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# Ambient Particulate Air Pollution and Daily Mortality in 652 Cities

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## ABSTRACT

### BACKGROUND

The systematic evaluation of the results of time-series studies of air pollution is challenged by differences in model specification and publication bias.

### METHODS

We evaluated the associations of inhalable particulate matter (PM) with an aerodynamic diameter of 10 $\mu$m or less ($PM_{10}$) and fine PM with an aerodynamic diameter of 2.5 $\mu$m or less ($PM_{2.5}$) with daily all-cause, cardiovascular, and respiratory mortality across multiple countries or regions. Daily data on mortality and air pollution were collected from 652 cities in 24 countries or regions. We used overdispersed generalized additive models with random-effects meta-analysis to investigate the associations. Two-pollutant models were fitted to test the robustness of the associations. Concentration–response curves from each city were pooled to allow global estimates to be derived.

### RESULTS

On average, an increase of 10 $\mu$g per cubic meter in the 2-day moving average of $PM_{10}$ concentration, which represents the average over the current and previous day, was associated with increases of 0.44% (95% confidence interval [CI], 0.39 to 0.50) in daily all-cause mortality, 0.36% (95% CI, 0.30 to 0.43) in daily cardiovascular mortality, and 0.47% (95% CI, 0.35 to 0.58) in daily respiratory mortality. The corresponding increases in daily mortality for the same change in $PM_{2.5}$ concentration were 0.68% (95% CI, 0.59 to 0.77), 0.55% (95% CI, 0.45 to 0.66), and 0.74% (95% CI, 0.53 to 0.95). These associations remained significant after adjustment for gaseous pollutants. Associations were stronger in locations with lower annual mean PM concentrations and higher annual mean temperatures. The pooled concentration–response curves showed a consistent increase in daily mortality with increasing PM concentration, with steeper slopes at lower PM concentrations.

### CONCLUSIONS

Our data show independent associations between short-term exposure to $PM_{10}$ and $PM_{2.5}$ and daily all-cause, cardiovascular, and respiratory mortality in more than 600 cities across the globe. These data reinforce the evidence of a link between mortality and PM concentration established in regional and local studies. (Funded by the National Natural Science Foundation of China and others.)

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The adverse health effects of short-term exposure to ambient air pollution are well documented.[1-3] Particulate matter (PM), especially, arouses public health concerns because of its toxicity and the widespread human exposure to this pollutant. PM, which includes inhalable particles with an aerodynamic diameter of 10 $\mu$m or less ($PM_{10}$) and fine particles with an aerodynamic diameter of 2.5 $\mu$m or less ($PM_{2.5}$), is emitted from combustion sources or formed through atmospheric chemical transformation. Given the extensive evidence regarding their effects of health, the daily and annual mean concentrations of $PM_{10}$ and $PM_{2.5}$ are regulated according to the World Health Organization (WHO) Air Quality Guidelines[4] and standards in major countries.

Numerous time-series studies have examined the associations between short-term PM exposures and daily mortality.[5-9] However, most evidence has been obtained from studies in single cities, regions, or countries, and there are challenges in comparing these results and in synthesizing effect estimates because of different modeling approaches and potential publication bias. These limitations can be addressed by performing international, multicenter studies that adopt the same analytic protocol and model specifications to estimate globally representative associations of $PM_{10}$ and $PM_{2.5}$ exposures with daily mortality. We established the Multi-City Multi-Country (MCC) Collaborative Research Network to perform a global assessment of the effects of weather or climate on mortality.[10,11] This network allowed us to examine and compare the associations of PM concentrations with daily all-cause, cardiovascular, and respiratory mortality at the global, regional, and country level with the use of a standardized analytic framework.

## Methods

### Data Collection

We obtained health and environmental data from the MCC database, which has been described previously.[10,12] The current analysis was limited to locations that had available data on air pollution (652 urban areas in 24 countries or regions, with the data covering the period from 1986 through 2015) (Table S1 in the Supplementary Appendix, available with the full text of this article at NEJM.org). Data on mortality were obtained from local authorities within each country. Causes of death were classified according to codes in the *International Classification of Diseases, 9th Revision* (ICD-9) or *10th Revision* (ICD-10), whichever was available. In each location, mortality was represented by daily counts of either death from nonexternal causes (ICD-9 codes 0 to 799 and ICD-10 codes A0 to R99) or, when such data were unavailable, daily counts of death from any cause. We also collected mortality data for two main causes of death: cardiovascular disease (ICD-10 codes I00 to I99) and respiratory disease (ICD-10 codes J00 to J99).[13]

