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Correlation Between Ozone Concentration and Mortality Rates from Chronic Respiratory Diseases Across U.S. Counties

Shiyu Zong[1,*],
Siying Chen[2],
Yanqiu Dai[3]

[1] College of Arts & Sciences, American University, Washington, DC, US, sz7071a@american.edu
[2] College of Arts & Sciences, American University, Washington, DC, US, sc6729a@american.edu
[3] College of Arts & Sciences, Georgia State University, Atlanta, US, ydai3@student.gsu.edu

Abstract:

This study focused on how exposure to high levels of ozone air pollution affects chronic respiratory disease mortality in different regions of the United States. The purpose of this study was to determine temporal and regional differences and thus to identify areas most affected by ozone pollution. The data for this study specifically focused on mortality rates and ozone index in different states in the United States in 2000. This study stratified the ozone data and used Linear Mixed Models (LLM)and Geographically Weighted Regression (GWR) models to determine the correlation between ozone levels and respiratory mortality. The study found significant differences in ozone distribution in the United States. Ozone has a greater impact on mortality in the west and central regions. In southern and eastern, ozone impact on mortality smaller or even negative. This study enriches existing knowledge by highlighting the relationship between regional ozone differences the mortality of air pollution and provides a foundation for future environmental health policy research.

Keywords: Air pollution, Chronic respiratory diseases, Regional differences, Mortality, United States.

1. Introduction

Chronic respiratory diseases (CRDs) affected the airways and other structures of the lungs. Chronic respiratory diseases were among the leading causes of death worldwide. According to the World Health Organization (WHO), CRDs caused approximately 4 million deaths annually.[1] Some of the most common CRDs included chronic obstructive pulmonary disease (COPD), asthma, occupational lung diseases, and pulmonary hypertension.[2] In this study, we focused on the overall mortality rate of chronic respiratory diseases as our research subject. Besides tobacco smoke, other risk factors included air pollution, occupational chemicals and dust, and frequent lower respiratory infections during childhood.

Chronic respiratory diseases (CRDs) had been extensively studied to identify various risk factors contributing to their prevalence and severity.[3] Among these risk factors, air pollution had been recognized as a significant contributor.[4] Air pollutants consisted of gaseous and particulate matter such as particulate matter with an aerodynamic diameter of <10 μm (PM10) and <2.5 μm (PM2.5), ozone, SO2, CO, and NO2.[5] These pollutants contributed to the development and exacerbation of respiratory diseases such as asthma, chronic obstructive pulmonary disease (COPD),[6] respiratory infections.[7] Among pollutants, ozone, PM 2.5and CO seemed to have the greatest impact on respiratory disease.[8]

Many studies had investigated various air pollutants, such as particulate matter (PM), sulfur dioxide (SO_2), and their impacts on respiratory health.[9] These studies had consistently shown that these pollutants were significant risk factors for chronic respiratory diseases.[10] However, there was a noticeable lack of information regarding the effects of ozone (O_3) on respiratory health. Ozone was a major global public health concern due to its ability to cause and exacerbate respiratory conditions. Therefore, it was essential to focus on ozone to better understand its impact and to address this gap in the existing research. As a result, in this study, we focused on the correlation between the number of days with ozone concentrations exceeding the standard and mortality from chronic respiratory diseases in the United States at the county level.

Ground-level ozone [11] was a harmful air pollutant due to its effects on people and the environment, and it was the main component of smog.[12] Ozone could react with volatile organic compounds (VOCs) in the air to form highly toxic secondary organic aerosols (SOAs). SOAs could penetrate deep into the respiratory tract and lungs, causing or exacerbating asthma, bronchitis, and other respiratory conditions. In the lungs and circulation, ozone induced inflammation by releasing interleukin-2 (IL-2) and tumor necrosis factor alpha (TNF-α).[13] Excessive IL-2 production could be part of a cytokine storm, a hyperactive immune response that could lead to severe tissue damage and organ failure. Short-term exposure to ozone resulted in detrimental respiratory effects.[14] It could also exacerbate conditions such as asthma, COPD, and interstitial pulmonary fibrosis.

Geographic differences in respiratory disease were also important.[15] Studies agreed that summer was a time of particular concern for ozone-related health issues, as higher concentrations of ozone formed with increased sunlight and temperature.[16,17] The article from the website where we obtained the data[18] primarily focused on analyzing the impact of geographic factors on respiratory disease mortality rates across different states in the United States. We incorporated ozone data to enhance the meteorological information.

