



Brief Original Contribution

Is the Relation Between Ozone and Mortality Confounded by Chemical Components of Particulate Matter? Analysis of 7 Components in 57 US Communities

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Epidemiologic studies have linked tropospheric ozone pollution and human mortality. Although research has shown that this relation is not confounded by particulate matter when measured by mass, little scientific evidence exists on whether confounding exists by chemical components of the particle mixture. Using mortality and particulate matter with aerodynamic diameter $\leq 2.5 \mu\text{m}$ ($\text{PM}_{2.5}$) component data from 57 US communities (2000–2005), the authors investigate whether the ozone-mortality relation is confounded by 7 components of $\text{PM}_{2.5}$: sulfate, nitrate, silicon, elemental carbon, organic carbon matter, sodium ion, and ammonium. Together, these components constitute most $\text{PM}_{2.5}$ mass in the United States. Estimates of the effect of ozone on mortality were almost identical before and after controlling for the 7 components of $\text{PM}_{2.5}$ considered (mortality increase/10-ppb ozone increase, before and after controlling: ammonium, 0.34% vs. 0.35%; elemental carbon, 0.36% vs. 0.37%; nitrate, 0.27% vs. 0.26%; organic carbon matter, 0.34% vs. 0.31%; silicon, 0.36% vs. 0.37%; sodium ion, 0.21% vs. 0.18%; and sulfate, 0.35% vs. 0.38%). Additionally, correlations were weak between ozone and each particulate component across all communities. Previous research found that the ozone-mortality relation is not confounded by particulate matter measured by mass; this national study indicates that the relation is also robust to control for specific components of $\text{PM}_{2.5}$.

air pollution; confounding factors; mortality; ozone; particulate matter

Abbreviations: EPA, Environmental Protection Agency; $\text{PM}_{2.5}$, particulate matter with aerodynamic diameter $\leq 2.5 \mu\text{m}$; PM_{10} , particulate matter with aerodynamic diameter $\leq 10 \mu\text{m}$.

Epidemiologic studies have linked ozone to adverse health outcomes including hospitalizations (1, 2) and death (1, 3–5), and this association is supported by toxicologic studies (1, 6). Evidence of these effects resulted in regulations aimed at lowering ozone (6). Particulate matter has been associated with heart failure, myocardial infarction, hospitalizations, and deaths (7–10). Historically, most research studied particulate matter by mass (e.g., particulate matter with aerodynamic diameter $\leq 2.5 \mu\text{m}$ ($\text{PM}_{2.5}$) or $\leq 10 \mu\text{m}$ (PM_{10})) (11–16).

Several studies found that observed ozone-mortality associations are robust to control for particulate matter mass

($\text{PM}_{2.5}$, PM_{10}) (3, 5, 17–22); however, the chemical composition of particulate matter varies geographically and seasonally (12, 23–31). Variations can depend on changes in sources (27, 32) (e.g., home heating fuel) and with weather (e.g., changes in mixing height (32), photochemical formation (26, 33)). Epidemiologic studies found health effects of particulate matter mass to vary by season and location (12–14, 28–30), which suggests that particulate matter composition might modify its health impact. Some studies measured the health impacts of specific $\text{PM}_{2.5}$ chemical components, either locally (24, 30, 32, 34–38) or nationally (12, 39, 40), and found health effects for organic carbon

Table 1. Ozone Effects on Human Mortality Without and With Control for 7 Chemical Components of PM_{2.5} in 56–57 US Communities, 2000–2005

Component	Total No. of Communities	Total No. of Days Analyzed	Total No. of Deaths Analyzed	Increase in Mortality Per 10-ppb Increase in 24-Hour Tropospheric Ozone ^a			
				Without Control for Component		With Control for Component	
				%	95% Posterior Interval ^b	%	95% Posterior Interval ^b
Ammonium	57	21,423	657,909	0.34	-0.31, 1.00	0.35	-0.35, 1.04
Elemental carbon	57	21,605	660,633	0.36	-0.28, 1.02	0.37	-0.31, 1.05
Nitrate	56	20,755	637,863	0.27	-0.40, 0.95	0.26	-0.45, 0.97
Organic carbon matter	57	21,561	658,271	0.34	-0.32, 1.00	0.31	-0.37, 0.99
Silicon	57	21,606	659,949	0.36	-0.30, 1.02	0.37	-0.29, 1.04
Sodium ion	56	20,394	628,322	0.21	-0.45, 0.88	0.18	-0.48, 0.85
Sulfate	57	21,425	657,915	0.35	-0.31, 1.00	0.38	-0.31, 1.07

Abbreviation: PM_{2.5}, particulate matter with aerodynamic diameter $\leq 2.5 \mu\text{m}$.

