongest reasons for the importance of research into air quality has been made apparent from events that have occurred since the beginning of this research project. The summer of 2023 saw the Eastern United States being hit with historically extreme levels of air pollution as a result of Canadian Wildfires, bringing out a large amount of focus onto air pollution impacts and how climate change can exacerbate these issues. Climate change has been found to result in an increase in forest fires [15], which can have a significant impact on air quality. A study into the 2020 wildfires on the West Coast found that areas in the region faced pollution levels that reached up to over 400 μg/m^3. Winds carried the smoke and pollution across the country to Northeastern cities [16]. These air pollution events can illustrate how climate change can bring about increased intensity and severity for these events. The health risks presented by forest fires is worthy of attention. In a study on the forest fires in Victoria, Australia in 2006, it was found that the increases in the interquartile range of 9 micrograms per cubic meter of $PM_{2.5}$ concentrations were correlated with increases of hospital admissions for cardiac arrests [17].

It is important that any major decision makers consider the potential impacts policies can have on air pollution, as even policies that can be seen to have little connection to air quality and air pollution can have impacts that result in changes in health incomes for a large number of people. A study into proposed cuts in service for the Massachusetts Bay Transit Authority and their potential effect on public health found that the cuts would result in an increase in car usage, and therefore air pollution emissions, along with cutting off access to healthcare services for households dependent on public transport. The result of the cuts would be an increase in mortality and hospitalization from air pollution related health conditions such as asthma, heart disease and lung disease [18]. Policy relating to climate change or carbon emissions can also have downstream effects on air pollution and public health, An examination on the health benefits of a carbon rebate bill in Massachusetts found that 300 lives would be saved and 2.9 billion dollars worth of health benefits would be gained [19]. Improving $PM_{2.5}$ monitoring to also track potential oxidative stress can also allow for a better way to understand air pollution due to the way oxidative stress responses and their related genetic genotypes can impact how $PM_{2.5}$ affects the human body [20].

Understanding what drives air quality variation on a neighborhood level is important information that can allow for improvements and better policies and decisions to come about. Concentrations of $PM_{2.5}$ can vary between areas on a small scale due to differing local conditions. An assessment of $PM_{2.5}$ levels in two villages bordering each other in Germany and Czech Republic were found to be 16 μg/m^3 and 21 μg/m^3 respectively [21]. Proximity to major roads and the contribution of suspended dust from vehicles have been found to be a notable potential vector of $PM_{2.5}$ air pollution. A study in Texas found that counting re-suspended dust emissions as part of $PM_{2.5}$ emissions could increase concentration readings by between 50 to 75 percent [22]. A study in Indianapolis that used low cost sensors found a negative correlation between $PM_{2.5}$ and tree canopy percentage, and a positive correlation with $PM_{2.5}$ and heavy industry [23]. Temporal and meteorological associations may also play an important role in $PM_{2.5}$ levels and deserve to be better understood, as they have been found to be potentially complex and multifaceted in nature. A study found that $PM_{2.5}$ concentrations were higher in the morning than in the afternoon while looking into traffic air pollution exposure in Minneapolis [24]. In New England, a study found temperature associations between $PM_{2.5}$ concentrations and hospitalizations for related health conditions. Respiratory admissions had associations with warmer days, while cardiac admissions had associations with colder days [25]. A nationwide assessment of $PM_{2.5}$ air pollution found associations to vary by region, but many areas saw elevation, wind speed, precipitation and temperature negatively associated with $PM_{2.5}$ levels and air stagnation to be positively associated [26]. A different study however found that precipitation and wind speed were still negatively correlated, but temperature increase was positively associated with $PM_{2.5}$ [27].

Previously, EPA air quality monitoring has been limited in its coverage. However, in recent years, there has been a development in low-cost air quality sensor technology. This has allowed for not only easier access to air quality data, but also for more spatially variable air quality data. This is in contrast to the stationary EPA monitors. Low-cost sensors have already been used in many studies, allowing for citizen scientists to conduct research and measure small-scale air quality variations [23].

