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Particulate air pollution and mortality in 38 of China's largest cities: time series analysis

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Abstract

Objectives To estimate the short term effect of particulate air pollution (particle diameter <10 μm, or PM_{10}) on mortality and explore the heterogeneity of particulate air pollution effects in major cities in China.

Design Generalised linear models with different lag structures using time series data.

Setting 38 of the largest cities in 27 provinces of China (combined population >200 million).

Participants 350 638 deaths (200 912 in males, 149 726 in females) recorded in 38 city districts by the Disease Surveillance Point System of the Chinese Center for Disease Control and Prevention from 1 January 2010 to 29 June 2013.

Main outcome measure Daily numbers of deaths from all causes, cardiorespiratory diseases, and non-cardiorespiratory diseases and among different demographic groups were used to estimate the associations between particulate air pollution and mortality.

Results A 10 μg/m^3 change in concurrent day PM_{10} concentrations was associated with a 0.44% (95% confidence interval 0.30% to 0.58%) increase in daily number of deaths. Previous day and two day lagged PM_{10} levels decreased in magnitude by one third and two thirds but remained statistically significantly associated with increased mortality. The estimate for the effect of PM_{10} on deaths from cardiorespiratory diseases was 0.62% (0.43% to 0.81%) per 10 μg/m^3 compared with 0.26% (0.09% to 0.42%) for other cause mortality. Exposure to PM_{10} had a greater impact on females than on males. Adults aged 60 and over were more vulnerable to particulate air pollution at high levels than those aged less than 60. The PM_{10} effect varied across different cities and marginally decreased in cities with higher PM_{10} concentrations.

Conclusion Particulate air pollution has a greater impact on deaths from cardiorespiratory diseases than it does on other cause mortality. People aged 60 or more have a higher risk of death from particulate air pollution than people aged less than 60. The estimates of the effect varied across cities and covered a wide range of domain.

Introduction

Air pollution and its negative consequences are major public health concerns in China.[1-3] According to the Global Burden of Disease Study, a loss of 25 million healthy years and more than 1.2 million premature deaths in China were attributed to outdoor air pollution in 2010.[4] In 2012 the Organisation for Economic Co-operation and Development estimated that by 2050 as many as 3.6 million people worldwide could die prematurely from air pollution each year. Most of the deaths were estimated to occur in China and India.[5]

Many time series studies conducted in Chinese cities have consistently found that temporarily higher air pollution levels were associated with increased mortality.[6 7] A common limitation in these studies was that the data were often from one city or just a few cities. Most of the studies focused on heavily polluted

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Supplementary figure: Map showing geographical location of the 38 study cities
Appendix: Supplementary materials

cities where air pollution levels were several orders of magnitude greater than those in cities with less air pollution. Therefore, the estimates from previous studies might be inadequate for contributing to environmental and public health policies at the national level. If air pollution effects are greater in more polluted cities and national pollution control policies are set based on estimates from these cities, the government might over-regulate pollution, which would hinder local economic growth in cities with less air pollution. Alternatively, if air pollution effects are smaller in more polluted cities, the government might underestimate the health risks and under-regulate pollution.

Most multi-city studies have focused on developed countries where data on both health and air pollution are readily available.[8-10] Estimates from these studies have had profound implications for developing environmental regulations designed to protect public health in the Western world. The data from the studies cannot be extrapolated to the Chinese population because of considerable differences in air pollution levels, composition of the particles, and population characteristics. In Europe and the United States the daily PM_{10} (particulate matter <10 µm diameter) concentrations range from 20 to 80 µg/m^3. In China the daily PM_{10} concentrations regularly exceed 500 µg/m^3.

Owing to the lack of multi-city studies in China, researchers have resorted to meta-analysis to combine estimates from different studies.[6-13] Meta-analyses based on published papers often suffer from publication bias, and their validity has been questioned owing to incomparability across different studies. Firstly, positive results are more likely to be published than negative results, leading to the censoring of studies with statistically non-significant results.[14] Secondly, heterogeneity in study samples (eg, the difference in age structure, ICD (international classification of diseases) codes, and study periods) leads to different interpretations of the coefficients in differing studies. Thirdly, the differences in study designs and statistical methods would affect the estimated sizes of air pollution effects, which make comparisons across different studies difficult or even impossible.

In this study, we assembled the most recent and comprehensive data on daily mortality and particulate matter air pollution for 38 large cities in China. For each city we then used flexible modelling strategies to estimate the relation between PM_{10} and mortality. We controlled for potential confounding factors, such as temperature, dew point, day of the week, public holidays, and year effects in a set of generalised linear models. Under this research design, we were able to provide estimates of air pollution effects for each city and to compare the estimates across cities with different levels of PM_{10} concentrations, estimate the national particulate air pollution effects using the random effects meta-analysis, and explore the heterogeneity of particulate air pollution effects.

Methods

Study area

We collected data on particulate matter air pollution, mortality, and weather conditions from the 38 most populated cities in China (see separate supplementary figure) daily from 1 January 2010 to 29 June 2013. The cities are located in 27 of the 31 provinces of China. The sampled population totals more than 200 million.

Air pollution data

Data on daily air quality were collected from the Ministry of Environmental Protection. The ministry reported the daily air pollution index and the primary pollutant in all the major Chinese cities during the study period. The air pollution index is based on the concentrations of three major air pollutants (particles <10 µm diameter (PM_{10}), sulphur dioxide, and nitrogen dioxide) and provides an overall measure of ambient air quality for each city. Supplementary material 1 in the web appendix explains how the air pollution index is constructed and how we were able to calculate the PM_{10}.

