Improving Weather Prediction Technologies: Establishing a Relationship between Air Pollution and Weather Phenomena

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The primary focus of this research is to establish a link between air quality, weather patterns, and climate dynamics. Employing a correlative methodology, the study aims to investigate the association between air pollution levels and the occurrence frequency of acid rain events. To accomplish this, extensive quantitative meteorological data gathered from weather stations situated in the Midwestern United States over a span of five years will be analyzed. The ultimate objective of this research paper is to underscore the significance of incorporating air particulate matter considerations in weather forecasting and prediction models, highlighting its potential implications for making atmospheric and weather assessments.

Keywords: acid rain; acid deposition; weather prediction; air pollution; machine learning

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Research Question

This essay asks the question **"To what extent can the use of machine learning be effective in establishing a relationship between air pollution and acid rain phenomena?"**

Justification

I chose this research topic because it combined my interests in machine learning and earth science. I was interested in the potential applications of machine learning within a research project and thought that applying it to an earth science-based field would be the best possible approach due to the gap that is currently present within the scientific research community in earth science-based research that involves machine learning. I originally chose to analyze all atmospheric weather data as a whole, which included but was not limited to air pressure, dew point, and temperature but slowly narrowed down my focus as I started to notice where the primary gap in research was. Past meteorological models are able to account for most atmospheric indicators within their predictions, however, what appears to be the greatest point of concern to most meteorological models are changes in the concentrations of air particulates such as ozone and sulfur dioxide. The accuracy, but more importantly the inaccuracies of these weather predictions not only ruin people's perfect summer days but also cause the deaths of millions of civilians yearly and cause billions of dollars in structural damage which could have been prevented by more accurate, reliable, and all-encompassing weather predictions.

Introduction

Intense anthropomorphic forces that elevate air pollution levels cause numerous and severe adverse effects. Namely, air pollution worsens air quality and damages human health (Liu et al. 2020). Elevated air pollution levels increase the incidence of cardiovascular and respiratory disorders (Vineis et al. 2004), diabetes and hypertension (Hoek et al. 2013), and dementia (Chen et al. 2017). Consequently, this increases the proportion of psychiatric, mental (Buioli et al. 2018), and premature deaths (Lelieveld et al. 2015). Additionally, studies show that elevated air pollution levels have affected cognitive ability (Zhang et al. 2018), resulted in impaired memory and recollection (Powdthavee et al. 2020), and reduced life expectancy regardless of gender and socioeconomic background (Ebenstein et al. 2017).

Serious air pollution can lead to disastrous societal and economic effects. One of these effects is increased criminal and nefarious activities as highlighted by a 2018 study conducted by the association for psychological science. The study concluded that air pollution could not only corrupt an individual's health but also contaminate their morality (Lu et al. 2018). Additionally, air pollution has been shown to lower solar power potential (Swwerts et al. 2019), decrease gross urban happiness (Zheng et al. 2018), and cause disastrous effects on road transport sectors of national economies (Xie et al. 2016).

Particulate Matter (PM) Influence on Weather

Particulates, also known as atmospheric aerosol particles, are microscopic particles of solid or liquid matter suspended in the air. Variations in PM concentrations over a short period of time have been reported to cause abnormalities in weather patterns (Tiwari et al. 2012). Wet weather conditions typically reveal lower concentrations of PMs compared to dry weather conditions, and light precipitation has been found to better air quality in urban and rural lands (Yadav, 2020). During wet weather conditions, concentrations of PM_{10} $PM_{2.5}$ were reduced by 46% and 18% compared to dry weather conditions (Yadav, 2020). Thus, high concentrations of $PM_{2.5}$ during dry weather can be harmful to exposed populations as direct inhalation may cause a variety of health-related issues and problems as mentioned earlier. This phenomenon can be explained by the fact that particulate matter concentrations are influenced, and to some extent governed, by diffusion conditions in the atmosphere. Atmospheric diffusion is defined as the motion of relatively small numbers of different gas molecules in the medium of the atmosphere. These diffusion conditions can be influenced by the concentrations of PM in the atmosphere. Thus, the formation and development of weather events and conditions are most likely a result of tremendous changes in particulate matter pollution levels (Wrobel, 2000).