^a Ozone effects are overall estimates pooled across all communities, with the particulate component concentration included at lag 1.

^b 95% posterior interval of overall pooled ozone effect.

(34–37, 40), elemental carbon (24, 30, 32, 34–40), sulfate (12, 24, 32, 35, 37, 38), nitrate (24, 34, 35, 40), ammonium (40), and silicon (12, 30, 37).

Although there is evidence that the ozone-mortality relation is robust to particulate matter mass, specific PM_{2.5} components could potentially be confounders. Ozone precursors originate from the same sources as some particulate matter components. Additionally, PM_{2.5} components and ozone can covary with weather and can have related complex atmospheric reactions (6, 41).

Little research has considered whether particulate matter components confound the relation between ozone and mortality, partially because data on joint ozone and particulate component concentrations are scarce. The US Environmental Protection Agency (EPA) began a network of chemical component monitors in 2000, which collect data in either 1 of 3 or 1 of 6 days, while many ozone monitors operate only during the warm season. One study found evidence that the ozone-mortality relation is confounded by sulfate PM_{2.5} but not by nitrate or organic carbon matter (42). However, this study had limited data (18 communities over 3–6 years/community).

Although particulate matter is composed of dozens of components, 7 components (sulfate, nitrate, silicon, elemental carbon, organic carbon matter, sodium ion, and ammonium) constitute 79%–85% of PM_{2.5} in communities across the United States (23). They were the only components to contribute >1% to PM_{2.5} mass, either seasonally or throughout the year (23). Here, we investigate whether the ozone-mortality relation is confounded by these 7 main components of PM_{2.5} in 57 US communities over a 6-year period. This study does not aim to improve on earlier estimates of ozone effects (3, 20, 22), but rather investigates whether these effects are confounded by PM_{2.5} components.

MATERIALS AND METHODS

Study data

We collected data on mortality, ozone, and PM_{2.5} chemical components for 74 US communities from 2000 to 2005. We aggregated mortality data from death certificate data (National Center for Health Statistics) for each day for each community (communities constitute ≥ 1 adjacent counties). Data covered all nonaccidental deaths (*International Classification of Diseases*, Ninth Revision, codes <800; *International Classification of Diseases*, Tenth Revision, codes <S), excluding deaths of nonresidents.

Ozone concentrations were available from the US EPA's Air Quality System (43), excluding source-oriented monitors. In communities with 1–2 ozone monitors, hourly concentrations were averaged across monitors to generate a community-level estimate; in communities with >2 monitors, a 10% trimmed mean was used (44). Hourly ozone concentrations were averaged to generate daily 24-hour mean concentrations.

PM_{2.5} chemical component data originated from the US EPA's Particulate Matter Speciation Trends Network (45). Monitors in this network collect data on schedules of either 1 of 3 days or 1 of 6 days. Data were collected from the US EPA's Air Quality System (43) for all components except organic carbon matter, for which information was collected from the US EPA's AirExplorer (which includes blank-corrected organic carbon matter measurements) (46). Community-level averages were obtained by averaging over all available monitors in a community on a given date. We excluded communities with <150 days with measurements of both ozone and particulate components. The number of communities with particulate component data varied by year (Web Table 1, available at <http://aje.oxfordjournals.org/>).

Weather data (daily mean temperature and dew point temperature) were collected from the National Climatic Data Center. Hourly measurements were converted to daily weather values. Community-level daily values were averaged across monitors by using the methods described for ozone.

Statistical analysis

We investigated confounding of the ozone-mortality relation by the 7 largest components of $PM_{2.5}$: sulfate, nitrate, silicon, elemental carbon, organic carbon matter, sodium ion, and ammonium (23). We calculated Pearson correlations between daily ozone concentration and each particulate component within each community.

To estimate ozone effects with and without control for particulate components, we fit community-specific generalized linear models, with mortality counts described by an overdispersed Poisson distribution. We estimated the association between daily mortality and the average of same-day and previous-day 24-hour ozone concentrations on the basis of previous research that ozone effects occur soon after exposure (3, 4, 22); this metric has been used in earlier studies (4). We included $PM_{2.5}$ components using the previous-day concentration (lag 1). Previous research has indicated stronger particulate matter-mortality associations at this lag than for same-day exposure (lag 0) (11, 34, 47). As a sensitivity analysis, we tested confounding of components at lags of 0 or 2 days. Because particulate matter components are not measured daily (45), we could consider only single-day lags of components.