Mortality data

Daily mortality data are provided by the Disease Surveillance Point System (see supplementary material 2 in the web appendix) of the Chinese Center for Disease Control and Prevention. This surveillance system collects mortality data from certain districts in each city it covers. Mortality data include basic demographic characteristics of the decedent and the causes of death. The causes of death are coded according to ICD-10 (international classification of diseases, 10th revision) codes. Mortality data are classified by causes of death: cardiovascular (I00-99) and respiratory (J00-99) diseases, and all other diseases. For this study we had the daily numbers of death by age, sex, and cause of death for all of the districts covered by the surveillance system in the 38 cities.

Weather conditions data

We obtained data on daily weather conditions, such as temperature and dew point, from local weather stations for all 38 cities in the study.

Model

We estimated the associations between PM_{10} and daily mortality using a set of generalised linear models. For each city, we estimated the associations from the equation in figure 1⇓ using daily time series data.

Meteorological factors Z_i were modeled in the regressions through a set of natural spline functions S_i. The spline functions allow flexible relations between meteorological factors and the outcomes. We chose the degrees of freedom for each meteorological factor (df_{Zi}) based on its best prediction for air pollution levels. Using degrees of freedom that best predict air pollution levels is advantageous because they produce unbiased or asymptotically unbiased estimates of the pollution log-relative risk.[15] The optimal degree of freedom for each natural spline was obtained using a generalised cross validation method that best predicts PM_{10} concentrations.[16] After controlling for these potential confounding factors, the data on high frequency PM_{10} concentrations should provide a plausible source of external variation.

Since air pollution might affect mortality in a lagged fashion, we examined the air pollution effects separately for different lag structures (lag of one day, two days, etc). We also explored heterogeneous air pollution effects by examining both sexes and different age groups.

To estimate national air pollution effects, we conducted a heterogeneity test and used random effects meta-analysis to produce estimates of air pollution effects for each city. In the meta-analysis we used the coefficients of PM_{10} and its standard errors estimated from figure 2 for each city. In a random effects meta-analysis, the true air pollution effects (β_k) are assumed to vary across different cities and to follow a normal distribution. Such heterogeneity in air pollution effects may be caused by differences in city populations, local socioeconomic conditions, and baseline population health. Specifically, we assumed the true air pollution effects were randomly and normally distributed around a mean effect (μ) with variance (σ^2). We then estimated the variance between cities using the DerSimonian and Laird method[17] and modified the weights used to calculate the summary estimate accordingly (fig 2⇓).

Using a set of linear regressions, we conducted exploratory analysis on the patterns of heterogeneous air pollution effects across the 38 cities. We investigated whether estimated air pollution effects are associated with a city's mean PM_{10} concentrations, geographical location (north or south), gross domestic product (GDP) per capita, and several demographic factors.

Patient involvement

No patients were involved in setting the research question or the outcome measures, nor were they involved in developing plans for recruitment, design, or implementation of the study. No patients were asked to advise on interpretation or writing up of results. There are no plans to disseminate the results of the research to study participants or the relevant patient community.

Results

Descriptive statistics

Table 1⇓ shows the daily mean PM_{10} concentrations, daily number of all cause deaths, and deaths from cardiorespiratory diseases for each city in our sample. Over the sample period (1 January 2010 to 29 June 2013), the daily mean of PM_{10} concentrations across all locations was 92.9 μg/m^3 (SD 46.3 μg/m^3). The most polluted city in our sample was Urumqi in Xinjiang Province, with an average daily mean PM_{10} concentration of 136.0 μg/m^3. The least polluted city was Qinhuangdao in Hebei Province, with an average daily mean PM_{10} concentration of 66.9 μg/m^3. The lowest daily PM_{10} concentration observed in our sample was 11 μg/m^3 in Changsha on 23 September 2010, whereas the highest was 420 μg/m^3 in Nanning on 3 February 2011. On average, there were 8.6 deaths each day in the sampled city districts, including 4.4 from cardiorespiratory diseases. Table SM2 in the web appendix provides more information about these cities covered by the Disease Surveillance Point System).

Mortality and PM_{10} associations

We estimated the air pollution effects of concurrent day and lagged (up to six days) PM_{10} concentrations on all cause deaths by fitting the model in figure 1 to the time series data for each city separately. Figure 3⇓ is a plot of the concurrent day PM_{10} estimates and their 95% confidence intervals for each city. The estimates of the effects ranged from 1.8% (95% confidence interval 0.60% to 3.00%) per 10 μg/m^3 in Yuxi to −0.98% (−2.45% to 0.48%) per 10 μg/m^3 in Panzhihua. Column 1 of table SM3 in the web appendix presents the coefficients and 95% confidence intervals.

Although the majority of estimates were positive (87% of 38 cities), heterogeneity was obvious across the cities. The I^2 statistics showed that 59% of heterogeneity between cities was attributable to variability in the true treatment effect, rather than to variation in sampling. Since we used the same model and data period for all cities, heterogeneity was smaller than that in meta-analysis using different studies. When we rejected the hypothesis of homogeneity, we took into account the variation identified between the cities and fitted a DerSimonian and Laird random effects model.[17] Overall, we found that a 10 μg/m^3 increase in PM_{10} concentrations was associated with a 0.44% (0.30% to 0.58%) increase in total mortality.