We obtained daily data on $PM_{10}$ in 598 cities and on $PM_{2.5}$ in 499 cities. Data on both pollutants were available in 445 cities in 16 countries or regions. The geographic distributions of the cities that had data on $PM_{10}$ and $PM_{2.5}$, as well as the annual mean PM concentrations over the period studied for each city, are provided in Figure 1 and Figure 2, respectively (also see the interactive map, available at NEJM.org). Daily data on gaseous pollutants (ozone, nitrogen dioxide, sulfur dioxide, and carbon monoxide) were obtained where available. We also collected data on the daily mean temperature and daily mean relative humidity. To avoid potential consequences of including outlying values of exposure data, we used trimmed data, in which the highest 5% and lowest 5% of $PM_{10}$ and $PM_{2.5}$ measurements were excluded.[14]

### Statistical Analysis

The associations of $PM_{10}$ and $PM_{2.5}$ concentrations with daily all-cause, cardiovascular, and respiratory mortality were assessed in separate analyses with the use of a standard time-series approach. We followed a two-stage analytic protocol, which had been developed and widely applied in previous multicity time-series studies.[15,16]

In the first stage, we estimated city-specific associations of PM concentration with mortality using quasi-Poisson generalized additive models. In accordance with the approaches used in previous studies,[16,17] the following covariates were included in the main model: a natural cubic smooth function with 7 degrees of freedom (df) per year to control for underlying time trends in mortality, an indicator day-of-week variable to account for short-term weekly variations, and natural spline functions with 6 df for temperature and 3 df



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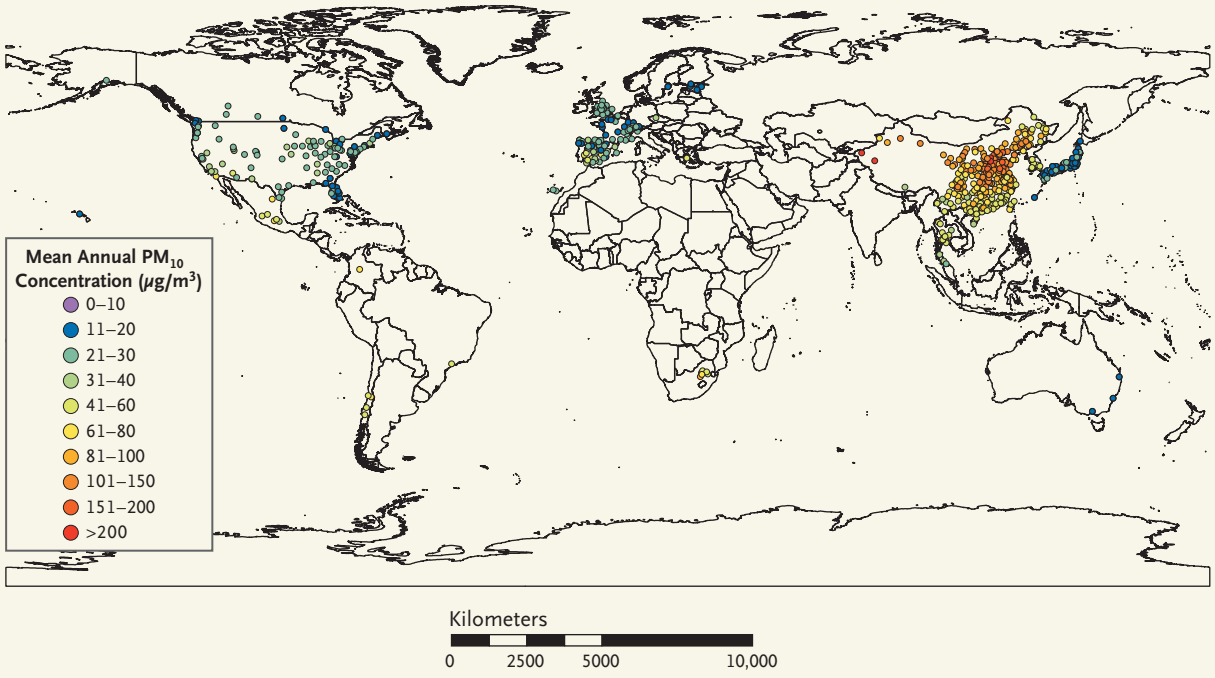



**Figure 1. Distribution of the Cities with Data on $PM_{10}$.**

Shown is the geographic distribution of the 598 cities in the 24 countries and regions that had available data on particulate matter with an aerodynamic diameter of 10 $\mu$m or less ($PM_{10}$) and were included in the analysis. Also shown are the annual mean $PM_{10}$ concentrations. See the interactive map, available at NEJM.org.

for relative humidity to control for potentially nonlinear confounding effects of weather conditions in areas where such data were available. To determine an appropriate lag time (i.e., the number of days between exposure and the estimated effect) for PM and temperature to be used in the main analyses, we compared a variety of lag days using generalized cross-validation scores.