Within each community-level model, we controlled for potential time-varying confounders, including day of week, long-term and seasonal trends in community mortality rates, and weather (temperature, dew point temperature). Our model is similar to models used previously to study ozone and mortality (3, 4, 22) (full model specifications in the Web Appendix).

We tested each of the 7 $PM_{2.5}$ components separately for confounding of the ozone-mortality relation. In each case, before fitting the regression model, we limited data to days with both ozone and component data, so the same data set was used for estimates with and without control. We then modeled the relation between ozone concentration and mortality twice: with and without control for the particulate component.

We combined community-level estimates to generate an overall estimate using 2-level normal independent sampling estimation, which incorporates between-community and within-community variance. This model has been used for similar analysis (3).

RESULTS

Some communities had very little daily data for both ozone and particulate components (Web Table 2). Of the 74 communities for which we originally collected data, 57 had ≥ 150 days of joint ozone and particulate component data for ammonium, elemental carbon, organic carbon matter, silicon, and sulfate, and 56 had data for nitrate and

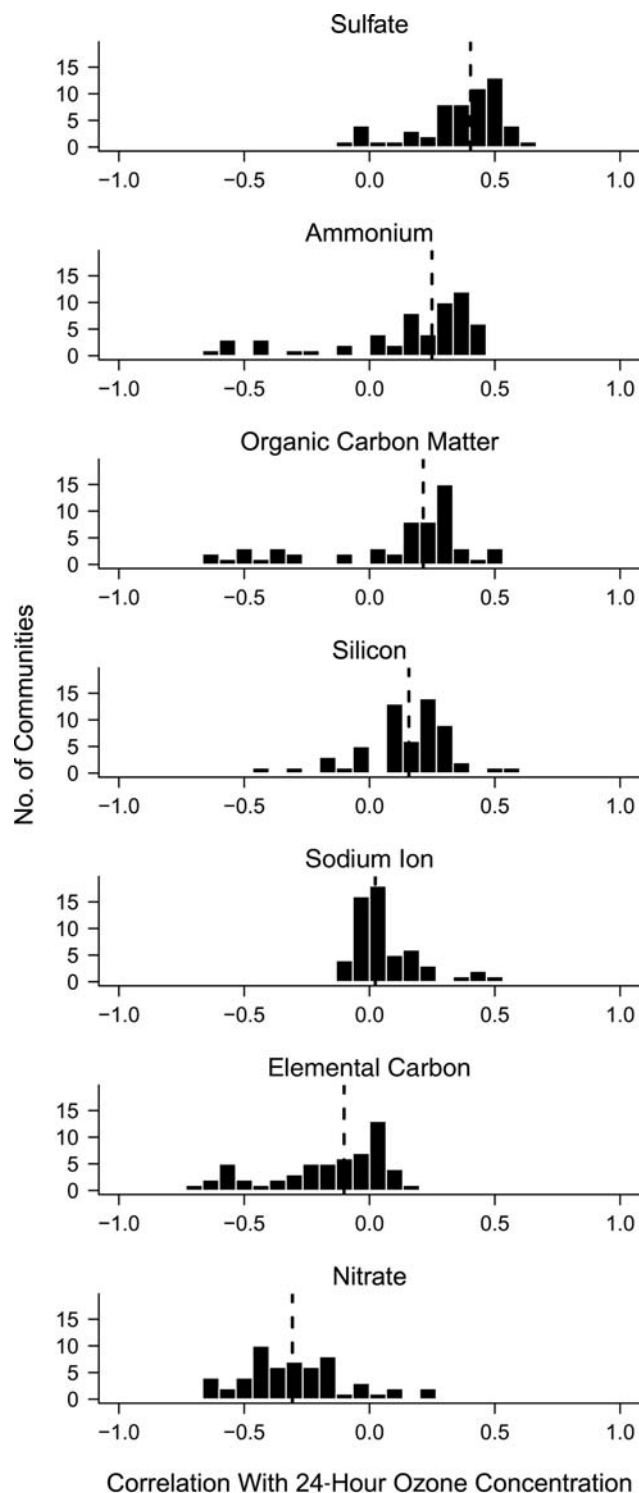


Figure 1. Distribution of community-level correlations between ozone concentration (24-hour metric, average of same- and previous-day lags) and different particulate component concentrations, 56–57 US communities, 2000–2005. Each graph shows a histogram of community-specific Pearson correlations between 24-hour ozone concentration and a given particulate component (the number of communities included is 57 for ammonium, elemental carbon, organic carbon matter, silicon, and sulfate, as well as 56 for nitrate and sodium ion). The dashed black vertical lines show median correlations across all communities with data for each particulate component.