The aim of our study is to use our own mobile air quality sensor to measure air quality on a smaller, neighborhood-level scale within different locations in Massachusetts. Our goals and main questions with the project include:

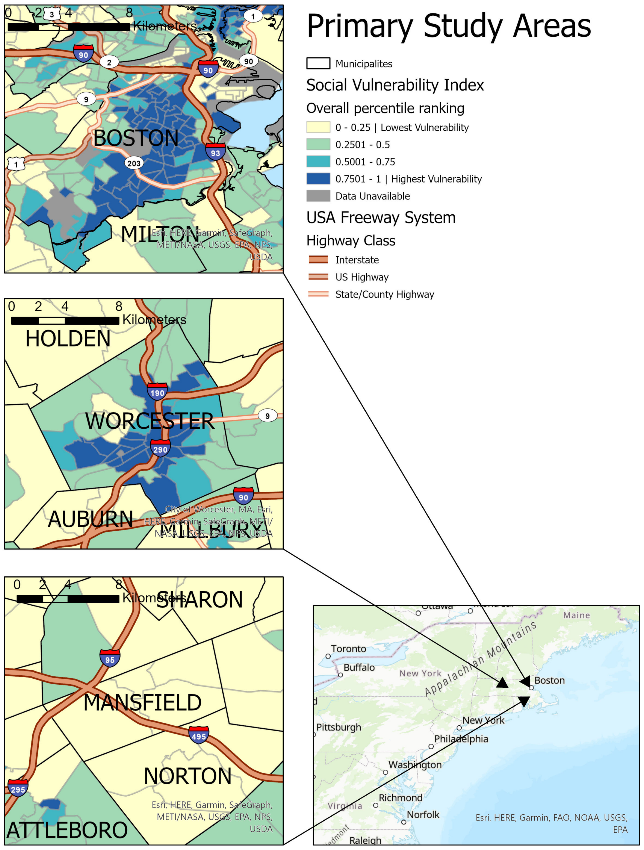

FIGURE 1. We conducted mobile air quality data collection in Eastern Massachusetts using an Airbeam 3 sensor attached to a car window. The device measured PM_{10}, $PM_{2.5}$, $PM_{1.0}$, relative humidity, time, and GPS location data. We collected data for 30-90 minutes once or twice a week from May to July 2023. The data was then loaded into JavaScript code or ArcGIS software with SVI data to map the two together.

1) Discovering any small-scale variations or hotspots that EPA stations are not detecting. 2) Understanding the impact that variables such as meteorological conditions, land use, and neighborhood socioeconomic status have on air quality. 3) Determining if a change in EPA maximum standards would make parts of Massachusetts not pass the new standards. We believe that this study will help to improve our understanding of air quality in Massachusetts and inform future air quality policies.

STUDY AREA AND METHODOLOGY

Our study area comprises various areas in Eastern Massachusetts. We are investigating the effect of socioeconomic status on $PM_{2.5}$ exposure, and we are using the SVI, or Social Vulnerability Index, to measure vulnerability to diseases and natural disasters. The SVI index is a useful metric created by the Center of Disease Control for understanding the vulnerability of different communities to environmental hazards.

The SVI index ranges from 0 (least vulnerable) to 1 (most vulnerable). We collected data along many different routes, but our main areas of focus are three regions: Worcester and its surrounding towns, Boston and its surrounding metro area, and Mansfield and the surrounding towns in North Bristol County and Southern Norfolk County. The three study areas chosen represent a range of socioeconomic conditions and levels of urbanization.

Worcester is a medium-sized city with varying SVI, including a number of socially vulnerable areas. Boston is a major metropolitan city with wide SVI variation and many potential sources of local pollution. Mansfield is a suburban area with generally low social vulnerability. These three different study areas allow us to understand $PM_{2.5}$ variation in vastly different levels of urbanity and socioeconomic level.

Mobile data collection involved use of an Airbeam 3, A

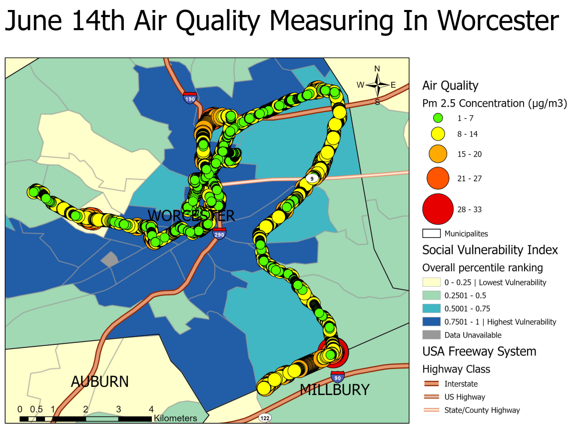

FIGURE 2. $PM_{2.5}$ readings on June 14th in Worcester paired with social vulnerability index.

mobile air quality sensor. The device was attached to a car window and driven around while activated, allowing for the capturing of air quality data while driving along different routes. The device measured temperature, PM_{10}, $PM_{2.5}$, $PM_{1.0}$, relative humidity, time and GPS data, allowing for the data to be mapped. Collection sessions were generally around 30 minutes to 1 ½ hour in length and done roughly once or twice a week from May to July 2023. After collection, data was loaded into JavaScript code or mapping software ArcGIS with SVI data in order to map the two together.