Acid Rain in the Midwest

Acid rain is a phenomenon that occurs when rainwater combines with pollutants in the atmosphere, forming sulfuric and nitric acids that fall to the ground as rain, snow, or fog. The Midwest region of the United States is particularly vulnerable to acid rain due to the high levels of industrial and agricultural activity in the area.

According to the Environmental Protection Agency (EPA), the Midwest is home to some of the largest sources of acid rain precursors, such as coal-fired power plants and industrial facilities, which emit sulfur dioxide and nitrogen oxide into the atmosphere (EPA, "Acid Rain").

The impact of acid rain on the Midwest environment is significant. It can lead to the acidification of lakes and rivers, which can harm aquatic life and make the water unsuitable for drinking or recreation. Additionally, acid rain can damage crops and forests, leading to reduced yields and ecological damage (Nunez, 2021). The effects of acid rain can be felt far beyond the region where it is produced, as winds can carry the pollutants to other areas, causing damage to natural resources and human health (EPA, "Acid Rain").

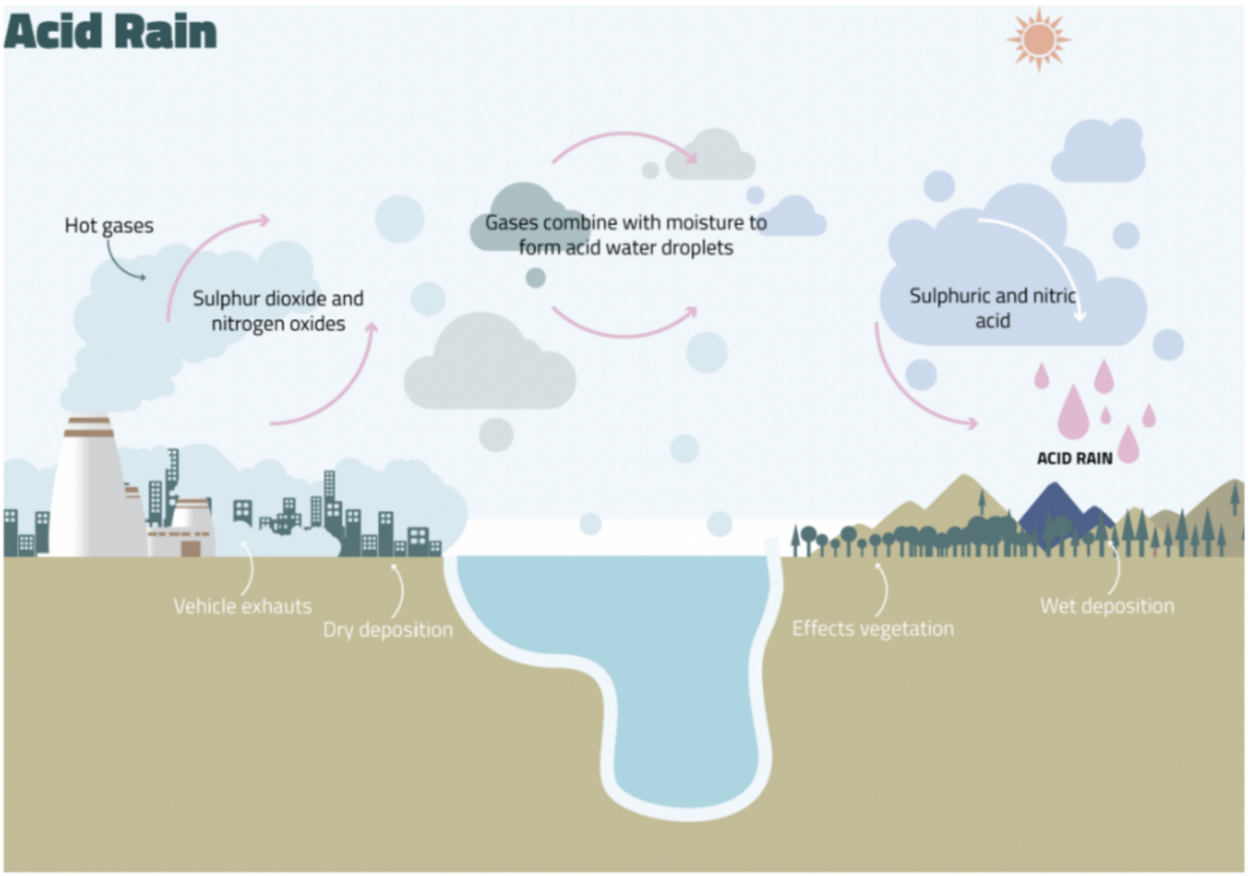

Figure 1 | Acid Rain pathway at large. Burning fossil fuels releases nitrogen and sulfur gases. These gases mix with water vapor in the air. When it rains, these chemicals precipitate to the ground, which deposits harmful chemicals on rivers and lands.

Efforts to reduce acid rain have been ongoing for decades, with some progress being made through the implementation of regulations such as the Clean Air Act. However, there is still much work to be done to address this ongoing environmental problem in the Midwest and beyond. By studying pollutant emission data and its impact on acid rain phenomena, we can work towards a future where acid rain is no longer a significant threat to our environment and communities.

Project Goals

The central theme of this research project is to draw a connection between air quality, weather, and climate. This research project intends to take a correlative approach to establish a relationship between air pollution and the frequency of acid rain events. This will be done by analyzing quantitative meteorological data collected by weather stations located in the Midwestern United States over the past five years. Ideally, this research paper will illustrate the importance of accounting for air particulate matter when making weather forecasts and predictions.

Study Design

This exploratory research study incorporated various methods, including the use of a variety of machine learning algorithms and individually collected atmospheric data, to analyze and establish a relationship between air particulate matter and acid rain phenomena through quantitative atmospheric measurements from stations located in the Midwestern United States. This study proposes a relationship between air pollution and observed weather conditions and suggests primary pollutant data can be used to predict weather phenomena, which has been theorized by past works but never properly analyzed or applied by past computational atmospheric science research. By examining the impact various concentrations of air particulate matter