Temporal changes in mortality risk associated with PM_{10} across 143 cities in 26 countries: a multicountry, multicity time-series study

Yongsoo Choi, Garam Byun, Honghyok Kim, Rory Stewart, Yimeng Song, Seulkee Heo, Jong-Tae Lee, Shilu Tong, Eric Lavigne, Nicolás Valdés Ortega, Patricia Matus Correa, Samuel Osorio, Souzana Achilleos, Jan Kyselý, Aleš Urban, Dominic Royé, Hans Orru, Marek Maasikmets, Jouni J K Jaakkola, Niilo Ryti, Mathilde Pascal, Alexandra Schneider, Susanne Breitner, Klea Katsouyanni, Evangelia Samoli, Hanne Krage Carlsen, Alireza Entezari, Fatemeh Mayvaneh, Raanan Raz, Massimo Stafoggia, Francesca de'Donato, Masahiro Hashizume, Chris Fook Sheng Ng, Lina Madaniyazi, Magali Hurtado Diaz, Eunice Elizabeth Félix Arellano, Jochem Klompmaker, Shilpa Rao, Joana Madureira, Vânia Gaio, Yuming Guo, Noah Scovronick, Rebecca M Garland, Ho Kim, Whanhee Lee, Bertil Forsberg, Ana Maria Vicedo-Cabrera, Martina S Ragettli, Yue Leon Guo, Shih-Chun Pan, Ben Armstrong, Francesco Sera, Antonio Gasparrini, Pierre Masselot, Malcolm Mistry, Antonella Zanobetti, Joel Schwartz, Michelle L Bell

Summary

Background Ambient PM_{10} is associated with mortality; however, potential changes in this association over time and the factors explaining such changes are unclear. Therefore, we aimed to examine whether mortality risk associated with PM_{10} has changed from 1979 to 2019 and whether changes in socioeconomic or environmental conditions can explain any temporal variation in the association between PM_{10} and mortality.

Methods We applied an extended two-stage time-series design to assess temporal change in the association between PM_{10} and all-cause mortality across 143 cities in 26 countries from 1979 to 2019. In the first stage, city-specific and time-specific associations between PM_{10} and mortality were estimated using quasi-Poisson regression after each city time series was divided into non-overlapping 3-year segments. In the second stage, these estimates were pooled by use of longitudinal random-effects meta-regression with calendar year as a predictor. We further investigated whether selected socioeconomic and environmental factors explained observed temporal trends by including these variables in the second-stage model.

Findings Totally, 23·2 million deaths were analysed. The overall association between PM_{10} and mortality had increased from 1979 to 2019, indicating a stronger association at a given PM_{10} concentration over time. A 10 μg/m^3 increase in daily PM_{10} was associated with a 0·23% increase in all-cause mortality in 1979 (95% CI 0·05–0·41), and this association increased to 0·51% in 2019 (0·36–0·65). Temporal patterns in the PM_{10}–mortality association varied across cities and were positively associated with population ageing over time and negatively associated with annual mean PM_{10} concentrations.

Interpretation The findings of this study suggest that the effect of a given increment of PM_{10} on mortality has increased over time. Applying historical risk estimates could underestimate the current health burden. Continuous updating of evidence on the health impacts of air pollution is essential to ensure accurate and valid estimates.

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School of the Environment, Yale University, New Haven, CT, USA (Y Choi PhD, G Byun PhD, R Stewart PhD, S Heo PhD, Prof M L Bell PhD); Division of Environmental and Occupational Health Sciences, School of Public Health, University of Illinois Chicago, Chicago, IL, USA (Prof H Kim PhD); Institute for Environmental Science and Policy, University of Illinois Chicago, Chicago, IL, USA (Prof H Kim); Department of Urban Planning and Design, Faculty of Architecture, The University of Hong Kong, Hong Kong, China (Prof Y Song PhD); Interdisciplinary Program in Precision Public Health, Department of Public Health Sciences, Korea University, Seoul, South Korea (Prof J-T Lee PhD); School of Health Policy and Management, Korea University, Seoul, South Korea (Prof J-T Lee); National Institute of Environmental Health, Chinese Center for Disease Control and Prevention, Beijing, China (Prof S Tong PhD); School of Public Health and Social Work, Queensland University of Technology, Brisbane, QLD, Australia (Prof S Tong); School of Epidemiology and Public Health, University of Ottawa, Ottawa, ON, Canada (Prof E Lavigne PhD); Environmental Health Science and Research Bureau, Health Canada, Ottawa, ON, Canada (Prof E Lavigne); Centro Latinoamericano de Excelencia