We then used different lags (one to six days) of PM_{10} as the primary explanatory variable in the equation in figure 2⇓. The forest plots of the estimates for individual cities and combined effects are summarised in figures SM1 to SM6 in the web appendix. Table SM4 in the web appendix reported the coefficients and 95% confidence intervals using the order of cities in figure 3⇓ for comparison. In general, the estimates for individual cities became smaller and the heterogeneity across cities decreased as the lag time became longer. The combined effects also converged to zero as the lag time became longer. For example, for a PM_{10} pollution with a lag of one day, the combined random effects estimate was 0.26% excess mortality (0.15% to 0.37%) per 10 μg/m^3 increase in PM_{10}. The overall effect decreased to 0.13% (0.03% to 0.23%) per 10 μg/m^3 increase in lag two days PM_{10} pollution. The combined effects became statistically insignificant and close to zero for PM_{10} lagged more than two days. Given these results, we also estimated the air pollution effect using the three day moving average (lags zero, one, and two). The estimates and their 95% confidence intervals are plotted in figure SM7 in the web appendix. The combined random effects estimate was 0.45% excess mortality (0.28% to 0.62%) per 10 μg/m^3 increase in PM_{10}. These estimates were quantitatively similar to those using concurrent day PM_{10}.

Heterogeneity by cause of death, sex, and age group

Figures 4 and 5 show the plots for the PM_{10} effects for deaths due to cardiorespiratory diseases and due to other diseases, respectively. Columns 2 and 3 of table SM3 of the web appendix shows the coefficients and 95% confidence intervals. We used concurrent day PM_{10} concentrations for analysis of specific diseases because the analysis for overall mortality showed that the estimates for concurrent day pollution were similar to those for the three day moving average. For both cardiorespiratory diseases and non-cardiorespiratory diseases, the pollution effect showed statistically significant heterogeneity across the different cities. For most cities, the PM_{10} effect for deaths due to cardiorespiratory diseases was more likely to be positive and greater than deaths due to non-cardiorespiratory diseases. The combined effect for deaths due to cardiorespiratory diseases was more than double that for deaths due to non-cardiorespiratory diseases. For the former, the combined effect for all cities was 0.6% (0.43% to 0.81%) per 10 μg/m^3 PM_{10}. For the latter, the combined estimate on the effects of PM_{10} was less than half (0.3% (0.09% to 0.42%) per 10 μg/m^3 PM_{10}). The I^2 value for figure 4⇓ was virtually the same as that for figure 3⇓ (59%), whereas that for figure 5⇓ was considerably smaller (38%). Therefore, the cities were more homogeneous for deaths due to non-cardiorespiratory diseases than for deaths due to cardiorespiratory diseases.

We then explored the sex and age specific effects of PM_{10} by including a sex or age indicator and its interaction with PM_{10} in the equation in figure 1. Figure SM8 in the web appendix plots the estimates and 95% confidence intervals for males and females, and their differences separately for each city. The majority of all estimates were positive for both sexes. The combined effect for males was 0.3% (0.16% to 0.50%) and for females was 0.58% (0.42% to 0.74%) per 10 μg/m^3. The overall difference between males and females was 0.24% (0.10% to 0.38%). Therefore, females were more susceptible to particulate air pollution shocks.

Figure SM9 in the web appendix plots the estimates and 95% confidence intervals for people aged less than 60 and people aged 60 or more, and their differences separately for each city. For people aged less than 60, the combined effect was −0.02% (−0.19 to 0.14) per 10 μg/m^3 and statistically insignificant. For people aged 60 or more, the combined effect was 0.57% (0.40% to 0.73%) per 10 μg/m^3 and statistically significant at the 5% level. The overall difference between people aged 60 or more and those aged less than 60 was 0.57% (0.36% to 0.78%). Therefore, air pollution mainly affected older people in the short term.

Air pollution effects and city specific characteristics

We explored the relation between the estimated air pollution effects and several characteristics specific to each city. Firstly, we examined the association between estimated air pollution effects and city mean PM_{10} concentrations. We found that the marginal air pollution effect was smaller in more polluted cities (figure SM10 in the web appendix). The regression result in column 1 of table 2⇓ shows that the estimated air pollution effect would decrease by −0.13% (−0.26% to −0.01%) if mean PM_{10} concentrations increased by 10 μg/m^3.

The estimated air pollution effects (PM_{10} coefficients) in figure 3 are regressedon mean PM_{10} concentrations (in 10 μg/m^3), a north indicator, GDP per capita (¥10 000), share of workers in construction industry, females in population (%), share of older population. GDP per capita obtained from city statistical yearbooks. Demographic variables are from 2005 micro census data. *P<0.05.

Northern China burns a lot of coal during the winter season to provide central heating, and its weather patterns are different from southern China. We therefore checked whether air pollution effects differed between the north and south in our data. Our division of the north and south followed the Huai River line (typically the demarcation used in the literature).[18] We examined the difference in PM_{10} between the north and south by adding a north indicator and its interaction with PM_{10}. These results are presented in column 2 of table 2⇓. Figure SM11 in the web appendix compares the relation for northern cities with that for southern cities. We found that the marginal effect of PM_{10} decreased rapidly as pollution levels increased in southern cities. In comparison, the marginal effect of PM_{10} in the northern cities (sum of PM_{10} coefficient and the interaction coefficient) was almost constant at different particulate air pollution levels.