Most importantly, the Geographic Sources of Ozone Air Pollution and Mortality Burden in Europe[19] aimed to quantify the national and import contributions to O3 levels and their associated mortality burden in 813 regions across 35 European countries. High O3 concentrations and associated mortality were more common in southern and eastern European countries as rising temperatures favored O3 formation. Sensitivity analyses assessing a safety threshold of 70 μg/m³ significantly reduced the number of attributable deaths, highlighting the impact of lower O3 levels on health outcomes. This article came from Nature and had high credibility. It studied the impact of geographic differences on ozone-related mortality, which greatly influenced our paper. For example, ozone concentrations were generally higher in low-altitude areas, leading to higher mortality rates.

Our study used advanced statistical techniques and models to control for confounding variables and ensure a more robust analysis of the correlation between ozone exposure and respiratory mortality. By doing so, it aimed to provide a clearer understanding of the geographic disparities and inform better public health practices and policies.

2. Methodology

2.1 Study Population/Dataset Description

2.1.1 Mortality Data

Data Source: Organization: Institute for Health Metrics and Evaluation (IHME).

The mortality data were collected by the National Center for Health Statistics (NCHS) from the National Vital Statistics System. These records, deidentified and spanning from January 1, 1980, to December 31, 2014, included information on the county of residence and underlying cause of death, coded according to ICD-9 (for deaths before 1999) and ICD-10 (for deaths from 1999 onwards). Data from 2000 to 2014 were analyzed. Small area estimation models were applied to estimate county-level mortality rates,[18] correcting for garbage codes using specific algorithms to redistribute deaths coded to intermediate or unspecified causes to plausible target causes. Population data were sourced from the U.S. Census Bureau and the Human Mortality Database to create annual county-level population counts.

2.1.2 Ozone Data

Source: Environmental Protection Agency (EPA).

Data on the number of days per year at county level exceeded the ozone standard were collected from air quality monitoring stations. These stations measured ozone levels and reported exceedances of the standard, which were then compiled and made available through the EPA's Air Quality System (AQS) database.

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2.2 Key Variables Explanation

2.2.1 Predictor Variable

Ozone Levels: Number of days per year each county exceeds the ozone standard, measured by air quality monitoring stations and reported in the EPA's AQS database. A day is counted as an exceedance day if the daily maximum 8-hour average ozone concentration exceeds 0.070 parts per million (ppm).

2.2.2 Outcome Variable

Mortality Rates: Mortality rates from chronic respiratory diseases, collected from deidentified death records by the NCHS and population data from the U.S. Census Bureau. Small area estimation models were used to derive county-level estimates, correcting for garbage codes using specific algorithms to ensure accurate attribution of causes of death.

2.2.3 Data preprocessing

The two databases were matched to ensure compatibility. Four years of ozone data were read and column names checked for necessary inclusions. County and state information, originally in one column, were split into separate columns. The mortality database was checked for relevant columns, with data from 1980, 1985, 1990, and 1995 removed. Ozone and mortality data were merged into one dataset and cleaned by removing missing values and duplicates. Statistical calculations, visualizations, and correlation analyses using Pearson and Spearman coefficients were performed.

3. Statistical Analysis

First, the effect of the time factor was removed using Linear Mixed Models (LMMs), allowing for identification of the specific year with the most unique relationship between ozone and mortality. By focusing on one year's data, time-related interference was avoided. Next, the Geographically Weighted Regression (GWR) model was used to remove the influence of geographical factors, isolating specific counties with notable ozone-mortality relationships. After removing time and geography effects, the analysis targeted a specific year and county, enhancing precision. Finally, a simple linear regression model tested the linear relationship between ozone levels and chronic respiratory disease mortality, validating the study hypothesis. This phased strategy effectively mitigated time and geography interference, resulting in more targeted and scientific analysis.