Introduction

Ambient particulate matter (PM) is a major public health burden worldwide. According to the Global Burden of Disease study, PM ranked as the fourth highest risk factor, contributing to 4·72 million deaths globally in 2021.[1] Short-term exposure to PM is associated with adverse health outcomes, including increased mortality,[2,3] and the PM–mortality association varies across populations and locations.[2,4] However, potential temporal changes in this association are unclear, as most previous studies have implicitly assumed that the PM–health relationship remains constant over time.[1,5,6] Here, the temporal change does not refer to PM concentrations but to the health impact associated with a given PM concentration (ie, the relative risk).

Several mechanisms can drive temporal changes in the health impacts of PM. First, PM is a complex mixture whose toxicity depends on chemical composition.[7] As emission sources change over time, PM composition and associated health impacts likely shift. Second, the effects of PM depend on population characteristics. For example, health impacts tend to be greater among older adults (aged 65 years and older) and socioeconomically disadvantaged populations, including those with low income

en Cambio Climático y Salud, Universidad Peruana Cayetano Heredia, Lima, Peru (N Valdés Ortega MSc); Department of Public Health, Universidad de los Andes, Santiago, Chile (Prof P Matus Correa PhD); Department of Environmental Health, University of São Paulo, São Paulo, Brazil (S Osorio PhD); Department of Primary Care and Population Health, University of Nicosia Medical School, Nicosia, Cyprus (Prof S Achilleos PhD); Institute of Atmospheric Physics, Czech Academy of Sciences, Prague, Czech Republic (Prof J Kyselý PhD, Prof A Urban PhD); Faculty of Environmental Sciences, Czech University of Life Sciences, Prague, Czech Republic (Prof J Kyselý, Prof A Urban); Climate Research Foundation (FIC), Madrid, Spain (D Roye PhD); Centro de Investigación Biomédica en Red de Epidemiología y Salud Pública (CIBERESP), Madrid, Spain (D Roye); Department of Family Medicine and Public Health, University of Tartu, Tartu, Estonia (Prof H Orru PhD); Estonian Environmental Research Centre, Tallinn, Estonia (M Maasikmets PhD); Center for Environmental and Respiratory Health Research, University of Oulu, Oulu, Finland (Prof J J K Jaakkola PhD, N Ryti PhD); Medical Research Center Oulu, Oulu University Hospital and University of Oulu, Oulu, Finland (Prof J J K Jaakkola, N Ryti); Santé Publique France, Department of Environmental and Occupational Health, Saint Maurice, France (M Pascal PhD); Institute of Epidemiology, Helmholtz Zentrum München, German Research Center for Environmental Health, Neuherberg, Germany (A Schneider PhD, S Breitner PhD); Chair of Epidemiology, Institute for Medical Information Processing, Biometry, and Epidemiology (IBE), LMU Munich, Munich, Germany (S Breitner); Department of Hygiene, Epidemiology and Medical Statistics, National and Kapodistrian University of Athens, Athens, Greece (Prof K Katsouyanni PhD, Prof E Samoli PhD); Environmental Research Group,

Research in context

Evidence before this study

We searched PubMed, Web of Science, Scopus, and Google Scholar for studies examining temporal changes in the association between PM_{10} exposure and mortality. Search terms included “temporal variation”, “temporal heterogeneity”, “temporal trend”, “temporal change”, “mortality”, “death”, “PM_{10}”, and “particulate matter”. We included population-based epidemiological studies assessing temporal changes in PM_{10}-related health effects, and excluded studies that did not examine PM_{10}-specific associations, did not assess temporal changes, or focused on individual physiological measurements such as peak expiratory flow. Few studies examined temporal changes within specific countries, and their findings varied across locations. One multicountry study was identified, but it did not report a significant temporal change with regards to the association between PM_{10} and mortality. We found no studies that have examined factors potentially influencing such temporal changes on an international scale.

Added value of this study

We found that the mortality effects associated with PM_{10} exposure increased over time across 143 cities in 26 countries. In this multicountry analysis, we identified significant temporal changes in the association between PM_{10} and mortality. Compared to a previous international study, our analysis benefits from a longer overall study period and longer duration of data available for individual cities. Additionally, temporal trends suggest that socioeconomic and environmental factors, such as the increasing proportion of older adults (aged 65 years or older) and changing ambient PM_{10} concentrations, partly explain the observed changes.

