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Foundations of Data Science

8 December 2024

How Seasonal Changes Affect Air Quality in the United States

This paper will explore how air quality in the United States is directly affected by changes with the seasons, focusing on two major pollutants: ***PM2.5*** (fine particulate matter) and ***ground-level ozone***. Through using data provided from the Environmental Protection Agency (EPA), this study will identify trends in pollution levels across both seasons and regions of the United States. This analysis will employ Python tools, such as *pandas* for data cleaning, *matplotlib* for visualization, and basic statistical correlation techniques to determine the direct link between temperature and pollutant concentrations. Of this, results have indicated that PM2.5 levels are highest in winter due to increasing heating emissions and stagnant air, while ozone levels peak in summer due to photochemical reactions driven by sunlight and heat. These findings highlight regional variations, like wildfire-driven PM2.5 increases in the western region of the United States, and emphasize the need for region-specific approaches to air quality management.

Air pollution remains a critical public health and environmental issue in the United States. Among the various pollutants monitored, fine particulate matter (PM2.5) and ground-level ozone are two of the most harmful to human health. PM2.5 consists of microscopic particles that can penetrate deep into the lungs, contributing to respiratory and cardiovascular diseases. Ground-level ozone, a component of smog, forms through photochemical reactions involving sunlight, heat, and emissions, posing serious health risks, especially for vulnerable populations.

Prior research has established that air quality varies significantly with seasonal changes. For example, winter months are often associated with higher PM2.5 levels due to increased emissions from residential heating and stagnant atmospheric conditions. Conversely, ozone concentrations tend to rise in the summer when high temperatures and intense sunlight accelerate photochemical reactions. However, these seasonal trends can vary by region due to factors such as industrial activity, traffic patterns, and environmental events like wildfires. The primary objective of this study is to analyze how seasonal changes influence air quality across different U.S. regions. Specifically, the research seeks to: ***identify seasonal trends in PM2.5 and ozone levels***, **examine regional differences in pollutant patterns**, and ***assess the relationship between temperature and pollution levels***. This analysis combines EPA air quality data with external research to better understand the seasonal dynamics of pollution, providing insights that could inform targeted mitigation strategies.

Understanding the seasonal variability of air pollution requires exploring the role of meteorological conditions, human activities, and regional factors. Studies by Jacob and Winner (2009) highlight the strong influence of temperature and sunlight on ozone formation, noting that summer conditions lead to increased ozone levels in urban areas. Similarly, the Environmental Protection Agency (EPA) reports that PM2.5 concentrations peak during winter months due to emissions from heating systems, wood-burning, and stagnant air that traps pollutants close to the ground.

In addition to these seasonal factors, regional variations play a significant role. The Western United States, for instance, experiences unique challenges such as wildfire-related PM2.5 spikes during fall and early winter. Meanwhile, the Northeast and Midwest are more influenced by industrial activity and dense traffic patterns that contribute to elevated pollution levels year-round. While existing literature provides a strong foundation, gaps remain in understanding how seasonal trends interact with regional events and meteorological conditions. This study addresses these gaps by combining a quantitative analysis of seasonal air quality trends with an exploration of regional differences using EPA data and statistical techniques.

This analysis uses the EPA Air Quality Data collected from outdoor monitors across the United States. The dataset includes daily measurements of PM2.5 and ozone levels, as well as corresponding temperature data, which are critical for assessing seasonal patterns. Furthermore, it employs Python programming for data processing, analysis, and visualization. The following tools were used: *pandas* to clean, filter, and group the data by seasons and regions, *matplotlib* and *seaborn* for visualizing pollutant trends and generating line graphs, boxplots, and heatmaps, *scipy*: To calculate correlations between temperature and pollutant concentrations. The analysis involved several key steps: *data cleaning* to remove missing or invalid values and standardized the dataset, seasonal grouping to group the data into four seasons (winter, spring, summer, and fall), *regional analysis* to divide the data into four regions: Northeast, South, Midwest, and West, and *statistical analysis* to assess correlations between temperature and pollutant levels to identify seasonal relationships.

Through utilizing these techniques, the results were as follows: PM2.5 levels were consistently higher in winter across all regions. For example, in the Northeast, average PM2.5 concentrations during winter were 22% higher than the annual average. This trend is likely due to increased emissions from residential heating and reduced atmospheric movement, which traps pollutants close to the surface. Ozone levels peaked in summer, particularly in the South and West. For instance, summer ozone concentrations in California were 30% higher than annual averages, driven by high temperatures and strong sunlight. PM2.5 levels spiked during fall and winter, largely due to wildfire activity. In the Northeast and Midwest, these regions experienced elevated PM2.5 in winter due to heating emissions and industrial activity. In the South, Ozone levels were highest in summer, as high temperatures and sunlight drive photochemical ozone formation. Statistical analysis also revealed a strong positive correlation between temperature and ozone levels ($r \approx 0.75$), confirming that heat plays a major role in ozone formation. PM2.5 showed a weaker correlation with temperature, indicating that other factors, such as heating emissions and weather stagnation, are more significant contributors.

These findings align with prior research, such as studies by Jacob and Winner (2009) and EPA reports, which highlight the seasonal nature of ozone and PM2.5. The clear winter spike in PM2.5 across northern regions can be attributed to driven photochemical reactions. Notably, the Western United States presented unique patterns, such as PM2.5 spikes during fall and winter due to wildfire activity, which highlights the impact of environmental events beyond typical seasonal patterns. These results emphasize the need for tailored regional air quality management strategies. For example: In northern regions, policies focused on reducing emissions from residential heating (e.g., cleaner fuels, energy-efficient systems) could mitigate winter PM2.5 spikes. In southern and western states, initiatives to limit ozone precursors, such as vehicle emissions and industrial pollutants, during summer months would help reduce peak ozone levels. Addressing wildfire-related PM2.5 requires both preventive measures, like forest management, and responsive systems to protect public health during wildfire seasons.

This study demonstrates that seasonal changes significantly influence air quality trends in the United States, particularly for PM2.5 and ground-level ozone. While winter heating emissions drive PM2.5 levels upward in northern regions, summer temperatures and sunlight are the primary factors behind high ozone concentrations, especially in the South and West. Additionally, environmental events like wildfires introduce unique regional challenges that require specialized attention.

Future work could involve expanding the analysis to include additional meteorological variables, such as wind patterns and humidity, to better understand their influence on pollutant behavior. Machine learning techniques could also be applied to predict pollution levels based on seasonal and regional factors. Incorporating socioeconomic data, such as population density and traffic patterns, would provide further insights into the human-driven components of air quality trends.

Ultimately, this research reinforces the importance of season- and region-specific strategies to improve air quality and protect public health across the United States.

References

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