Finally, we examined the relation between the estimated air pollution effects and several socioeconomic factors: gross domestic product (GDP) per capita, the percentage of workers in the construction industry, the percentage of female population, and the percentage of people aged 60 or more. Per capita GDP measured relative socioeconomic status across different cities. The percentage of workers in the construction industry was used as an alternative to pollution exposure, because construction workers worked outside for long hours and were among those exposed to the highest concentrations of air pollution. We included the percentage of female population and the percentage of people aged 60 or more because estimates revealed that air pollution effects varied across the sexes and different age groups for each city.

The regression result in column 3 of table 2⇓ shows a positive and statistically significant association between pollution effects and the percentage of workers in the construction industry (6.67%, 1.14% to 12.20%). This relation is plotted in figure SM12 of the web appendix. We found no correlation between GDP per capita, percentage of females, and percentage of people aged 60 or more and particulate air pollution effects, largely consistent with the time series findings. We conducted similar analyses by excluding an outlier city, Urumqi, which had particularly high PM_{10} concentrations, and re-estimated all the regressions. The results were qualitatively similar to those in table 2⇓ and are reported in table SM5 in the web appendix.

Discussion

Acquiring internally coherent estimates of air pollution effects for each city in rapidly developing countries such as China is valuable to the cost-benefit analysis of pollution abatement strategies and for setting standards for air quality. In this study we estimated the associations between PM_{10} concentrations and daily mortality from all causes, cardiorespiratory diseases, and non-cardiorespiratory diseases for 38 large cities in China. We employed a set of flexible generalised linear models to obtain the estimates of air pollution effects. The specification of the statistical model required a series of analytical choices, including the specification of lag structure of the air pollution variable and how to adjust flexibly for weather conditions.

Principal findings

Our analysis showed positive associations between daily mortality and exposure to PM_{10} in most sampled cities. Compared with a lag of one or more days for PM_{10} pollution, concurrent day PM_{10} pollution had the largest impact on mortality. Meta-analyses suggested that on average a 10 μg/m^3 increase in concurrent day PM_{10}, one day lagged PM_{10}, and two day lagged PM_{10}, was associated with 0.44%, 0.26%, and 0.13% increase in the daily number of deaths, respectively. We failed to find similar positive and statistically significant effects for air pollution lagged longer than two days. In other words, lagging of particulate pollution had a relatively short acute effect on mortality.

The PM_{10} mortality associations were substantially heterogeneous across different cities. According to our estimates, the effect estimates covered a wide range and included both negative and positive domains, and PM_{10} concentrations were not statistically significantly associated with mortality for half of all cities. These findings showed the limitation of past studies that focused on a particular city or a few large cities and were often biased towards positive results.[14] Air pollution effects were affected by many local factors specific to each city. Results from one city or a few cities could not be extrapolated to all cities.

On a closer examination of heterogeneity in the PM_{10} effects on mortality, we found that air pollution had a much greater impact on deaths due to cardiorespiratory diseases than it did on deaths due to non-cardiorespiratory diseases. Our finding was consistent with the previous literature that patients with cardiorespiratory diseases were more sensitive to short term deterioration in air quality than those with other diseases. In the subgroup analysis, we found that PM_{10} pollution had a greater impact on females than on males; and that air pollution primarily affected people aged 60 years or more.

Interestingly, the average PM_{10} effects from the meta-analyses in our study were comparable to those found in several large meta-analyses. For example, summarising 33 time series and case crossover studies, Shang et al reported that a 10 μg/m^3 increase in PM_{10} concentration was associated with a 0.32% (95% confidence interval 0.28% to 0.35%) increase in deaths not due to accidents, a 0.44% (0.33% to 0.54%) increase in mortality due to cardiovascular diseases, and a 0.32% (0.23% to 0.40%) increase in mortality due to respiratory diseases.[7]

China is a vast country with more than 1.3 billion people. According to the World Bank, the annual total number of deaths in China was around 9.46 million in 2010 (with a death rate of 7.11 per 1000 and total population of 1.33 billion). In our data, the mean daily PM_{10} concentration across all cities was 92.9 μg/m^3. A back-of-envelope calculation reveals that bringing China's PM_{10} level to the WHO standard—20 μg/m^3—would save 0.3 million premature deaths each year. This number is likely to be a lower bound estimate of the total number of deaths related to air pollution because the air pollution effect can be larger in rural areas and PM_{10} is more detrimental to human health in the long run. Our findings suggest that adopting and enforcing tighter air quality standards in China will bring about tremendous public health benefits.

Explanation of heterogeneity

The pattern of the associations between air pollution effects and baseline PM_{10} level and city specific characteristics is enlightening. Firstly, the marginal effect of particulate air pollution was smaller in cities with more air pollution. This could be because of the saturation effect, in which underlying biochemical and cellular processes became saturated when exposed to a high level of a toxic component.[19 20] It is also possible that in cities with higher air pollution, people adopted more defensive measures, such as reducing outdoor activities, wearing face masks, or installing air filters. As a result, despite living in cities with more air pollution, avoidance behaviours may have reduced people's actual exposure. Secondly, the particulate air pollution effects were more homogenous in northern cities than in southern cities. This result might also relate to avoidance behaviours. A recent study showed that people living in northern China were more likely to buy air filters than those living in southern China.[21] Thirdly, if a city had a larger percentage of workers in the construction industry, then the particulate air pollution effects would be greater. A possible explanation for the result may be that construction workers were more likely to be exposed to air pollution. Much of this discussion is, however, conjectural because the sample size in this analysis was small (38 data points).