have on atmospheric conditions such as air pressure and moisture content, the efficiency of air pollution to predict acid rain phenomena can be determined. Because the goal of this study is to determine a relationship between pollution and meteorological behavior, it was important to analyze data from the Midwestern United States that was not controlled, filtered, or compiled through any specific factors or interventions from a computational approach. Since machine learning is an efficient way to analyze large amounts of data (e.g., air pollution) and determines which data, variables, and values lead to specific results (e.g., observed weather phenomena), it was useful for the purposes of this project. Throughout the observational study, control was maintained over all variables to ensure that only air particulate matter concentration affected the results. This was done by analyzing data through computational models developed through statistical software, which are discussed in further detail in the methods section of this paper. As such, other variables such as location, altitude, population, and vegetation levels were isolated to ensure they did not impact results.

Ethical Considerations

Because the dataset used includes no personally identifiable information there are essentially no ethical considerations that must be addressed for the identified research topic. No hazardous chemicals, items, or activities were conducted for the purposes of the project. With this in mind, an Institutional Review Board (IRB) reviewed the contents and focus of the study and approved the methodology.

Equipment and Resources

As this paper was designed as an observational and correlational study, all of the procedures were conducted from a computing device. This project required the use of machine learning models which were created through a free and open-source programming platform known as R. The use of these machine learning models allowed for pattern recognition over expansive amounts of data which would take endless amounts of time for a typical human to analyze. These machine learning models allowed for the further use of indices to standardize the data into a form that weighted each variable based on the total impact it had on observed weather conditions. Finally, the handbook: Statistical Data Analysis Explained: Applied Environmental Statistics with R, provided the backbone behind the data analysis and, altogether, the fundamental study design conducted in this paper.

Procedures

This study was most optimized through the involvement and use of a programming language known as R (which is a common programming environment used for statistics and machine learning). Through R, air particulate matter data from weather stations in Indiana, Michigan, and Ohio were compiled, sorted, and cleaned.

Next, the dataset was fed into a recursive neural network and through a process known as backpropagation, an association between air particulate matter and weather predictions was made by assigning certain weights to concentrations of specific air particulate matters such as Sulfur Dioxide and Carbon Dioxide. These weights were established based on the impact each air pollution particle had on observed weather phenomena.