4. Result

4.1 Descriptive Statistics of Mortality Rates and Ozone Exposure Across U.S. Counties

Table 1. Descriptive Statistics for Study Variables

Statistic	Mortality_Rate	Ozone	Days_Ozone	Year	FIPS
Min	19.69	1.000	1.0	2000	1003
1st Qu.	49.83	1.000	165.0	2005	17165
Median	58.14	2.000	207.0	2010	31157
Mean	58.71	2.497	218.5	2008	29866
3rd Qu.	67.11	3.000	281.0	2014	42055
Max	136.36	4.000	366.0	2014	56045

In this study, we examined the correlation between ozone concentration and mortality rates from chronic respiratory diseases across U.S. counties. The descriptive statistics for the key variables, namely Mortality Rate and Days Ozone, provide insights into the distribution and potential impact of ozone exposure on respiratory health (Table 1).

4.2 Mortality Rate

The mortality rate due to chronic respiratory diseases exhibits significant variability across the sampled counties, ranging from 19.69 to 136.36 deaths per 100,000 people. The distribution of mortality rates is relatively symmetric, as indicated by the close values of the mean and median: The minimum mortality rate observed is 19.69 deaths per 100,000 people. The 1st quartile, representing the 25th percentile, is 49.83 deaths per 100,000 people, indicating that 25% of the counties have a mortality rate lower than this value. The median, or 50th percentile, is 58.14 deaths per 100,000 people, suggesting that half of the counties have mortality rates below this level. The 3rd quartile, representing the 75th percentile, is 67.11 deaths per 100,000 people, meaning that 75% of the counties have mortality rates below this value. The mean mortality rate is 58.71 deaths per 100,000 people, which is close to the median, indicating a balanced distribution without significant skewness.

4.3 Days Ozone

The number of days per year that ozone levels exceeded the standard shows a considerable range, reflecting the extent of ozone pollution across different counties:
The minimum number of days with ozone exceedance is 1, indicating that some counties experience very few high ozone days. At the 1st quartile (25th percentile), counties

experience approximately 165 days per year with ozone levels exceeding the standard. This means that in 25% of the counties, ozone levels exceed the standard for about half the year. The median (50^{th} percentile) number of days with ozone exceedance is 207, indicating that in half of the counties, ozone levels are high for more than half the year. At the 3^{rd} quartile (75^{th} percentile), the number of days with high ozone levels reaches 281. This shows that in 25% of the counties, ozone levels are excessive for most of the year. The mean number of days with ozone exceedance is 218.5, suggesting that on average, counties experience high ozone levels for a substantial portion of the year.

4.4 Categorical Ozone Levels

The ozone levels were categorized into four levels based on the number of days with exceedance. This categorization is as follows:

Level 1: Counties with 165 days or fewer of high ozone levels. Level 2: Counties with 166 to 207 days of high ozone levels. Level 3: Counties with 208 to 281 days of high ozone levels. Level 4: Counties with more than 281 days of high ozone levels.

This categorization helps in understanding the varying degrees of ozone exposure and their potential impact on respiratory health: The first quartile and median being both at level 1 indicates that a significant portion of the counties fall into the lowest category of ozone exposure. The mean category level is approximately 2.5, suggesting that while many counties experience low ozone exposure, a considerable number also fall into higher exposure categories. The third quartile at level 3 highlights that a significant number of counties are in the higher categories of ozone exposure, which is concerning for public health.

"Temporal and Regional Variations in Ozone's Impact on Mortality: A Decadal Analysis from 2000 to 2009"

First, this study planned continuous days ozone, and then stratified ozone, refitted the data, and drew two conclusions. The number of consecutive days of ozone has no significant impact on time-varying mortality, but ozone classification, RS+RI mode is significant, only the RI mode is not significant. When analyzing the effects of continuous variables (such as ozone days) on mortality, in practice the relationship between pollutants and health outcomes may be non-linear. This linear relationship is better captured by converting ozone days into a categorical variable. For example, there may be significant differences in the impact on mortality between high and low pollution days, but smaller changes in the medium range. Because the variation range of continuous ozone levels is not large throughout the study area and time, or the direct impact of small changes in ozone levels on mortality is small, it cannot be significantly reflected. However, when we categorize ozone days, we are better able to capture extreme changes in ozone levels (e.g., low, moderate, and high pollution days). Categorical variables more easily reveal nonlinear relationships or threshold effects. For example, the number of days with high pollution may significantly affect mortality, but this effect is averaged out among the subtle changes in the continuous variable days ozone and is difficult to see. This phenomenon shows that the influence of environmental factors is sometimes non-linear. Classification processing can more intuitively reflect the significant effects in extreme cases. The impact of categorical days of ozone on time-varying death is significant in the RS+RI model, but not significant in the RI model.