In the second stage, we used random-effects models to pool the estimates of the city-specific associations of PM concentrations with mortality.[18] We then reported the pooled estimate and related 95% confidence intervals as the percentage change in daily mortality per 10-$\mu$g-per-cubic-meter increase in PM concentrations. Between-city heterogeneity was quantified with the use of the $I^2$ statistic.

In addition to the main model described above, we fitted two-pollutant models, each of which included adjustment for one of four gaseous pollutants. The association of PM concentration with mortality was considered robust if the effect estimates in the single-pollutant and two-pollutant models were not significantly different, as determined with a paired z-test.

Using the aforementioned two-stage approach, we also performed regional analyses, with the regions grouped according to WHO region and according to the gross domestic product (GDP) per capita (Table S2 in the Supplementary Appendix), and likelihood-ratio tests were used to determine whether the differences between regions in associations of PM with mortality were significant. To further explore potential effect modifications, we fit meta-regression models with annual mean concentrations of PM and copollutants, annual mean temperature, latitude of locations, WHO region and region classified according to the GDP per capita, rates of missing data on daily mortality and $PM_{10}$ and $PM_{2.5}$ concentrations, and GDP per capita.

To estimate the overall shape of the associations between $PM_{10}$ and $PM_{2.5}$ concentrations and mortality at the global or country level, we plot-

*An interactive map is available at NEJM.org*



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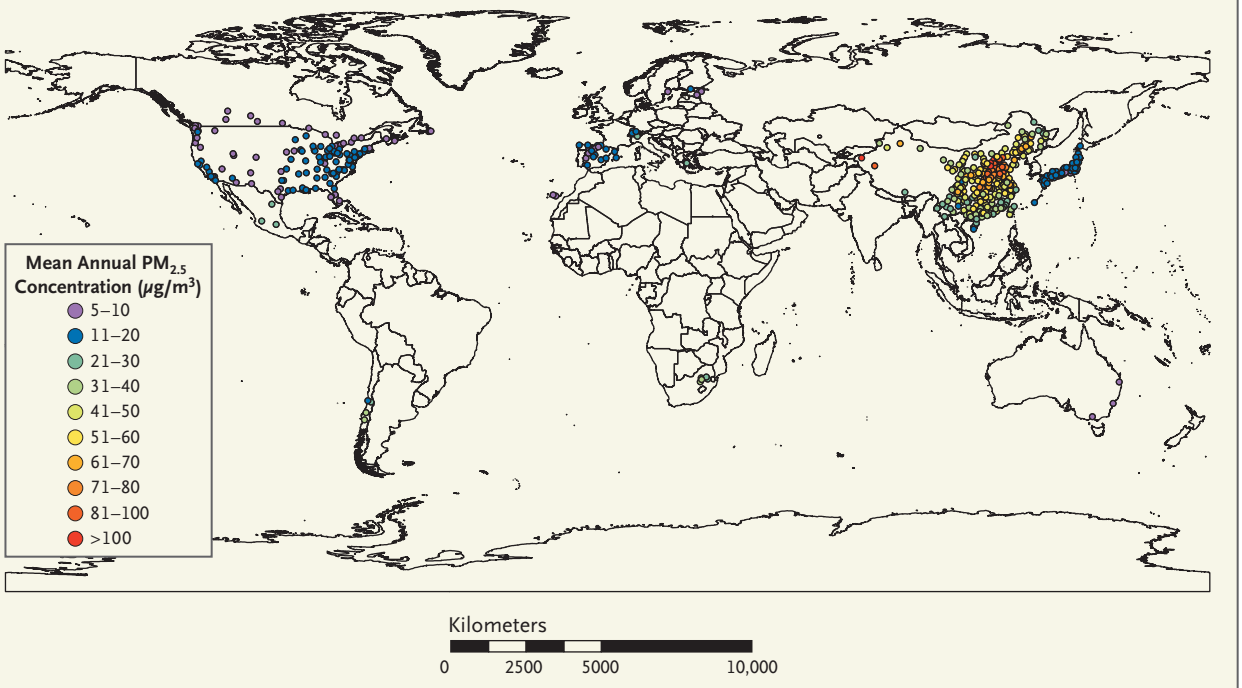



**Figure 2. Distribution of Cities with Data on $PM_{2.5}$.**

Shown is the geographic distribution of the 499 cities in the 16 countries and regions that had data on particulate matter with an aerodynamic diameter of 2.5 μm or less ($PM_{2.5}$) and were included in the analysis. Also shown are the annual mean $PM_{2.5}$ concentrations. See the interactive map, available at NEJM.org.

ted concentration–response curves using the same approach that was used in previous studies.[16,19] In brief, we replaced the linear term of PM in the main model with a B-spline function with two knots at the 25th and 75th percentiles of the mean PM concentrations across all cities.