Afterward, the accuracy of the model was tested. From the dataset that was collected, 20% of the data acted as testing data for the developed neural network while the remaining 80% was used to train the neural network. This was done to avoid an issue known as overfitting which would result from the neural network modeling the fed training data too well resulting in a model that is unable to apply new data. In order to avoid such an issue, the number of features present in the dataset was reduced and a sizable portion of the dataset was never presented as training data to the model to avoid model memorization, and hence, overfitting.

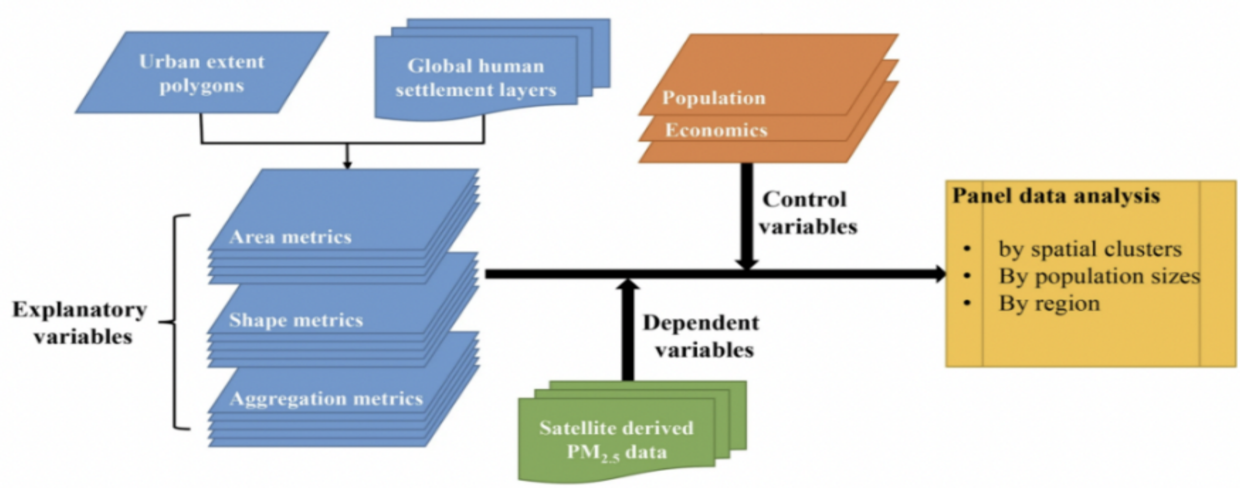

Figure 2 | Methodology Workflow

Warrants

I believe that the methodology outlined was the best approach to scientifically scrutinize my research question as it allowed for the conduction of an engineering project with the backbone of machine learning. With this approach, vast swaths of data were manipulated and explored in a time-efficient manner. Additionally, as the use of machine learning in meteorology has been fairly limited, the methodology applied in this study has the potential to have a large impact on the scientific community as the results from this study can determine whether or not future researchers in the atmospheric sciences and prediction field should apply similar approaches.