Along with our mobile session data, Data from EPA air quality stations were downloaded and used in the study. The station present in Worcester had its data downloaded in order to conduct statistical analysis on long term temporal $PM_{2.5}$ trends. For the purpose of looking into data collected on days of high $PM_{2.5}$ readings due to forest fire smoke, remote sensing data was used and downloaded. Satellite data measuring aerosol optical depth from days of low air quality due to forest fires were downloaded and loaded into ArcGIS, where it was mapped along with mobile sensor data collected the same days.

RESULTS AND DISCUSSION

Throughout the summer season, we conducted multiple air quality data collection sessions across various study areas. Our efforts aimed to cover diverse routes and locations, including major interstate routes such as I-93, I-95, I-495, and I-290. The air quality measurements displayed significant variability, both spatially and temporally. For a concise summary of each air quality data collection session, please refer to the Appendix at the end of this study.

To generate maps for these collection sessions, we utilized the Google Colab Software tool. In contrast, maps displaying air sensor data in conjunction with Social Vulnerability Index (SVI) information were created using ArcGIS software. Figure 2 illustrates a map produced from our air quality collection session in Worcester on June 14th. This route traversed various parts of Worcester, encompassing areas of high or medium social vulnerability. The data revealed numerous locations where air quality exceeded 8 micrograms per cubic meter, a level potentially posing long-term health risks.

It's essential to recognize that AOD, as measured by satellite remote sensing, represents the cumulative effect of particulates dispersed throughout the atmospheric column. In contrast, surface measurements of $PM_{2.5}$ reflect concentrations at ground level. This discrepancy is vital in understanding the vertical distribution of aerosols. We would like to emphasize that while AOD and $PM_{2.5}$ might exhibit similar trends, the differences in their observed values reveal significant details about the vertical stratification of particulates. This disparity arises due to various factors, including atmospheric variables, dispersion of aerosol types, and their sources. AOD measurements are an integrated column representation. Therefore, it can be influenced by particles at different altitudes, which may not directly correlate with ground-level $PM_{2.5}$ concentrations.

The variations in $PM_{2.5}$ readings, both in terms of space and time, stem from multiple factors, some more discernible than others. Notably, we recorded rapid $PM_{2.5}$ spikes when following heavy-duty vehicles such as semi-trailer trucks, with their influence on readings being unmistakable. Average readings between sessions exhibited considerable fluctuations, with some days falling within the EPA's approved standards for long-term air pollution and others exceeding them significantly. One noteworthy influence on day-to-day variations was the impact of the Canadian wildfires, as depicted in Figure 3. Additionally, we observed that speed and highway travel could lead to higher readings, although this effect was more pronounced on certain days. Our research underscores the necessity for a more sophisticated surface monitoring network. Such a network would enhance our understanding of air pollutant exposure by providing higher-resolution data. This is crucial for more accurate assessments of air quality and its impact on public health. The divergence pattern between AOD and surface $PM_{2.5}$ readings may not be just a measurement discrepancy but a window into the complex dynamics of atmospheric particulates.

When considering spatial and neighborhood-level variations, discernible patterns were challenging to identify. $PM_{2.5}$ measurements were taken across varying levels of urban development and social vulnerability, with minimal observable shifts between different areas. Overall, day-to-day variations over the broader study area appeared to be the primary driving factor. It is probable that mete-