Implications of all the available evidence

Our findings suggest that the association between PM_{10} exposure and mortality is not static but has increased over time and is associated with factors such as population ageing and changes in ambient PM_{10} concentrations. Applying historical risk estimates to contemporary populations could lead to a systematic underestimation of the current health burden, although the overall health burden attributable to PM_{10} depends on other factors that might change over time (eg, pollution level, population characteristics). Continuous updating of evidence on the health impacts of air pollution is essential to ensure accurate and valid estimates.

than others.[4,8] Thus, PM health impacts could change as populations age and socioeconomic conditions shift. Third, environmental conditions such as temperature or greenness influence the PM–health association.[9]

Few studies have investigated temporal changes in PM effects on mortality, and results are highly heterogeneous. Evidence from China, Greece, and South Korea suggests increasing associations, whereas studies from the USA, Germany, and Japan report decreasing effects.[10–15] The reasons for these discrepancies remain unclear, and comparing findings is challenging because of substantial variation in analytical methods. Moreover, the respective data originate predominantly from high-income countries, which limits generalisability and applicability to low-income and middle-income countries. Addressing these gaps requires multicountry studies applying a consistent analytical framework across diverse populations.

In this study, we aimed to examine whether mortality risk associated with PM_{10} has changed over time, using data from 143 cities in 26 countries. We further examined whether temporal changes in socioeconomic or environmental conditions could explain any temporal variation in the association between PM_{10} and mortality. Although $PM_{2·5}$ is also associated with health, we focused on PM_{10} because monitoring data are available over longer and more widespread time series and include the coarse fraction, which has distinct health effects beyond those attributable to $PM_{2·5}$ alone. Moreover, PM_{10} remains a key regulated air quality standard in many countries and serves as the primary metric when $PM_{2·5}$ data are unavailable.

Methods

Study design

This multicountry, multicity time-series study included 26 countries and 143 cities with data collected between Jan 1, 1979, and Dec 31, 2019. To examine temporal changes in the association between PM_{10} and mortality, we applied an extended two-stage design that can be used in a longitudinal setting.[19,20] This design separates the analysis into two parts: estimating location-specific and time-specific exposure-response associations and pooling the resultant estimates with linear predictors of the calendar year.

This study did not require institutional review board approval, as confirmed by the Yale University institutional review board (protocol ID: 2000036560). Written informed consent from individuals was not required owing to the nature of the study.

PM_{10}, temperature, and mortality data

Daily mean PM_{10}, temperature, and all-cause mortality counts for 143 cities in 26 countries (1979–2019) were obtained from the Multi-Country Multi-City (MCC) Collaborative Research Network. The MCC network is an international collaboration of researchers to compile city-level environmental and mortality data from official national or governmental sources.[2] Air pollution and meteorological data were collected from fixed-site monitoring stations operated by public authorities, and mortality data from national or regional death registries. Each city had at least one monitoring station. When data from multiple stations were available, we averaged daily values across stations to obtain a single city-level PM_{10} and temperature series, which we matched to the daily all-cause mortality for that city. Although the overall study period spanned 1979 through 2019, the specific study periods varied by city because of data availability (appendix pp 10–12)). Further details on the data are provided in the appendix (pp 5–8).

Explanatory variables

We gathered information that could be related to the temporal changes in the association between PM_{10} and mortality. Annual statistics on population size, the percentage of the population aged 65 years or older, and per capita gross domestic product for each city during the study period were sourced from open-source datasets, including the Organization for Economic Co-operation and Development, the World Bank, and statistics from national or local governments.[16,17] When city-specific values were unavailable, we used data from larger administrative units (eg, county, metropolitan area, or country). Annual averages of PM_{10} and temperature were calculated from the MCC dataset, and the annual geographical average of the enhanced vegetation index, representing green space density, was derived from NASA MODIS satellite data.[18]