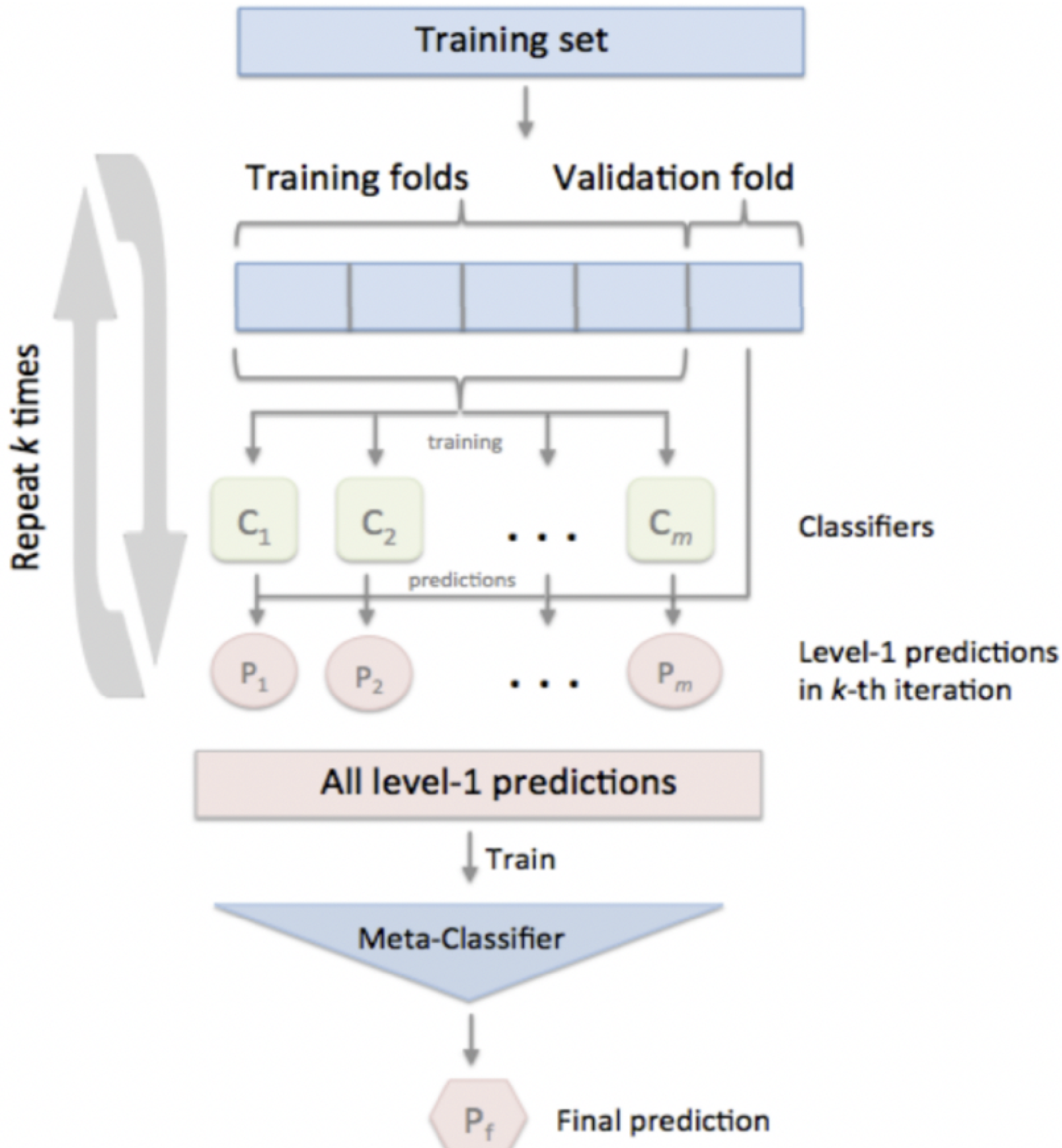

Figure 3 | Outline of the stacked generalization ensemble algorithm used for the purposes of this study