The random intercept (RI) model was not significant, indicating that although there were differences in mortality across regions, these differences were not significantly different in mortality trends over time. This means that mortality trends over time are similar across all regions. This finding highlight that there may be regional differences in mortality, but that temporal trends remain consistent across regions, suggesting the need for a more nuanced model that captures potential regional differences in temporal variation. Under the new more comprehensive model, we found that the model with random slopes and random intercepts (RS+RI) was significant, indicating that not only were there significant differences in mortality across regions (FIPS codes), but These differences vary over time. This means that different regions have different patterns in mortality trends over time. This suggests that mortality rates in different regions have different temporal trends, which may be affected by various factors such as local health policies, environmental conditions, and socioeconomic factors. The change in slope means that the effect of time on mortality is not uniform across all regions. After determining that classified ozone has a relationship under the RI+RS model, we believe that a reasonable choice to determine the year may be 2000. The year 2000 will be an important year for the global implementation of important environmental regulations and health care interventions. This may affect mortality. Because in the ten years from 2000 to 2009, environmental issues have become a mainstream issue, and more and more people have begun to pay attention to the environment. It has been discussed from a political perspective to a religious perspective. The environment has been a major issue in the three US presidential elections in this decade. Key issues, more and more companies are beginning to pay attention to green actions, and religions and celebrities are also calling for environmental protection.[20] 2000 is the tenth

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year since the United States enacted the Air Act. The U.S. government improved air quality by limiting sulfur dioxide and controlling toxic emissions. This study can better study the relationship between ozone index and mortality in the United States.[21]

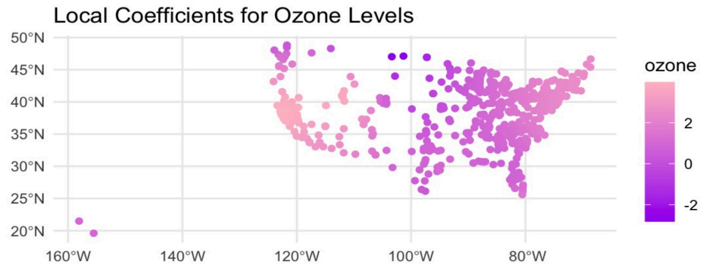

Figure 1. Local Coefficients for Ozone Levels Across U.S. Counties

Legend: This map shows the local coefficient between ozone levels and chronic respiratory disease mortality by county in the United States. The higher the positive coefficient (shown in purple), the stronger the positive correlation between ozone levels and mortality, while the negative coefficient (shown in pink) indicates the inverse relationship between ozone levels and mortality.

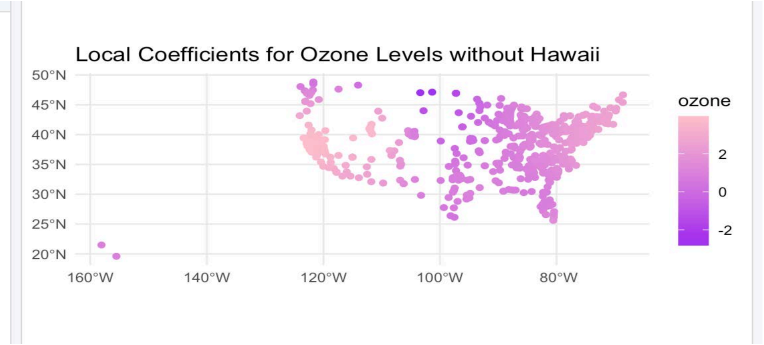

Figure 2. Local Coefficients for Ozone Levels Across U.S. Counties (Excluding Hawaii)

Legend: This chart shows the local coefficient between ozone levels and chronic respiratory disease mortality, with Hawaii excluded from the analysis. The color gradient indicates the strength and direction of the correlation, with purple indicating a positive correlation and pink indicating a negative correlation.