Statistical analysis

Estimating temporal change in PM_{10} effects

In the first stage of the analysis, the study period for each city was divided into smaller datasets, each covering non-overlapping 3-year time windows (2000–02, 2003–05, and so on). Within each window, the associations between PM_{10} and all-cause mortality were estimated using quasi-Poisson generalised additive models. The 2-day moving average of PM_{10} (including the event day and the day before) was used as the main exposure, following a prior MCC analysis.[2] The 2-day average provided the best fit, indicated by the lowest mean generalised cross-validation score.[2] Covariates included a natural spline function with six degrees of freedom (df) for the 4-day moving average of temperature (from lag 0 to 3 days), a natural cubic spline function of time with seven df per year, and an indicator variable for the day of the week.[2]

In the second stage, we modelled the temporal trend in the PM_{10}–mortality association using a longitudinal random-effect meta-regression, accounting for both within-city and between-city variations, with best linear unbiased predictions. This model is an extension of the standard meta-regression model along the lines of a mixed-effects linear model, to further account for the longitudinal structure of the data.[19] With the first-stage estimates for each year (defined as midpoints of 3-year time windows) as the independent variable, we added a linear term for the calendar year indicating the temporal change in the association between PM_{10} and mortality. We also included random intercept terms at the city and country levels. The temporal changes in the association between PM_{10} and mortality were predicted using the coefficient of calendar year for the period 1979 to 2019. The association between PM_{10} and mortality was presented as the percent increase in mortality per 10 $\mu g/m^3$ increment in PM_{10} and their 95% CI.

Explaining the temporal trend

After identifying the temporal trend using the longitudinal random-effect meta-regression model, we extended the model by adding five potential explanatory city-level time-varying variables (per capita gross domestic product, the percentage of the population aged 65 years or older, annual mean PM_{10}, temperature, and enhanced vegetation index) as fixed-effect terms to assess whether they explained part of the temporal variation. We incrementally introduced explanatory variables into the primary model that identified temporal trends in PM_{10} effects. Each variable was first added individually to the primary model, followed by a multivariable model built using forward selection. The significance of the explanatory variable was tested through likelihood ratio tests. Further methodological details are available in appendix (pp 8–9), and R code and simplified synthetic example datasets are available on GitHub and archived on Zenodo.

Sensitivity analysis

We conducted several sensitivity analyses. First, we modified random intercepts to include either city or country levels. Second, we tested 4-year and 5-year time windows (instead of 3 years). Third, we re-estimated trends for three subperiods (1979–92, 1993–2006, and 2007–19) and for the period with the maximum data availability across cities (2000–15). Fourth, we fitted the temporal trend using non-linear terms and varied the df for temperature. Fifth, we adjusted for co-pollutants (SO_2, NO_2, CO, and O_3) and relative humidity, using both station-based observations (where available) and ERA5-Land data for relative humidity. Sixth, we restricted analysis to cities with 20 or more daily deaths. Finally, we tested alternative PM_{10} lags up to 7 days.

Role of the funding source

The funder of the study had no role in study design, data collection, data analysis, data interpretation, or writing of the report.

Results

This study included 23·2 million deaths across 143 cities in 26 countries from 1979 to 2019; the study periods varied among cities owing to data availability. On average, cities recorded 27·2 deaths per day and a daily PM_{10} concentration of 30·6 $\mu g/m^3$. These numbers varied considerably among countries, with the lowest average number of deaths per day recorded at 2·9 in Cyprus and the highest at 134·1 in Iran. Average PM_{10} concentrations ranged from 14·9 $\mu g/m^3$ in Sweden to 88·4 $\mu g/m^3$ in Iran (table 1). Daily mortality and PM_{10} concentration both declined over time. From 2000 to 2015, which is the period with the greatest data availability across cities, average daily deaths decreased from 27·7 to 22·6, and the average PM_{10} concentration decreased from 30·4 to 26·1 $\mu g/m^3$. Country-specific