Results

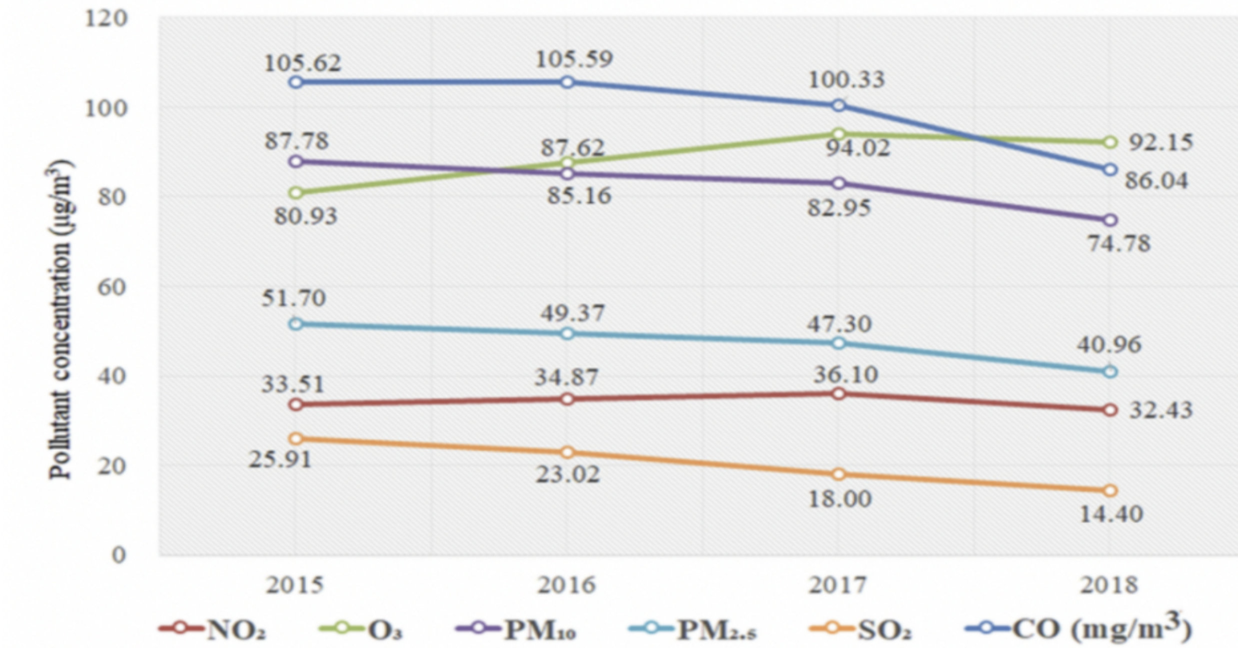

Figure 4 | Graph displaying the general trend of atmospheric pollutants over the past few years

Results indicated that there was a significant correlation between the concentration of primary pollutants and acid rain phenomena. The models were able to accurately predict the occurrence of acid rain events based on the concentration of primary pollutants in the atmosphere. Results indicate that sulfuric acid (H_2SO_4) and nitric acid (HNO_3) were the most significant pollutants that influenced acid rain formation in the Midwest region of the United States.

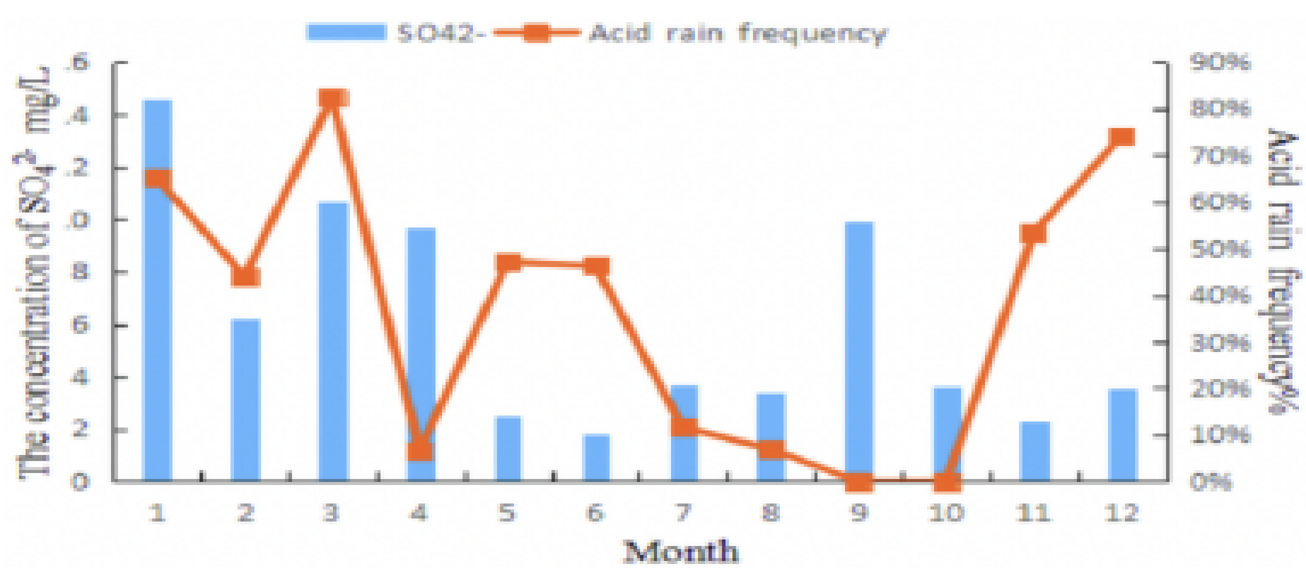

Figure 5 | Graph displaying the variability in acid rain frequency during each month of the year