"Geographical Disparities in Ozone's Impact on Mortality: Insights from GWR Models with and without Hawaii"

Figure 1 shows the distribution of ozone coefficients in the GWR model including Hawaii across the United States. The lighter the color (closer to pink), the higher the coefficient, and the darker the color (closer to purple), the lower the coefficient or even negative. Some areas in the figure are shown in light pink, indicating that ozone has a greater impact on mortality in these areas. These areas are mainly distributed in some areas in the west and central regions. Purple areas indicate that ozone has a smaller impact on mortality in these areas, or may even be negative. Mainly distributed in some areas in the east and south. Due to its unique geographical location and environmental characteristics, Hawaii's coefficient shows obvious differences and is located in the lower range (dark purple). Figure 2 is the GWR model without Hawaii, from which it is found that the west (especially California) and some central regions are still shown in light pink, indicating that ozone has a greater impact on mortality. The east and south are shown in dark purple, indicating that ozone has a smaller impact on mortality or even negative. After removing the Hawaii data, the coefficient distribution in the continental United States is more consistent, without the influence of extreme values, and the coefficient changes more smoothly. The areas with higher ozone coefficients in both models are mainly concentrated in the western and central United States, while the areas with lower coefficients are concentrated in the east and south. After removing Hawaii, the low coefficient areas in the east and south are more obvious, and the overall distribution looks smoother, without the extreme values in the Hawaii data. The p-values for both models are very low, indicating that the effect of ozone on mortality is statistically significant.

5. Discussion

The article focuses on the relationship between high levels of ozone air pollution and chronic respiratory disease mortality in different regions of the United States. By employing a linear mixed effects model (LMM), the study aimed to understand the impact of ozone concentration levels on mortality.

5.1 The significance of ozone concentration levels

The analysis showed that ozone concentration levels significantly affected chronic respiratory disease mortality. This importance is highlighted by comparing models with and without ozone concentration level interaction terms, with the former having lower Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) values. Several reasons explain this importance. Threshold effect: The health effects of air pollutants often exhibit a threshold effect, meaning that only concentrations above a certain level cause significant health effect. According to research findings, short-term exposure to high concentrations of ozone is associated with increased mortality during periods of high pollution.[22] Cumulative exposure: Long-term exposure to pollutants can lead to chronic respiratory disease. Ozone concentration levels capture cumulative exposure effects more effectively than individual daily measurements. The importance of considering cumulative exposure in assessing long-term health effects has been emphasized in the research literature.[22] Population sensitivity: Certain populations, such as older adults and people with pre-existing health conditions, are more sensitive to higher ozone levels. These groups are more likely to experience adverse health outcomes at higher concentrations, which is better reflected by considering concentration levels rather than daily fluctuations. Studies have shown that older adults face a higher risk of death with increased ozone exposure.[23]

5.2 Importance of concentration levels versus specific values

There are several advantages to focusing on concentration levels rather than specific values. First are policy implications. Regulatory standards and public health policies are developed based on concentration levels. Understanding the effects of different levels helps develop effective regulations. The Environmental Protection Agency (EPA) develops National Ambient Air Quality Standards (NAAQS) based on such levels to protect public health. Then, risk communication. Communicating risks based on concentration levels is more direct and understandable to the public and policymakers. This simplifies the understanding of health risks associated with different pollution levels, as shown by the Air Quality Index (AQI), which categorizes air quality into levels of health concern. Lastly is resource allocation. Public health interventions and resource allocation can be more effectively targeted to areas with higher pollution concentrations, ensuring that efforts are focused where they are most needed. The effectiveness of targeted interventions to high-pollution areas has been highlighted.

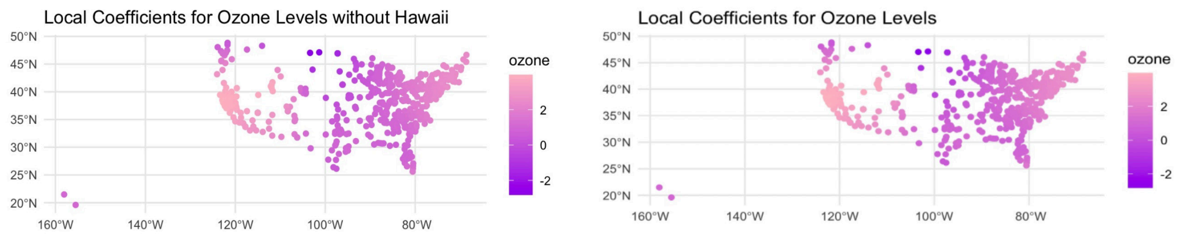

Figure 3: Factors Influencing Ozone Levels in Different Parts of the United States

Legend: As can be seen from the map (Figure 3), the visual analysis highlights significant regional differences in the impact of ozone on mortality. Observed from the local coefficient map. The map presented shows clear geographic differences in the effects of ozone on mortality.