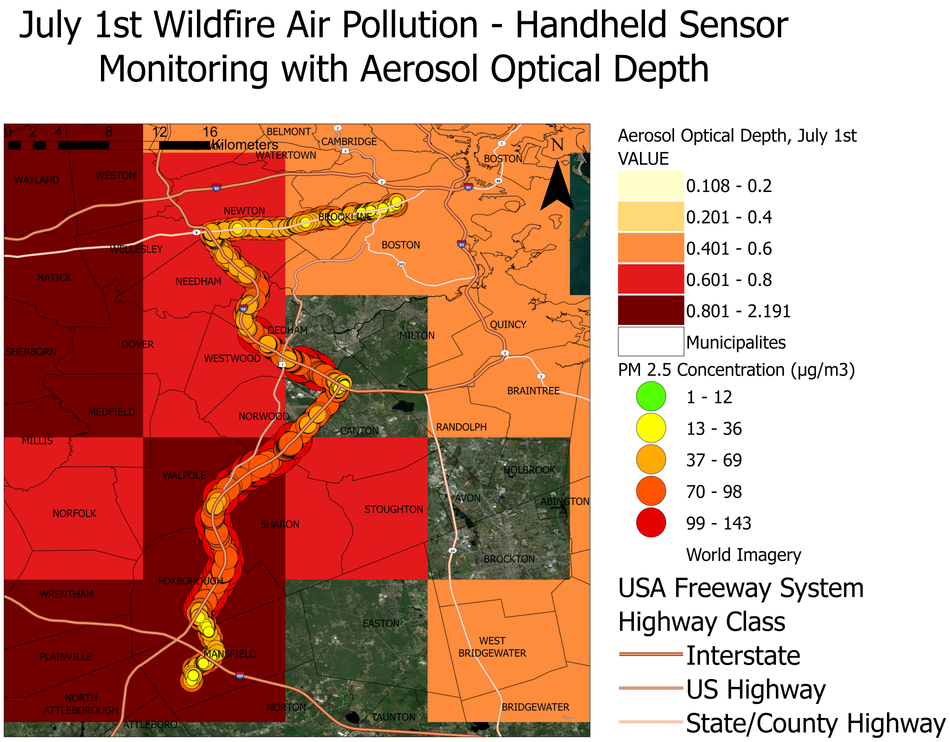

FIGURE 3. Mobile sensor data collected on a day with high air pollution as a result of forest fires, along with satellite Aerosol Optical Depth data. The Air Quality Sensor Data shows particularly high levels of air pollution, far above what is considered passable by EPA standards. The AOD data shows some correlation with the mobile sensor data, pointing to high atmospheric pollution on this day.

orological changes, including weather and wind systems, play a more substantial role in $PM_{2.5}$ variation than spatial differences within the study areas. Any small-scale spatial variation, if it exists, may require more extensive statistical analysis to become apparent or better understood.

Assessing $PM_{2.5}$ readings against EPA standards, we found numerous instances where the daily average exceeded the annual standard for $PM_{2.5}$ air pollution of 12 $\mu g/m^3$. The frequency of such occurrences and the extent to which the Canadian Wildfires influenced these readings, especially on days with less extreme levels, remain uncertain. Considering the proposed stricter standards due to the associated health risks at the current acceptable levels, the potential for adverse health impacts cannot be dismissed. However, it's worth noting that only a handful of days saw average readings surpass the short-term 24-hour limit of 25 $\mu g/m^3$.

Statistical Analysis of Worcester EPA data presents some noticeable trends in air pollution over a long temporal scale. Figure 4 displays the seasonal trends of air pollution data in the years 2010 and 2020. It can be seen that summer and winter have generally higher average $PM_{2.5}$ concentration levels, while spring and fall tend to have lower average concentration levels. In terms of annual trend, there is a noticeable decrease in average $PM_{2.5}$ concentration from 2010 to 2020. The means, 75th percentiles, and maximum values can be seen to be sharply lower in 2020 compared to 2010, showing a trend towards more consistently lower air pollution within Worcester. Figure 5 also shows the progression year by year of air pollution and displays a noticeable decrease in average air pollution, with the graphs going from right skewed to be more bell-curved as the average and frequency tend towards lower $PM_{2.5}$ concentrations.

We conducted a calibration session to align our air sensor with the EPA station in Worcester. During this session, the sensor was run for a few minutes outside the EPA station at around 6:30 PM. The average $PM_{2.5}$ reading during this session was 2 mug/m^3. However, the Air Quality Index (AQI) reading for the same day, according to the AirNow website, is rated at 35, equivalent to 8.3 $\mu g/m^3$. This represents a noticeable disparity in readings.