School of Public Health, Imperial College London, London, UK (Prof K Katsouyanni); School of Public Health, University of Iceland, Reykjavik, Iceland (H K Carlsen PhD); Faculty of Geography and Environmental Sciences, Hakim Sabzevari University, Sabzevar, Iran (Prof A Entezari PhD); Institute of Epidemiology and Social Medicine, University of Münster, Münster, Germany (F Mayvaneh PhD); Braun School of Public Health and Community Medicine, The Hebrew University of Jerusalem, Jerusalem, Israel (R Raz PhD); Department of Epidemiology, Lazio Regional Health Service, Rome, Italy (M Stafoggia PhD, F de'Donato PhD); Department of Global Health Policy, The University of Tokyo, Tokyo, Japan (Prof M Hashizume PhD, Prof C F S Ng PhD); School of Tropical Medicine and Global Health, Nagasaki University, Nagasaki, Japan (Prof L Madaniyazi PhD); Department of Environmental Health, National Institute of Public Health, Cuernavaca, Mexico (Prof M Hurtado Diaz PhD, E E F Arellano MSc); Centre for Sustainability, Environment and Health, National Institute for Public Health and the Environment, Bilthoven, Netherlands (J Klompmaker PhD); Institute for Risk Assessment Sciences, Utrecht University, Utrecht, Netherlands (J Klompmaker); Norwegian Institute of Public Health, Oslo, Norway (S Rao PhD); Department of Environmental Health, Instituto Nacional de Saúde Dr Ricardo Jorge, Porto, Portugal (J Madureira PhD); EPIUnit - Instituto de Saúde Pública, Universidade do Porto, Porto, Portugal (J Madureira); ITR—Laboratório para a Investigação Integrativa e Translacional em Saúde Populacional, Porto, Portugal (J Madureira); Department of Epidemiology, Instituto Nacional de Saúde Dr Ricardo Jorge, Lisbon, Portugal (V Gaio PhD); Public Health Research Center, Escola Nacional de Saúde Pública, Universidade NOVA de Lisboa, Lisbon, Portugal (V Gaio); Comprehensive Health Research

Center, Universidade NOVA de Lisboa, Lisbon, Portugal (V Gaio); Department of Epidemiology and Preventive Medicine, Monash University, Melbourne, VIC, Australia (Prof Y Guo PhD); Climate, Air Quality Research Unit, Monash University, Melbourne, VIC, Australia (Prof Y Guo); Department of Environmental Health, Emory University, Atlanta, GA, USA (Prof N Scovronick PhD); Department of Geography, Geoinformatics and Meteorology, University of Pretoria, Pretoria, South Africa (Prof R M Garland PhD); Graduate School of Public Health, Seoul National University, Seoul, South Korea (Prof H Kim PhD); School of Biomedical Convergence Engineering, Pusan National University, Yangsan, South Korea (Prof W Lee PhD); Department of Public Health and Clinical Medicine, Umeå University, Umeå, Sweden (Prof B Forsberg PhD); Institute of Social and Preventive Medicine, University of Bern, Bern, Switzerland (Prof A M Vicedo-Cabrera PhD); Oeschger Centre for Climate Change Research, University of Bern, Bern, Switzerland (Prof A M Vicedo-Cabrera PhD); Department of Public Health, Environments and Society, London School of Hygiene & Tropical Medicine, London, UK (Prof A M Vicedo-Cabrera, Prof B Armstrong PhD); Swiss Tropical and Public Health Institute, Allschwil, Switzerland (M S Ragettli PhD); University of Basel, Basel, Switzerland (M S Ragettli); Environmental and Occupational Medicine, National Taiwan University, Taipei, Taiwan (Prof Y L Guo); Research Center for Environmental Changes, Academia Sinica, Taipei, Taiwan (Prof Y L Guo, S-C Pan PhD); Graduate Institute of Environmental and Occupational Health Sciences, National Taiwan University, Taipei, Taiwan (Prof Y L Guo); Department of Statistics, Computer Science and Applications "G. Parenti", University of Florence, Florence, Italy (Prof F Sera PhD); Environment and Health