Limitations of this study

This study was limited by the air pollution data and study area. Firstly, we were unable to examine the pollution effects of other air pollutants, such as nitrogen dioxide, sulphur dioxide, and ozone owing to limitations with data. Quantification of the health effect of other air pollutants is also important for setting appropriate air quality standards. Secondly, we only focused on cities, so the estimates of air pollution effects cannot be generalised to rural areas. Air pollution, including indoor air pollution, might have a greater impact on rural residents[3].

Conclusions

This study estimated the associations between PM_{10} and mortality using daily time series data from 38 Chinese cities. Our analysis showed that PM_{10} was robustly associated with worse health outcomes in most cities. We documented important heterogeneity in the PM_{10} effect: PM_{10} had a larger impact on people with cardiorespiratory diseases, the old population, and the female population. The PM_{10} effect also depended on demographic, socioeconomic conditions in different cities.

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Contributors: PY, GH, and MF contributed equally to this manuscript. MYF, GH, PY, and MZ designed the study. PY and MZ collected and cleaned the mortality data. MYF, KYC, and GH conducted the analyses. MRF, AX, and CL reviewed the literature, conducted Geographic Information Systems matching, and contributed to interpretation of the results. TL, YP, and QM collected the pollution data, collected socioeconomic data, and summarised the results. MYF and GH prepared the first draft. All authors commented on this draft and contributed to the final version. All authors had full access to all of the data (including statistical reports and tables) in the study and can take responsibility for the integrity of the data and the accuracy of the data analysis. MYF, GH, PY, and MZ are the guarantors.

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Ethical approval: Not required.

Data sharing: The pollution data and weather data are available from MYF (mfan@bsu.edu). The mortality data can only be applied for through a government data sharing portal (www.phsciencedata.cn/Share/edtShare.jsp).

Transparency: A lead author (MYF) affirms that the manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned (and, if relevant, registered) have been explained.

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What is already known on this topic

Many studies have shown a positive association between daily mortality and particulate air pollution

The air pollution effects in developed countries cannot be extrapolated to China because of differences in air pollution levels, compositions of particles, and population characteristics

Despite immense interest in the effect of air pollution on a national scale in China, multi city analysis is rare

What this study adds

The short term effects of particulate air pollution are city specific, therefore estimates obtained from one city should not be generalised to all cities

In China the effects of particulate air pollution are smaller in cities with more air pollution and are more homogenous in northern cities than in southern cities

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Tables

Table 1| **Summary statistics**

City	Mean (SD) values daily		
	PM_{10} (µg/m^3)	All cause deaths	Deaths due to cardiorespiratory diseases
Urumqi	136.0 (74.2)	5.2 (2.4)	2.6 (1.7)
Beijing	113.4 (71.5)	21.8 (5.4)	12.0 (4.0)
Chengdou	109.5 (57.2)	7.1 (2.9)	3.4 (2.0)
Zaozhuang	108.9 (53.0)	2.4 (1.6)	1.3 (1.2)
Zhengzhou	108.5 (51.1)	6.3 (3.5)	3.2 (2.3)
Xining	108.3 (55.8)	10.0 (4.8)	4.0 (2.7)
Nanjing	104.4 (53.4)	9.1 (3.3)	5.0 (2.6)
Anshan	102.7 (45.9)	11.9 (3.9)	7.3 (2.9)
Wuhan	101.8 (54.3)	12.2 (4.1)	6.4 (3.0)
Tianjin	101.4 (53.9)	3.7 (2.6)	2.1 (1.7)
Tongchuan	100.9 (44.6)	3.0 (1.9)	1.6 (1.4)
Shenyang	100.7 (49.6)	19.4 (5.4)	10.3 (3.6)
Harbin	100.2 (47.7)	6.5 (2.8)	3.7 (2.0)
Yinchuan	98.3 (49.6)	4.8 (2.6)	2.8 (2.0)
Panzhihua	97.8 (31.1)	5.5 (2.5)	2.7 (1.8)
Maanshan	97.3 (37.9)	3.8 (2.0)	1.7 (1.4)
Xuzhou	97.0 (49.7)	21.8 (5.4)	12.0 (4.0)
Chongqing	96.5 (49.4)	3.3 (2.0)	1.8 (1.4)
Hangzhou	92.5 (47.1)	6.5 (3.0)	2.9 (1.9)
Yichang	92.3 (42.3)	6.0 (2.8)	2.5 (1.7)
Taiyuan	92.2 (53.4)	6.5 (3.3)	3.2 (2.1)
Changde	92.1 (43.7)	2.5 (1.6)	1.3 (1.1)
Changchun	89.9 (45.6)	7.6 (2.8)	4.2 (2.1)
Qingdao	89.8 (49.3)	21.8 (5.4)	12.0 (4.0)
Nanchang	89.8 (42.0)	3.4 (2.2)	2.1 (1.8)
Tangshan	88.7 (51.9)	10.6 (3.6)	5.1 (2.7)
Changsha	86.0 (44.4)	6.0 (2.6)	3.1 (1.9)
Suzhou	84.9 (45.7)	7.3 (3.3)	3.5 (2.2)
Zunyi	83.6 (30.4)	7.9 (3.3)	4.5 (2.4)
Hohhot	82.2 (44.9)	4.0 (2.7)	2.1 (1.7)
Liuzhou	80.0 (35.0)	5.0 (2.5)	2.0 (1.5)
Qiqihar	75.9 (37.2)	21.8 (5.4)	12.0 (4.0)
Shanghai	75.1 (47.6)	2.8 (1.8)	1.7 (1.4)
Guilin	72.4 (38.7)	1.8 (1.4)	0.8 (0.9)
Yantai	71.4 (38.9)	9.5 (3.2)	4.6 (2.2)
Yuxi	70.4 (24.7)	7.1 (3.1)	3.7 (2.1)
Guangzhou	69.3 (31.9)	19.2 (5.6)	9.1 (3.7)
Qinhuangdao	66.9 (35.2)	5.7 (2.6)	2.7 (1.6)
All cities	92.9 (46.3)	8.6 (6.9)	4.4 (4.1)

Source: Ministry of Environmental Protection of China and Chinese Center for Disease Control and Prevention.