We performed several sensitivity analyses. First, in fitting the concentration–response curves, we placed knots at different PM values. Second, we tested the potential confounding effect of humidity in cities that had available data on this variable by comparing the results of models that adjusted for humidity with the results of models that did not in a paired z-test. Third, we restricted the analyses to data available after the year 2000.

We conducted all statistical analyses with R software, version 3.3.1 (R Foundation for Statistical Computing), using the mgcv package for fitting main models and the rmeta package for performing random-effect models. A P value of less than 0.05 was considered to indicate statistical significance. More details are presented in the Methods section in the Supplementary Appendix.

## RESULTS

### DESCRIPTIVE ANALYSES

The final analysis included 59.6 million deaths from any cause or nonexternal causes, 20.1 million deaths from cardiovascular diseases, and 5.6 million deaths from respiratory diseases (Table S1 [nontrimmed data] and Table S3 [trimmed data] in the Supplementary Appendix). On average, the annual mean concentration of $PM_{10}$ in 598 cities was 56.0 μg per cubic meter (median, 44.3 μg per cubic meter [range, 11.0 to 295.0; interquartile range, 37.9 to 70.1]), and the annual mean concentration of $PM_{2.5}$ in 499 cities was 35.6 μg per cubic meter (median, 31.9 μg per cubic meter [range, 4.1 to 116.9; interquartile range, 21.5 to 43.5]). $PM_{10}$ was strongly correlated with $PM_{2.5}$, with a mean Pearson correlation coefficient of 0.78. The mean Pearson correlation coefficients between $PM_{10}$ and gaseous pollutants



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were 0.46 with nitrogen dioxide, 0.20 with ozone, 0.38 with sulfur dioxide, and 0.40 with carbon monoxide. The corresponding coefficients between $PM_{2.5}$ and gaseous pollutants were 0.48, 0.22, 0.40, and 0.45. Other descriptive statistics and the correlations between daily mean PM concentrations and weather variables are summarized in the Results section in the Supplementary Appendix.

### REGRESSION ANALYSES

The choice of a 2-day moving average for PM concentration, which represents the average over the same and previous day (lag 0 to 1 day), and a 4-day moving average for temperature, which represents the average of the same and previous 3 days (lag 0 to 3 days), generated the smallest mean generalized cross-validation scores (Tables S4 and S5 in the Supplementary Appendix). These moving averages were then applied in subsequent analyses. For both $PM_{10}$ and $PM_{2.5}$, the associations were significant on lag 0 day and then attenuated substantially on lag 1 to 2 days; the estimates of the associations were strongest on lag 0 to 1 day (Table S4 in the Supplementary Appendix).

Overall, we observed positive and significant associations between $PM_{10}$ and $PM_{2.5}$ concentrations and all-cause mortality (Table 1). In 598 cities that had data on $PM_{10}$, an increase of 10 $\mu$g per cubic meter in the $PM_{10}$ concentration was associated with an increase of 0.44% (95% confidence interval [CI], 0.39 to 0.50) in a pooled estimate of daily all-cause mortality. In 499 cities that had data on $PM_{2.5}$, the same increase in the $PM_{2.5}$ concentration was associated with an increase of 0.68% (95% CI, 0.59 to 0.77) in a pooled estimate of daily all-cause mortality. The country-specific estimates of the percentage change in daily all-cause mortality showed considerable variations, ranging from 0.03% (for Colombia) to 1.32% (for Australia) in association with a 10-$\mu$g-per-cubic-meter increase in $PM_{10}$ concentration and ranging from 0.03% (for Portugal) to 2.54% (for Greece) in association with the same increase in $PM_{2.5}$ concentration. Estimates of the effect in France, Estonia, and Switzerland were close to the global median estimate of 0.46% in association with $PM_{10}$ concentration; estimates of the effect in Switzerland and South Africa were close to the global median estimate of 0.80% in association with $PM_{2.5}$ concentration.

In cause-specific analyses, an increase of 10 $\mu$g per cubic meter in $PM_{10}$ concentration (in 528 cities) was associated with an increase of 0.36% (95% CI, 0.30 to 0.43) in daily cardiovascular mortality and an increase of 0.47% (95% CI, 0.35 to 0.58) in daily respiratory mortality. The corresponding increases in daily cardiovascular and respiratory mortality for the same increase in $PM_{2.5}$ concentration (in 488 cities) were 0.55% (95% CI, 0.45 to 0.66) and 0.74% (95% CI, 0.53 to 0.95%) (Figs. S1 and S2 in the Supplementary Appendix). In 445 cities that had data on both $PM_{2.5}$ and $PM_{10}$, the percentage increases in all-cause mortality per 10-$\mu$g-per-cubic-meter increase in $PM_{2.5}$ concentration were larger than those with the same increase in $PM_{10}$ concentration, both in the pooled results and in most country-specific estimates (Fig. S3 in the Supplementary Appendix).