	Number of cities	Period	Total deaths*	Daily mean deaths	Daily mean PM_{10} (μg/m^3)	Daily mean temperature (°C)
Canada	3	2000–2011	140	11·3 (6·5)	17·6 (13·6)	5·3 (12·2)
Chile	2	2004–2013	61	9·5 (5·9)	50·9 (41·6)	13·0 (3·9)
Colombia	1	2002–2013	327	74·6 (10·4)	62·7 (19·3)	13·9 (0·9)
Cyprus	5	2005–2019	74	2·9 (2·4)	43·7 (41·6)	20·6 (6·2)
Czech Republic	1	1994–2009	214	36·6 (7·3)	36·2 (24·6)	8·8 (8·1)
Ecuador	1	2014–2019	67	35·6 (12·2)	43·9 (17·0)	15·5 (1·1)
Estonia	4	2003–2019	105	5·3 (5·2)	16·4 (12·3)	6·2 (9·0)
Finland	1	1994–2014	153	20·0 (4·7)	19·9 (16·4)	6·2 (8·9)
France	20	2000–2017	2034	15·6 (23·8)	22·0 (11·8)	12·7 (6·8)
Germany	13	2000–2019	2521	30·5 (22·0)	22·6 (13·9)	10·5 (7·3)
Greece	1	2001–2010	288	78·9 (12·4)	43·9 (23·5)	18·7 (7·5)
Iceland	1	2002–2018	23	3·7 (2·0)	21·0 (18·9)	5·5 (5·0)
Iran	1	2002–2012	539	134·1 (15·0)	88·4 (47·2)	17·3 (9·9)
Israel	4	2000–2019	373	13·3 (9·4)	51·2 (77·7)	20·6 (6·1)
Italy	13	2006–2015	663	14·2 (17·1)	33·2 (22·0)	15·6 (7·4)
Japan	7	1979–2019	4277	56·6 (56·0)	35·5 (23·9)	15·0 (8·7)
Mexico	4	2000–2012	1530	102·2 (100·5)	52·1 (26·0)	17·1 (3·5)
Norway	1	2000–2018	85	12·4 (3·9)	21·5 (12·4)	5·7 (8·2)
Portugal	4	1999–2018	818	32·0 (21·8)	23·7 (17·2)	15·8 (5·4)
South Africa	1	2004–2013	345	94·4 (17·5)	56·8 (29·9)	16·7 (4·3)
South Korea	7	1999–2015	1662	38·6 (32·0)	52·2 (32·6)	13·9 (9·5)
Sweden	1	1994–2010	161	25·9 (5·6)	14·9 (8·7)	7·2 (8·2)
Switzerland	8	1995–2013	234	4·5 (3·4)	25·3 (16·8)	10·5 (7·6)
Taiwan	3	1994–2014	1210	52·6 (23·0)	63·6 (33·9)	24·0 (4·8)
UK	23	1992–2016	2823	19·6 (39·6)	22·0 (12·2)	10·7 (5·2)
USA	13	1987–2006	2499	35·1 (40·4)	30·2 (18·5)	11·7 (10·3)
Pooled	143	1979–2019	23 226	27·2 (39·0)	30·6 (27·4)	12·9 (8·3)

Data are mean (SD). *Total deaths are expressed in thousands and rounded to the nearest 1000.

Table 1: **Summary of all-cause mortality, PM_{10}, and temperature in 143 cities across 26 countries**

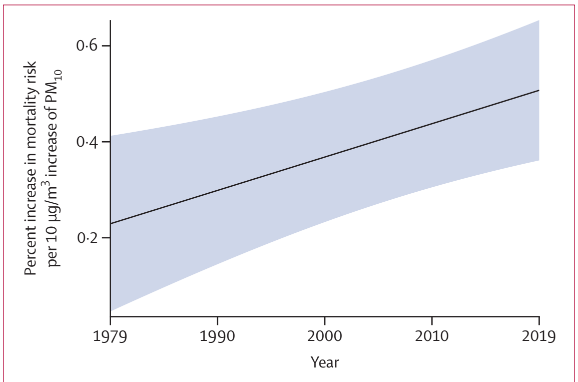

Figure 1: **Estimated temporal trend of the association between PM_{10} and all-cause mortality across 143 cities in 26 countries from 1979 to 2019**

temporal trends in daily mortality and PM_{10} concentration are presented in the appendix (p 19).

Overall, across the 143 cities, the effects of PM_{10} on mortality increased over time. A 10 μg/m^3 increase in PM_{10} was associated with a 0·23% (95% CI 0·05–0·41) increase in all-cause mortality in 1979, which increased to 0·51% (0·36–0·65) in 2019 (figure 1). This increase corresponds to an annual change of 0·0069% (0·0022–0·0117) in mortality risk from a given increment in PM_{10}.

The overall estimate showed an increasing temporal trend, whereas the country-specific analyses revealed heterogeneous results (figure 2). The association between PM_{10} and mortality increased over time in Iceland, Japan, and Portugal (p=0·013, p=0·0002, and p<0·0001, respectively), whereas that in France and South Africa lessened. Some countries, including Canada, Israel, Germany, and the UK, showed no distinct temporal changes in the effects of PM_{10}. The city-level estimates also showed heterogeneous results (appendix p 20).