Table 2| **Relations between air pollution effect and city specific factors**

Variables	Regressions (95% CI)		
	1	2	3
Mean PM_{10} (10 μg/m^3)	−0.13* (−0.26 to −0.01)	−0.27* (−0.54 to −0.003)	−0.31* (−0.56 to −0.07)
Mean PM_{10}×north indicator	—	0.27 (−0.01 to 0.54)	0.29* (0.03 to 0.54)
North (=1)	—	−2.81* (−5.27 to −0.35)	−2.91* (−5.15 to −0.68)
GDP per capita (¥10 000)	—	—	−0.05 (−0.16 to 0.06)
Workers in construction industry (%)	—	—	6.67* (1.14 to 12.20)
Female population (%)	—	—	5.80 (−19.14 to 30.73)
People aged ≥60 years (%)	—	—	6.15 (−0.17 to 12.46)
No of observations (R^2)	38 (0.07)	38 (0.25)	38 (0.49)

¥10 000 (£1169; $1456; €1377).

GDP=gross domestic product.

Figures

$$y_t \sim Poisson\ (u_t)$$

$$\log (u_t) = a + \beta PM_{10t-l} + \textstyle\sum_{i=1}^{p} S_i\ (Z_{it}, df_{Z_i}) + DOW_t + HOD_t + Year_t + f(t) \quad (1)$$

where y_t is the number of deaths on day t; we assume y_t originates from a Poisson distribution with $E[y_t] = u_t$ and a canonical log-link in the regression. PM_{10t-l} is the PM_{10} concentrations on day t-l, and l is a day lag. β represents the log-relative rate of mortality associated with air pollution . Z_{it} is meteorological factors that are correlated with air pollution levels, which include temperature and dew point. Also included are several sets of dummy variables representing different time effects. They are dummy variables for day of the week (DOW_t), holidays (HOD_t), and year ($Year_t$). Dummy variables for day of the week capture daily mortality patterns within a week. Holiday dummy variables were used to capture the effect of holiday related conditions on mortality such as unusually heavy traffic. Year dummy variables control for potential discontinuous change in mortality levels in different years owing to yearly changes in policies. A cubic function of time $f(t)$ was also included to control for the long term trends.

Fig 1 Equation for estimating associations between PM_{10} and daily mortality, using generalised linear models

$$SE = \frac{\sum_{i=1}^{K} w_i\, PE_i}{\sum_{i=1}^{K} w_i}$$

where PE_i is the estimated pollution effect for city i, $w_i = \frac{1}{v_i + \hat{\sigma}^2}$, and v_i is the variance of the estimated effect in city i. The variance of the random effects summary pollution effect is $\frac{1}{\sum_{i=1}^{K} w_i}$