Regional analyses indicated differences between areas (Table S6 in the Supplementary Appendix), with higher estimates of the effect in the region of the Americas and smaller estimates in the Western Pacific region. We observed stronger associations between $PM_{10}$ and $PM_{2.5}$ concentrations and all-cause mortality in locations with lower annual mean concentrations of PM and higher annual mean temperatures ($P<0.001$ for all comparisons); there was no significant modification of the effect according to annual mean concentrations of PM and copollutants, latitude of location, WHO region and region classified according to the GDP per capita, rates of missing data on daily mortality and $PM_{10}$ and $PM_{2.5}$ concentrations, and GDP per capita ($P>0.05$ for all comparisons).

In two-pollutant models (Table 2), the magnitude (i.e., the size of the estimated effect) of the associations of $PM_{10}$ and $PM_{2.5}$ concentrations on lag 0 to 1 day with all-cause mortality decreased, but all associations between PM and mortality remained significant after adjustment for gaseous pollutants. Notably, the estimates of the percentage change in mortality per 10-$\mu$g-per-cubic-meter increase in $PM_{10}$ concentration decreased significantly after adjustment for nitrogen dioxide (difference of 35%; $P<0.001$) and sulfur dioxide (difference of 18%; $P=0.007$). Similarly, the percentage change in mortality with the same increase in $PM_{2.5}$ concentration decreased by 36% after adjustment for nitrogen dioxide ($P<0.001$) and by 22% after adjustment for sulfur dioxide ($P=0.007$).



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**Table 1. Percentage Change in All-Cause Mortality per 10-μg-per-Cubic-Meter Increase in 2-Day Moving Average Concentrations of Inhalable Particulate Matter ($PM_{10}$) and Fine Particulate Matter ($PM_{2.5}$).***

| Country or Region | $PM_{10}$ | | $PM_{2.5}$ | |
|---|---|---|---|---|
| | Cities with Available Data | Pooled Estimate | Cities with Available Data | Pooled Estimate |
| | *no.* | *% (95% CI)* | *no.* | *% (95% CI)* |
| Australia | 3 | 1.32 (0.22 to 2.44) | 3 | 1.42 (–0.12 to 2.99) |
| Brazil | 1 | 1.22 (0.97 to 1.47) | 0 | NA |
| Canada | 13 | 0.76 (0.25 to 1.27) | 25 | 1.70 (1.17 to 2.23) |
| Chile | 4 | 0.33 (0.14 to 0.53) | 4 | 0.27 (–0.68 to 1.23) |
| China | 272 | 0.28 (0.22 to 0.34) | 272 | 0.41 (0.32 to 0.50) |
| Colombia | 1 | 0.03 (–0.34 to 0.39) | 0 | NA |
| Czech Republic | 1 | 0.40 (–0.02 to 0.82) | 0 | NA |
| Estonia | 4 | 0.46 (–0.69 to 1.63) | 3 | 0.23 (–4.24 to 4.90) |
| Finland | 1 | 0.07 (–0.51 to 0.65) | 1 | 0.14 (–0.55 to 0.83) |
| France | 18 | 0.46 (–0.15 to 1.07) | 0 | NA |
| Greece | 1 | 0.53 (0.17 to 0.90) | 1 | 2.54 (1.28 to 3.83) |
| Italy | 18 | 0.65 (0.26 to 1.04) | 0 | NA |
| Japan | 47 | 1.05 (0.78 to 1.31) | 47 | 1.42 (1.05 to 1.81) |
| Mexico | 8 | 0.67 (0.48 to 0.86) | 3 | 1.29 (0.21 to 2.39) |
| Portugal | 2 | 0.11 (–0.27 to 0.49) | 1 | 0.03 (–1.14 to 1.21) |
| South Africa | 6 | 0.41 (0.14 to 0.68) | 5 | 0.80 (0.16 to 1.44) |
| South Korea | 7 | 0.42 (0.27 to 0.58) | 0 | NA |
| Spain | 45 | 0.87 (0.60 to 1.15) | 19 | 1.96 (1.18 to 2.75) |
| Sweden | 1 | 0.20 (–1.03 to 1.44) | 1 | 0.08 (–1.44 to 1.62) |
| Switzerland | 8 | 0.47 (–0.36 to 1.31) | 4 | 0.79 (–0.96 to 2.58) |
| Taiwan | 3 | 0.25 (–0.03 to 0.53) | 3 | 0.62 (–0.39 to 1.64) |
| Thailand | 19 | 0.61 (0.24 to 0.99) | 0 | NA |
| United Kingdom | 15 | 0.06 (–0.36 to 0.48) | 0 | NA |
| United States | 100 | 0.79 (0.60 to 0.98) | 107 | 1.58 (1.28 to 1.88) |
| Total | 598 | 0.44 (0.39 to 0.50) | 499 | 0.68 (0.59 to 0.77) |

* Pooled estimates represent the percentage changes in daily all-cause mortality per 10-μg-per-cubic-meter increase in concentrations of particulate matter (PM) with an aerodynamic diameter of 10 μm or less ($PM_{10}$) and PM with an aerodynamic diameter of 2.5 μm or less ($PM_{2.5}$), as determined with the use of trimmed exposure data in which the highest 5% and lowest 5% of $PM_{10}$ and $PM_{2.5}$ measurements were excluded. NA denotes not available.