There are a few possible explanations for this discrepancy. First, pollution levels can vary throughout the day. The AQI reading for the day is likely an average of the pollution levels throughout the day, while the sensor read-

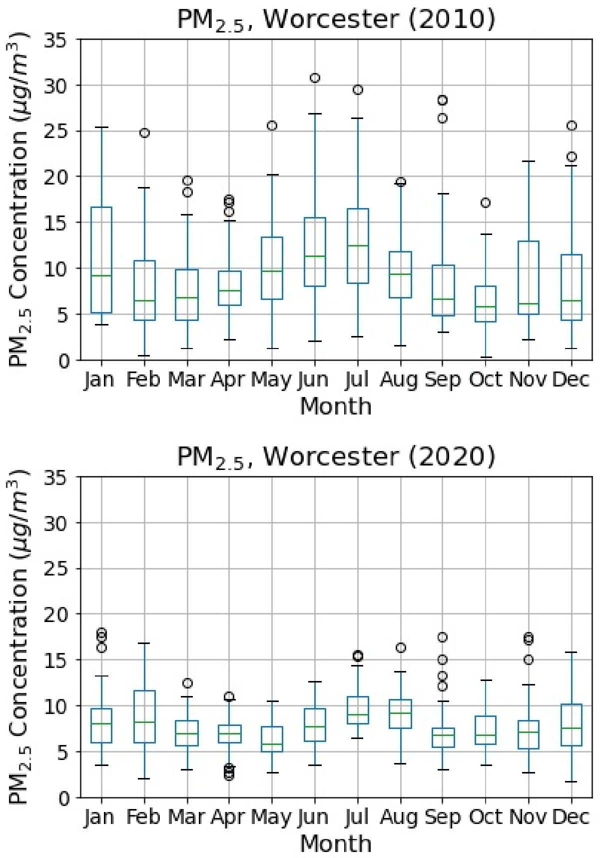

FIGURE 4. Box plots showing the season variations in $PM_{2.5}$ readings from the EPA station in Worcester in 2010 and 2020.

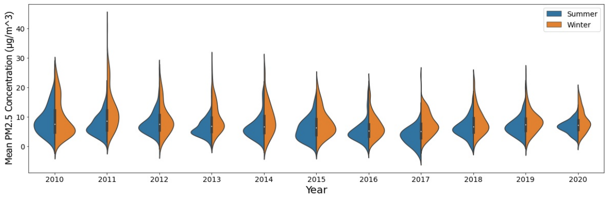

FIGURE 5. Frequency chart of mean $PM_{2.5}$ concentration in Worcester from 2010 to 2020, for the months of Summer and Winter.

ing was taken at as specific point in time. Second, relative humidity can influence $PM_{2.5}$ measurements. The relative humidity during the calibration session was 43%. It is known that relative humidity levels below 50% can lead to an underestimation of $PM_{2.5}$ levels [28].

Finally, it is worth noting that low-cost monitors typically exhibit strong accuracy and correlation when compared to regulatory monitors [29]. However, there are some factors that can affect the accuracy of low-cost monitors, such as relative humidity and pollution levels. Overall, the calibration session was successful in aligning the air sensor with the EPA station in Worcester. However, the discrepancy in readings between the sensor and the AQI highlights the importance of considering factors such as pollution levels and relative humidity when interpreting air quality data.

CONCLUSION

Our research has shed light on the variations in $PM_{2.5}$ air pollutants across Massachusetts. We found that there were some minor differences in $PM_{2.5}$ levels at the neighborhood level, but these differences were overshadowed by the significant temporal variations observed on different days.

These temporal variations can be attributed to a number of factors, including events like wildfires and meteorological phenomena. For example, our data showed that $PM_{2.5}$ levels often exceeded the recommended long-term healthy threshold on days when there were wildfires in Canada. This highlights the role of climate change in air pollution, as wildfires are becoming more frequent and intense due to rising temperatures.

Despite these variations, our statistical analysis revealed a promising downward trend in air pollution levels in Massachusetts. This trend was particularly pronounced in the Worcester area, which has seen a significant reduction in $PM_{2.5}$ levels in recent years. This progress is encouraging, but it is important to continue to implement air quality policies in order to further protect public health.

In conclusion, our research has shown that $PM_{2.5}$ air pollutants vary significantly across Massachusetts, both at the neighborhood level and over time. These variations can be attributed to a number of factors, including events like wildfires and meteorological phenomena. While there has been some progress in reducing air pollution levels in recent years, it is important to continue to implement air quality policies in order to protect public health.

EDITORS' NOTE

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