In high coefficient areas. For example, the Western United States, especially California and some central areas, are shown in light pink, indicating a stronger positive effect of ozone on mortality. This may be due to higher pollution levels, larger urban populations, and potentially higher baseline health vulnerabilities in these areas. Probably due to industrial and vehicle emissions. In California, especially cities like Los Angeles, are known for their high levels of vehicular traffic and industrial activity. Emissions from these sources include nitrogen oxides (NOx) and volatile organic compounds (VOCs), which are precursors to ozone formation. Large urban populations and active industrial activities lead to increased emissions of these pollutants, leading to rising ozone levels. Analysis based on geographical and meteorological conditions. California's geography and meteorological conditions result in higher ozone levels. For example, the Los Angeles

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basin is surrounded by mountains, which trap pollutants inside and prevent them from spreading, resulting in higher ozone concentrations. The warm, sunny climate of the western United States enhances the photochemical reactions that convert NOx and VOCs into ozone, especially in the summer. Transportation based on contamination. Pollution from Asia and other regions can be transported across the Pacific Ocean to the western United States, increasing background ozone levels. This cross-border pollution increases local emissions, exacerbating ozone concentrations.

In low coefficient areas. That's the Eastern and Southern United States, which are dark purple, indicating a small or even negative impact of ozone on mortality. It is possible that lower baseline pollution levels, different environmental regulations, and potentially better overall health may contribute to this observation. Analysis based on climate and weather patterns. The eastern and southern United States generally have more rainfall and higher humidity than the western United States. Rainfall helps remove pollutants from the air, while high humidity inhibits the formation of ozone. The lower temperatures and lower sunlight intensity in the eastern region reduce the rate of photochemical reactions that form ozone. in vegetation and land use. The eastern and southern United States have more extensive vegetation and forest cover than the western regions. Vegetation can act as a sink for ozone and its precursors, absorbing these pollutants and reducing ozone levels in the environment. Land use patterns here (such as lower urban density and less industrial activity) help reduce emissions of ozone precursors compared to the western United States. Analysis based on pollution control measures. Historically, the eastern United States has implemented strict pollution control measures, particularly targeting coal-fired power plants and industrial polluters. These measures reduce emissions of nitrogen oxides and volatile organic compounds, thereby lowering ozone levels.

In Hawaii the results appear dark purple, indicating that ozone has minimal impact on mortality. Perhaps the remote location and low levels of industrial pollution may be responsible for this small effect.

6. Conclusion

This study draws the following key conclusions by analyzing the impact of ozone air pollution levels on chronic respiratory disease mortality in different regions of the United States. First, ozone pollution has a significant impact on mortality in the western and central regions of the United States, while the impact is smaller or even negative in the southern and eastern regions. Second, both the linear mixed model (LMM) and the geographically weighted regression model (GWR) showed that ozone pollution has a significant impact on time-varying mortality, but its effect differs significantly among different regions. Differences in ozone levels between the western and eastern United States are influenced by a variety of factors, including industrial and vehicle emissions, geographic and meteorological conditions, pollutant transport, climate and weather patterns, vegetation and land use, and pollution control measures. Understanding these regional differences is critical to developing targeted air quality management strategies to mitigate the health effects of ozone pollution. This study highlights the critical role of ozone concentration levels in determining mortality from chronic respiratory diseases. Focusing on concentration levels rather than specific values provides a stronger framework for understanding and mitigating the health effects of air pollution. This approach is consistent with existing literature and regulatory practice, emphasizing the importance of targeted interventions and policies to protect vulnerable populations from the adverse effects of high ozone levels. This study also has some limitations. First, this study only used data from 2000 and cannot reflect the changing trends over a longer time span. Secondly, the model used in the study failed to fully capture all potential influencing factors, such as socioeconomic status, local medical level, etc. Taken together, this study reveals the significant impact of ozone air pollution on chronic respiratory disease mortality, particularly in the western and central United States. These findings provide a scientific basis for formulating effective environmental health policies and point to directions for future research.

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Shiyu Zong, Siying Chen and Yanqiu Dai contributed equally to this work and should be considered co-first authors

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