The concentration–response associations of daily mean $PM_{10}$ and $PM_{2.5}$ concentrations with all-cause mortality were positive, and the curves showed a consistent increase with no discernible thresholds (Fig. 3). The slopes for both curves were steeper at concentrations lower than 40 μg per cubic meter for $PM_{10}$ and lower than 20 μg per cubic meter for $PM_{2.5}$. The slopes seemed to flatten at high ranges. In addition, positive associations were still detectable at levels below most global and regional air-quality guidelines or standards. Country-specific concentration–response curves are provided in Figures S4 and S5 in the Supplementary Appendix.

Sensitivity analyses confirmed these results. The use of alternative knots did not substantially change the shape of the concentration–response curves, and adjustment for humidity resulted in



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**Table 2. Percentage Change in All-Cause Mortality in Association with an Increase of 10 μg per Cubic Meter in the 2-Day Moving Average Concentrations of $PM_{10}$ and $PM_{2.5}$, with and without Adjustment for Copollutants.***

| Models | $PM_{10}$ | | | $PM_{2.5}$ | | |
|---|---|---|---|---|---|---|
| | Cities with Available Data | Pooled Estimate | P Value for Difference | Cities with Available Data | Pooled Estimate | P Value for Difference |
| | *no.* | *% (95% CI)* | | *no.* | *% (95% CI)* | |
| PM and ozone | 559 | | 0.90 | 487 | | 0.75 |
| Single-pollutant model of PM | | 0.43 (0.37–0.48) | | | 0.68 (0.58–0.77) | |
| Two-pollutant model of PM with adjustment for ozone | | 0.43 (0.37–0.49) | | | 0.66 (0.56–0.77) | |
| PM and nitrogen dioxide | 495 | | <0.001 | 466 | | <0.001 |
| Single-pollutant model of PM | | 0.43 (0.37–0.49) | | | 0.66 (0.57–0.76) | |
| Two-pollutant model of PM with adjustment for nitrogen dioxide | | 0.28 (0.22–0.35) | | | 0.42 (0.31–0.53) | |
| PM and sulfur dioxide | 495 | | 0.007 | 466 | | 0.007 |
| Single-pollutant model of PM | | 0.44 (0.38–0.50) | | | 0.67 (0.57–0.76) | |
| Two-pollutant model of PM with adjustment for sulfur dioxide | | 0.36 (0.30–0.42) | | | 0.52 (0.42–0.62) | |
| PM and carbon monoxide | 445 | | 0.75 | 416 | | 0.50 |
| Single-pollutant of PM | | 0.40 (0.34–0.46) | | | 0.61 (0.51–0.71) | |
| Two-pollutant model of PM with adjustment for carbon monoxide | | 0.39 (0.32–0.46) | | | 0.57 (0.46–0.68) | |

* Pooled estimates are of the percentage change in daily all-cause mortality per 10-μg-cubic-meter increase in $PM_{10}$ or $PM_{2.5}$ concentration. The P value for difference was calculated by evaluating a binary variable (with and without the adjustment for the copollutant) in a paired z-test with estimates from both single-pollutant and two-pollutant models. A P value of less than 0.05 was considered to be statistically significant for the difference.