The R-squared value of the model was 0.63, indicating that 63% of the variability in acid rain

The R-squared value of the model was 0.63, indicating that 63% of the variability in acid rain formation can be explained by the variation in primary pollutant concentrations. The model showed that sulfuric acid had the strongest influence on acid rain formation, with a coefficient of determination of 0.43. Nitric acid also had a significant influence on acid rain formation, with a coefficient of determination of 0.28.

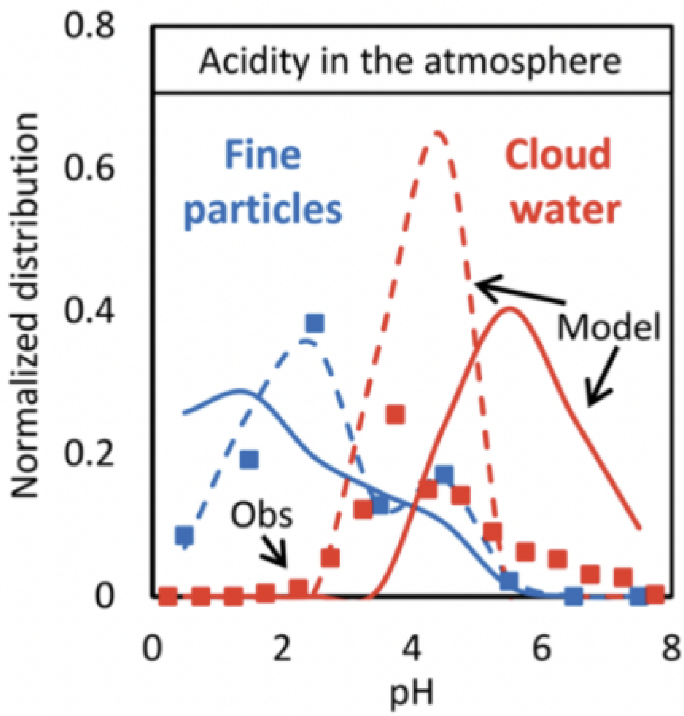

Figure 6 | Comparison between the predictions made by the machine learning model, represented by the solid red line, and the actual observed atmospheric water pH (dotted red line). The model was able to capture 63% of the variability in atmospheric water pH, as indicated by the area calculated underneath the curve created by the intersection of cloud water and model curves.

Overall, findings suggest that machine learning can be an effective tool for establishing the relationship between air pollution data and acid rain phenomena. These results highlight the importance of primary pollutant concentrations in predicting acid rain formation and may have implications for future efforts to mitigate the negative effects of acid rain on the environment and human health. Further research is needed to investigate the potential of machine learning in other locations and to validate these findings in other contexts.