Fig 2 DerSimonian and Laird random effects summary estimate

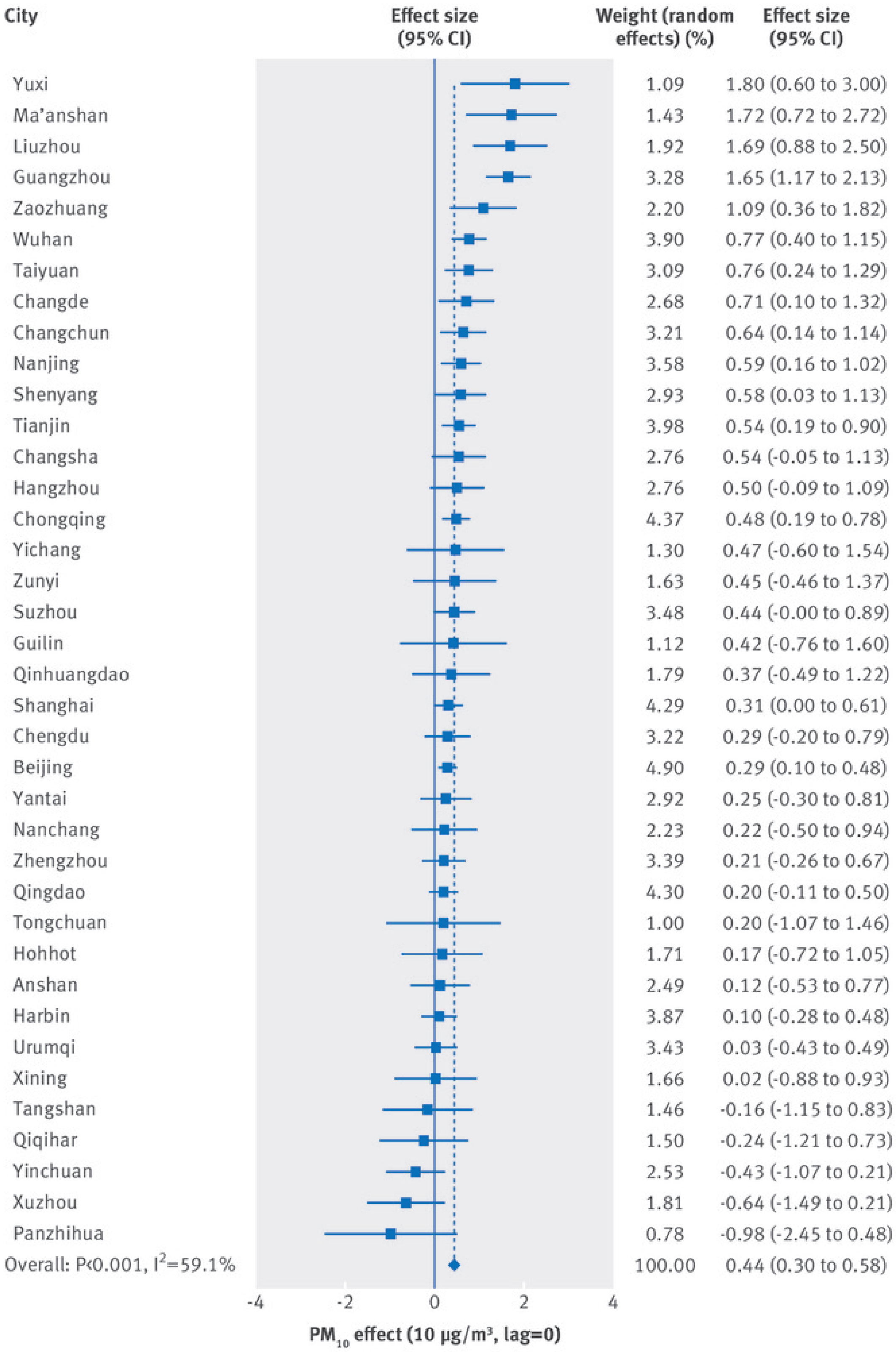

Fig 3 Maximum likelihood estimates (percentage) and 95% confidence intervals of the impact of 10 μg/m^3 PM_{10} (lag=0) on total mortality in 38 large cities in China. Solid squares represent effect size and lines indicate 95% confidence intervals