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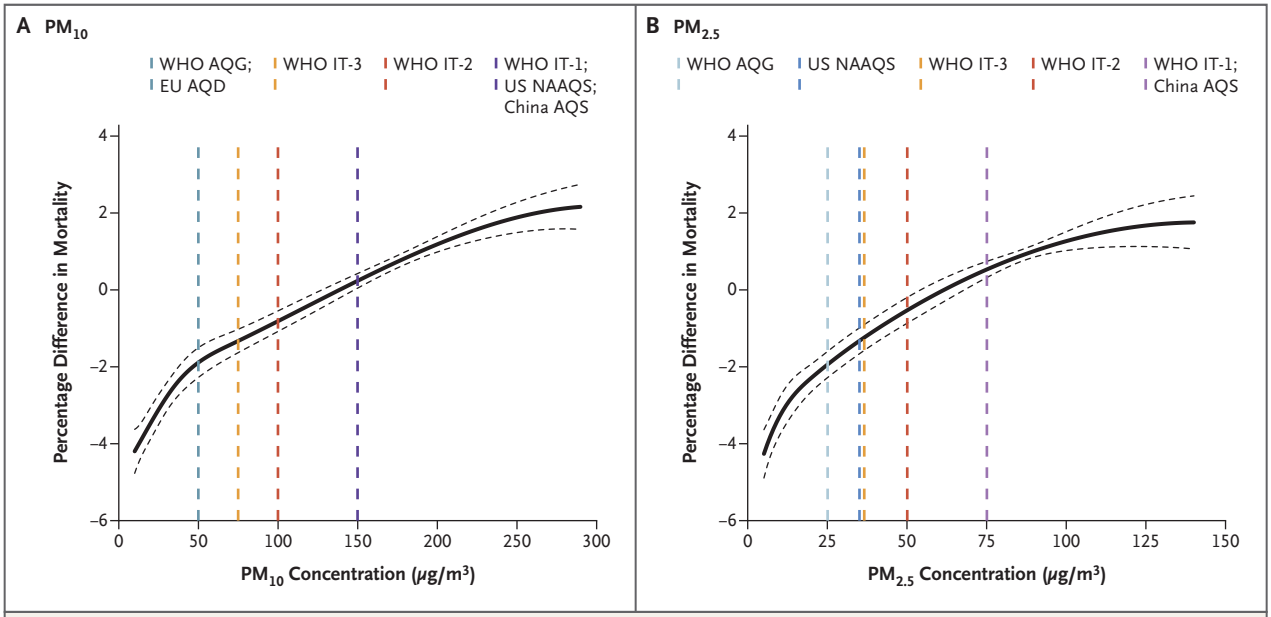



**Figure 3. Pooled Concentration–Response Curves.**

Shown are the pooled concentration–response curves for the associations of 2-day moving average concentrations of $PM_{10}$ (Panel A) and $PM_{2.5}$ (Panel B) with daily all-cause mortality. The y axis represents the percentage difference from the pooled mean effect (as derived from the entire range of PM concentrations at each location) on mortality. Zero on the y axis represents the pooled mean effect, and the portion of the curve below zero denotes a smaller estimate than the mean effect. The dashed lines represent the air-quality guidelines or standards for 24-hour average concentrations of $PM_{10}$ or $PM_{2.5}$ according to the World Health Organization Air Quality Guidelines (WHO AQG), WHO Interim Target 1 (IT-1), WHO Interim Target 2 (IT-2), WHO Interim Target 3 (IT-3), European Union Air Quality Directive (EU AQD), U.S. National Ambient Air Quality Standard (NAAQS), and China Air Quality Standard (AQS).

no significant changes (Figs. S6 and S7 and Table S7 in the Supplementary Appendix). Finally, the analysis in which the subset of data since the year 2000 was used provided similar estimates. Estimates based on nontrimmed PM data are provided in Table S8 in the Supplementary Appendix.

## DISCUSSION

Our study analyzed multisite data on air pollution and mortality in 652 cities across different countries and regions, although most countries and cities were in the northern hemisphere. Because the data from each city were analyzed according to the same protocol, the estimate of the percentage change in mortality per 10-$\mu$g-per-cubic-meter increase in PM concentration was based on a large data set. This study also provides the statistical power to examine the global concentration–response functions of particulate air pollution at both low and high baseline levels.

In the analysis of $PM_{10}$, we observed an increase of 0.44% in all-cause mortality per 10-$\mu$g-per-cubic-meter increase in $PM_{10}$ concentration. The magnitude of the association is generally similar to previous findings in other multicity or multicountry studies.[7-9,20] For example, the Air Pollution and Health: A European and North American Approach (APHENA) study reported increases of 0.86%, 0.33%, and 0.29% in daily all-cause mortality in Canada, Europe, and the United States, respectively.[9] The percentage increase in mortality for the same increase in $PM_{10}$ concentration was 0.77% in the Multicity Study of Air Pollution and Mortality in Latin America (ESCALA),[8] 0.55% in the Public Health and Air Pollution in Asia (PAPA) study,[7] and 0.19% in the reanalysis of the U.S. National Morbidity Mortality Air Pollution Study (NMMAPS).[21]

In the analysis of $PM_{2.5}$, we observed an increase of 0.68% in all-cause mortality per 10-$\mu$g-per-cubic-meter increase in $PM_{2.5}$ concentration. Our estimates were somewhat smaller than those obtained from previous multicity studies and a meta-analysis that used data mainly from devel-