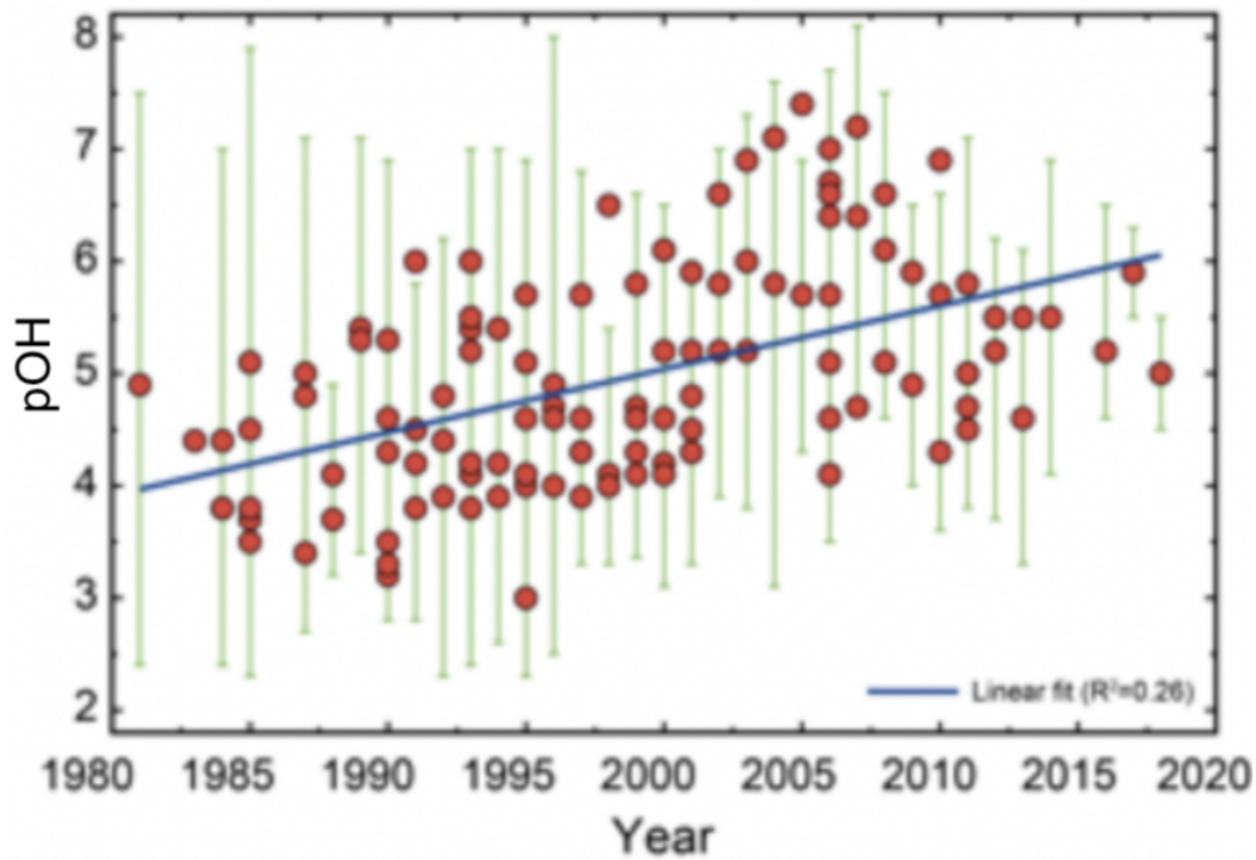

Figure 7 | Trend in pH values of clouds measured in the Midwest. Dots represent the average value reported at each site while green interval bars represent the range of reported pH values at each site. Trendline indicates that there has been an increase in pOH by 0.56 pOH units per decade. Conversely, pH has decreased (clouds have become more acidic) by pH units per decade.

Discussion

In conclusion, the results of this study provide valuable insights into the impact of anthropogenic emissions on aerosol and cloud acidity in the Midwest region of the United States. Findings suggest that while sulfur dioxide and nitrogen oxide emissions may have little impact on aerosol pH, the relative abundance of H_2SO_4, HNO_3, and NH_3 has a significant effect on cloud pH. These results are consistent with previous research on the relationship between emissions and acid rain, but they also highlight the need for continued monitoring and research on this topic.

It is important to note that there are limitations to this study. Firstly, data analyzed in this study was collected from a limited number of locations in the Midwest region of the United States, and may not be representative of other regions. Additionally, this study only focused on the impact of anthropogenic emissions on aerosol and cloud acidity and did not consider other factors that may affect acid rain, such as natural sources of sulfur and nitrogen. Future research could address these limitations by expanding the scope of the study to include more locations and factors.

Despite these limitations, this study provides a foundation for further research on the impact of anthropogenic emissions on aerosol and cloud acidity. This study's findings may have implications for policymakers and regulatory bodies seeking to reduce emissions and mitigate the negative effects of acid rain on the environment and human health. Further research could also explore the potential of new technologies and approaches for reducing emissions, such as carbon capture and storage and renewable energy sources.

Overall, this study underscores the importance of continued monitoring and research on the impact of anthropogenic emissions on aerosol and cloud acidity. It is only through a better understanding of this complex relationship that we can hope to develop effective strategies for reducing emissions and mitigating the negative effects of acid rain.

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