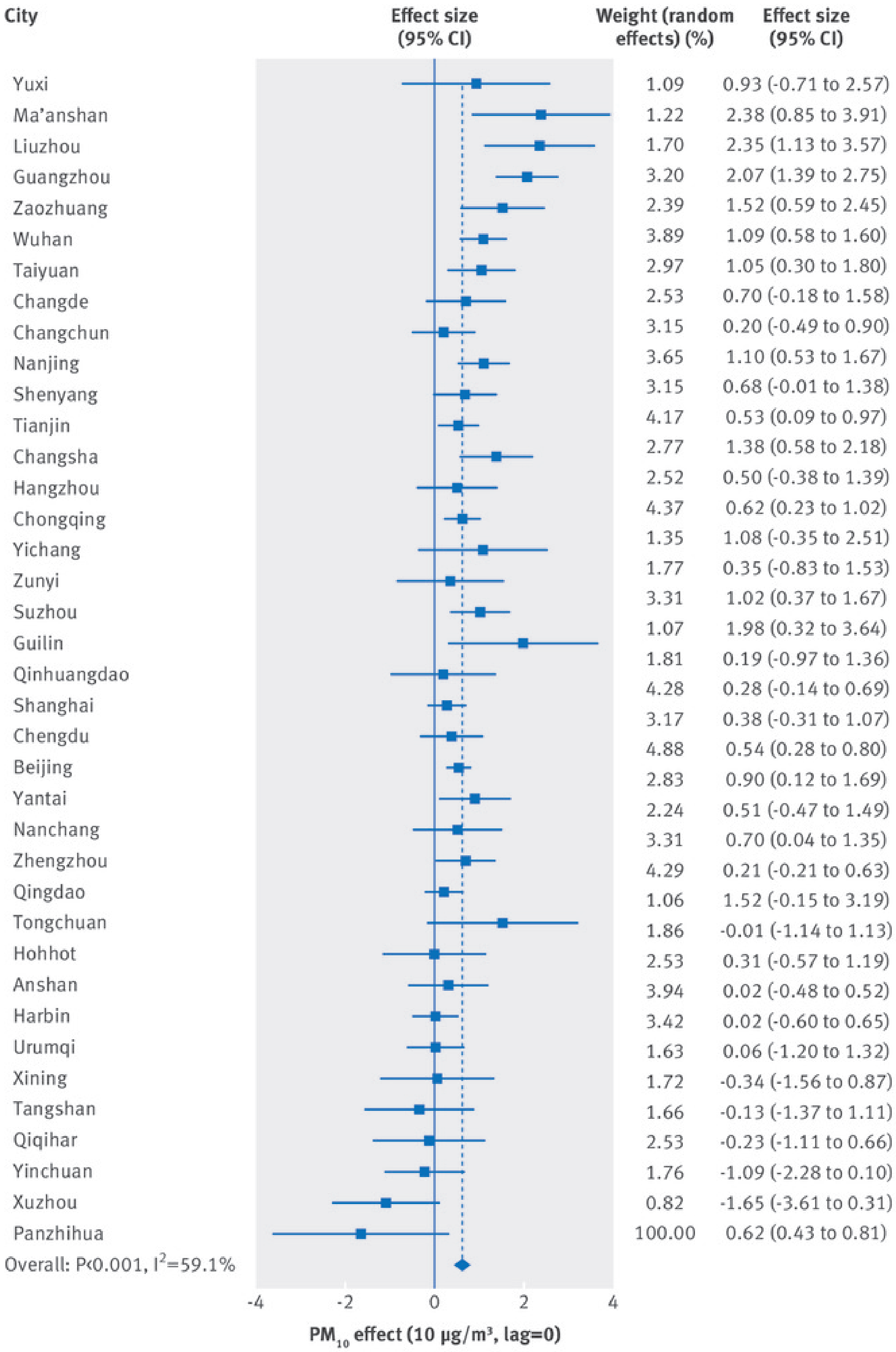

Fig 4 Maximum likelihood estimates (percentage) and 95% confidence intervals of the impact of 10 μg/m³ PM_{10} (lag=0) on total mortality for deaths due to cardiorespiratory diseases in 38 large cities in China. The dependent variable is the percentage change in number of daily deaths due to cardiorespiratory diseases. Each solid square represents an effect size. Horizontal lines indicate 95% confidence intervals

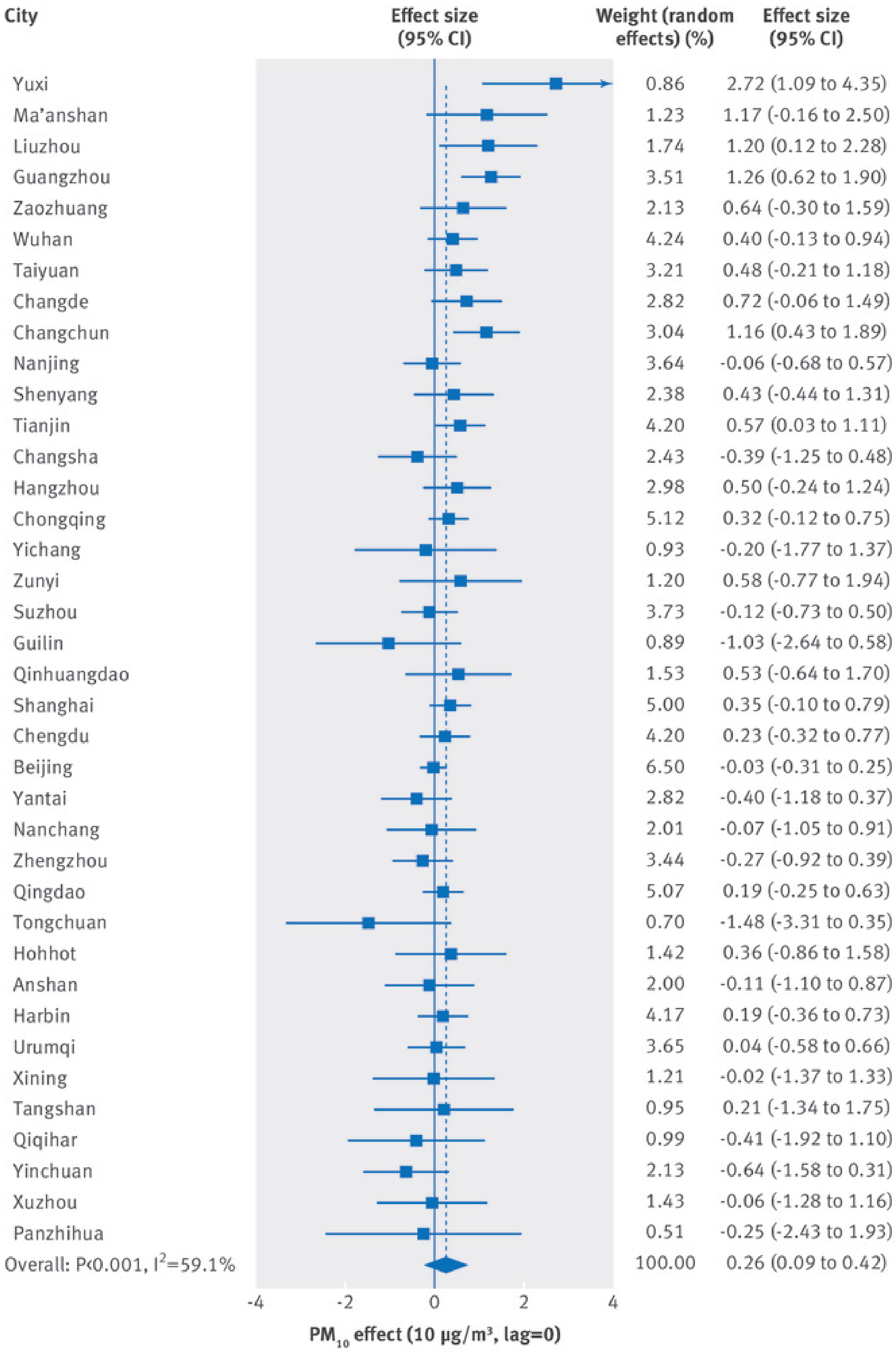

Fig 5 Maximum likelihood estimates (percentage) and 95% confidence intervals of the impact of 10 µg/m^3 PM_{10} (lag=0) on total mortality for deaths due to non-cardiorespiratory diseases in 38 large cities in China. The dependent variable is the percentage change in number of daily deaths for non-cardiorespiratory diseases. Each solid square represents an effect size. Horizontal lines indicate 95% confidence intervals