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oped countries.[22,23] This difference may be interpreted as reflecting the nonlinearity of our concentration–response curve, which indicated a steeper slope at lower concentrations. In addition, we found that the associations of mortality with PM concentrations were slightly stronger with $PM_{2.5}$ than with $PM_{10}$ in most countries and regions, which added to the evidence that $PM_{2.5}$ accounted for a larger proportion of the effects of $PM_{10}$ and $PM_{2.5}$ combined.[6] The stronger effects of $PM_{2.5}$ may also be supported by the abundant evidence that this particulate fraction contains more small particles that can absorb toxic components from the air and penetrate deep into the lungs.[24]

The question of whether the observed associations for PM were independent from other pollutants is important for air-quality regulation and health-risk assessment. In our data, although the magnitude of the associations for $PM_{10}$ and $PM_{2.5}$ decreased in two-pollutant models, the associations for both remained significant, a finding that provides evidence of the independent health effects of PM. It is notable that the estimates of the percentage change in mortality per 10-$\mu$g-per-cubic-meter increase in $PM_{10}$ and $PM_{2.5}$ concentrations decreased more after adjustment for nitrogen dioxide and sulfur dioxide than after adjustment for ozone and carbon monoxide, a finding that may be interpreted as reflecting closer correlations of PM with nitrogen dioxide and sulfur dioxide caused by similar sources and seasonal patterns.

In accordance with the findings from the majority of previous studies, the concentration–response curves between PM concentration and daily mortality derived from this global study showed a consistent increase without evidence of a threshold.[16,19,22] In both curves, the percentage increase in mortality per unit change in PM concentration seemed to be smaller (i.e., the concentration–response curves seemed to flatten) at high ranges of daily mean PM concentration. This potential saturation effect may be explained by smaller effects of changes in daily mean PM concentration in cities with higher baseline levels of PM, as suggested in our meta-regression analyses. Furthermore, the higher proportion of young people in developing countries may decrease population susceptibility to PM, and less outdoor activity during days with high pollution levels may decrease exposure. Nevertheless, the concentrations of PM below the current air-quality guidelines and standards may still be hazardous to public health. However, associations estimated for extreme PM concentrations are characterized by wider confidence intervals, with greater uncertainty about the actual mortality risk at such values. We should also be cautious about the uncertainty in the concentration–response curves, because they were pooled from cities or countries with diverse PM ranges and varying population susceptibility and data quality and representability.

We found significant evidence of spatial heterogeneity in the associations between PM concentration and daily mortality across countries and regions. A number of factors could contribute to this variability, including different PM components, long-term air pollution levels, population susceptibility, and different lengths of study periods. We also found that higher annual mean concentrations of $PM_{10}$ and $PM_{2.5}$ were accompanied by weaker associations with daily mortality, a finding that has been reported in previous studies.[16,25] The possible adaptive response to PM in populations living in areas with higher long-term exposure to PM may lead to smaller estimate-per-unit changes in exposure. In addition, we identified stronger associations of PM with mortality in regions with higher GDP per capita, which may also be in relation to lower long-term air pollution levels (Pearson coefficient, −0.68 for $PM_{10}$ and −0.74 for $PM_{2.5}$) and decreased population susceptibility due to higher socioeconomic status.[26] The estimates of the association between PM and mortality in some countries (e.g., France, Finland, Sweden, and the United Kingdom) were smaller and not significant. These countries had fewer cities included and shorter periods evaluated, which may increase the statistical uncertainty in the estimation of the effect. Furthermore, these countries are generally located in areas with a low annual mean temperature, which may decrease the association between PM and mortality, as shown in meta-regression analyses. More interpretations on this issue are provided in the Discussion section in the Supplementary Appendix.

This study has several limitations. First, although the analysis included 24 major countries and regions on six continents, our findings cannot be interpreted as fully globally representative because the 652 cities were mainly located in



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East Asia, Europe, and North America, with a smaller number of cities in Latin America and Africa. Second, we relied on fixed-site environmental measurements, which could introduce exposure misclassification. Third, diagnostic or coding errors in health data are also inevitable in such a global study that spans multiple decades; the effects of these errors on our results are difficult to evaluate, which presumably makes the estimates of the effects on cause-specific mortality less reliable than those of effects on all-cause mortality. Fourth, there are some missing data, but their influence on our estimates was not substantial (see the Discussion section and Table S9 in the Supplementary Appendix).

Our multicountry time-series analysis provides evidence on positive associations between short-term exposure to $PM_{10}$ and $PM_{2.5}$ and daily all-cause, cardiovascular, and respiratory mortality. This study indicated independent associations of $PM_{10}$ and $PM_{2.5}$ concentrations with daily mortality after adjustment for gaseous pollutants. Further, concentration–response curves for the effects of PM on mortality showed a consistent increase, with flattening of the slopes at higher concentrations, and the associations were still detectable at concentrations below the current air-quality guidelines and regulatory limits.

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## APPENDIX

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