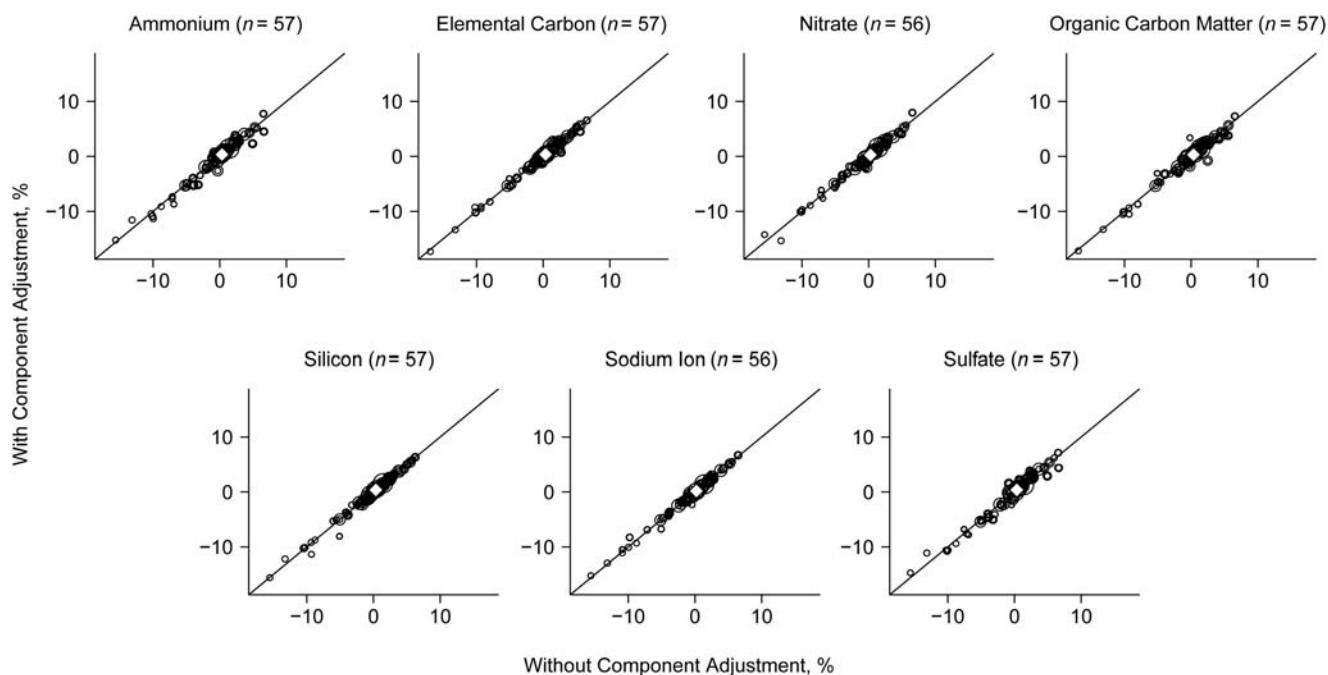


Figure 2. Pooled and community-level estimates of ozone-mortality effects with and without control for 7 chemical components of $PM_{2.5}$ in 56–57 US communities, 2000–2005. Each circle represents a community and shows the estimate of ozone effect (% increase in mortality for a 10-ppb increase in 24-hour ozone concentration), both without control for the particulate component (x-axis) and with control for the particulate component (y-axis). Circle size corresponds to certainty of the ozone effect estimate (as measured without control for the particulate component): Larger circles indicate estimates with greater certainty. Solid white diamonds show overall estimates, aggregated across all communities. $n = xx$, number of communities contributing to analysis; $PM_{2.5}$, particulate matter with an aerodynamic diameter $\leq 2.5 \mu m$.

sodium ion (Web Figure 1); only these 56–57 communities were further considered. Of these communities, 34 had ozone data year-round, and the remainder had ozone data only during the warm season. Across these 56–57 communities, we analyzed 628,322–660,633 deaths in total, depending on the particulate component under consideration (Table 1).

Among the 7 components, sulfate was most strongly correlated with ozone (median of community-specific correlations: 0.40) (Figure 1). Other particulate components were more weakly correlated with ozone: Ammonium, organic carbon matter, silicon, and sodium ion all had weak positive correlations, while elemental carbon and nitrate were negatively correlated, although correlations varied across communities. Correlations remained weak when analysis was restricted to consider only communities with year-round data (Web Table 3).

Community-specific and overall ozone effects were extremely robust to control by all 7 particulate components (Figure 2; Table 1). Ozone effects with and without control for each component were very similar in all communities. In Figure 2, a reference line shows where points would fall if estimates were identical under models with and without control for that $PM_{2.5}$ component. When we aggregated estimates across all communities, ozone effect estimates were almost identical in models with and without control for these 7 $PM_{2.5}$ components (Table 1).

Estimates controlled for particulate components at a 1-day lag. As sensitivity analysis, we tested confounding of

ozone effects with particulate components at lags 0 and 2 days (Web Table 4) and when both ozone and particulate components were included at lag 0 (Web Table 5). Again, we found no evidence of confounding by any particulate components considered.

DISCUSSION

Various studies linked specific $PM_{2.5}$ chemical components and health (12, 39, 40) and ozone and mortality (1, 3–5); here, we examined whether $PM_{2.5}$ components confound ozone-mortality associations. We found very similar ozone effects with and without control for each component, both for individual communities and overall. Further, we found that correlations between ozone and $PM_{2.5}$ components were generally weak, with the highest correlation for sulfate (median of community-specific correlations: 0.40). Both ozone and sulfate particulates are secondary pollutants resulting from chemical reactions driven by sunlight and temperature, so conditions favorable to ozone creation can also favor sulfate creation. For the other $PM_{2.5}$ components considered, correlations with ozone were much weaker, making confounding less likely.

Several multicity studies have investigated whether particulate matter confounds the ozone-mortality relation. Most considered particulate matter mass (e.g., $PM_{2.5}$) and found ozone effects robust (3, 5, 17–20). One study investigated

confounding by PM_{2.5} and PM₁₀ in 98 US communities (22), testing various ozone metrics (24-hour average, daily 8-hour maximum, daily 1-hour maximum), lag times of ozone and particulate matter, and subsets of data limited to certain ranges of ozone or particulate matter concentrations. The authors also investigated correlation between ozone and particulate matter mass by season (22). Based on extensive investigation, they found no evidence that PM_{2.5} or PM₁₀ confounds the ozone-mortality relation, although they note that they could not determine potential confounding by specific particulate matter components (22).

To our knowledge, only one other study has investigated whether the ozone-mortality relation is confounded by specific PM_{2.5} chemical components. That study considered 3 secondary components (sulfate, nitrate, and organic carbon matter) and found evidence of confounding by sulfate, but not by nitrate or organic carbon mass (42). The study was limited to 18 communities, investigating 86,419 deaths. Because only limited data were available in each community and analysis was limited to May–September, the study controlled for weather by using linear model terms. Differences in either control for weather or time of year considered may explain some of the differences between these earlier results and those presented here.

Our study considered 57 US communities and analyzed 628,322–660,633 deaths for each particulate component, making it the largest study to date of confounding of the ozone-mortality relation by particulate matter components. The communities spanned the United States with the exception of the central north region, where ozone levels are low and few monitors operate. Additionally, our study investigates 4 PM_{2.5} components not previously studied (elemental carbon, silicon, ammonium, and sodium ion) in addition to the 3 components considered in earlier research (42). Because our model includes more data than earlier studies, we were able to test confounding using complex control for weather and year-round data for most communities, in a model very similar to models used in epidemiologic studies of ozone and mortality (3, 20).

One challenge of multipollutant studies is that few data exist with concurrent measurements of multiple pollutants (12, 48). Thus, our estimates of ozone effects are not the best possible estimates of ozone effects, for which a different study design would have been used. Earlier research used meta-analysis or larger national data sets and found that mortality increased 0.25%–0.87% per 10-ppb increase in daily ozone (3, 20, 22). Those results give better national estimates of ozone effects than this study, which does not aim to improve on earlier estimates of ozone effects. Rather, our study investigates whether ozone effects are confounded by PM_{2.5} components.

As with any study of community-level health effects of air pollution, this study may be subject to spatial misalignment and other measurement error. Previous research investigated PM_{2.5} constituents measured at different locations within the same community and found spatial heterogeneity in daily measurements (49). This source of uncertainty differs by pollutant (49). Future analysis, when more particulate component data are available, could address such concerns, although this may be less of a concern with sulfate,

the component most strongly correlated with ozone concentration (49).

Substantial evidence indicates that ozone effects are robust to particulate matter measured by mass (PM_{2.5}, PM₁₀) (3, 5, 17–20, 22); in addition, we found no evidence that the ozone-mortality relation is confounded by the 7 components constituting most of PM_{2.5}. This indicates that earlier ozone-mortality studies did not misspecify health effects from these components as effects of ozone.

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