We examined whether city-specific, time-varying socioeconomic and environmental factors could explain variation in temporal trends of PM_{10} effects. Two variables were significantly associated with the changing PM_{10}-related mortality, ie, the percentage of the population aged 65 years and older (likelihood ratio test p=0·013) and the annual mean PM_{10} concentration (p=0·034). The percentage of the population aged 65 years and older was positively associated with an increased PM_{10}-related mortality risk over time, whereas annual PM_{10} concentrations showed a negative association (table 2). We further attempted to expand the model by including both the population aged 65 years and older and the annual PM_{10} concentration; however, including both explanatory variables simultaneously did not improve the model fit significantly (p=0·25; appendix p 13).

We performed several sensitivity analyses, and the results were consistent. Varying model parameters, using longer time windows, and modelling temporal trends with non-linear terms produced similar estimates (appendix p 14). Stratified analyses using three study-period intervals continued to show increasing temporal trends in PM_{10} effects, although these trends were not statistically significant (p=0·16 for 1979–92, p=0·08 for 1993–2006, and p=0·32 for 2007–19). Similar results were observed when analyses were restricted to the most common period across cities (2000–15; p=0·49), likely reflecting the shorter study periods and reduced statistical power (appendix pp 21–22). Additional adjustment for co-pollutants, adjustment for relative humidity, extension of PM_{10} lag period, and exclusion cities with low mortality counts did not considerably change our results (appendix p 23).

Discussion

We examined the potential change in PM_{10}-related mortality risk using data from 143 cities across 26 countries from 1979 to 2019. The effects of a given increment of PM_{10} concentrations have increased over time. These changes were likely associated with the changes in population structure and PM_{10} concentrations. Our results are consistent with those of previous studies that investigated the temporal heterogeneity in of PM_{10}– mortality associations. Similar increases in all-cause mortality were observed in Seoul, South Korea,[12,21] and Athens, Greece, in the early 2000s.[14] By contrast, Renzi and colleagues[22] did not observe a clear temporal pattern in Rome, Italy, from 1998 to 2014, consistent with our country-specific results for Italy (p=0·79). In the eastern USA, the effects of PM_{10} on mortality decreased from 1987 to 2000.[11] A different study reported that the risk of respiratory hospitalisation per 10 μg/m^3 increase in $PM_{2·5}$ decreased from 1999 to 2008 but then increased until 2016.[23] Another study found that the association between $PM_{2·5}$ and circulatory hospitalisations increased over time in 968 USA counties from 2000 to 2016.[24] Our results also showed a heterogeneous temporal trend within the USA.

A 2024 multicountry study using MCC data examined temporal changes in mortality effects associated with air pollutants.[25] This previous analysis investigated temporal variations in the associations of PM_{10}, $PM_{2·5}$, and NO_2 with circulatory and respiratory mortality across 380 cities in 24 countries from 1995 to 2016, reporting an increasing effect of $PM_{2·5}$ on circulatory mortality over time. Although their findings for PM_{10} were not significant (p=0·71), the direction of the observed associations suggested an increasing temporal trend in the effects of PM_{10} on respiratory and cardiovascular mortality. Compared with this previous study, our analysis benefits from a longer overall study period (41 *vs* 22 years) and a more extended duration of data available per city (at least 9 years *vs* at least 5 years). Furthermore, our study provided evidence for all-cause mortality, and we examined the factors behind temporal changes, considering both spatial and temporal dimensions, which are aspects that were not previously investigated. Despite some differences, both studies suggest that the effects of PM on mortality have increased over time.

Several factors can explain the increasing impact of PM_{10} on mortality over time, including changes in PM composition, population characteristics, and other environmental conditions. In our study, population ageing appeared to be an important contributor to the increasing PM_{10}–mortality association over time. Adults aged 65 years and older are generally more susceptible to air pollution than those younger than 65 years at the same exposure level, and the proportion of older adults is increasing in many populations because of longer life expectancy and declining fertility.[4] As societies age, a larger share of the population could become vulnerable to PM_{10}, which could contribute to higher mortality risks associated with PM_{10} over time.

Our findings also suggest that the temporal changes in the mortality effect of PM_{10} might be related to changes in PM_{10} characteristics over time. In the extended model, annual PM_{10} concentration was included as a proxy for such changes, and decreasing PM_{10} concentrations over time were significantly (p=0·034) associated with stronger mortality effects. Previous studies have reported that reductions in PM mass are not uniform across all chemical components and that some species decline preferentially depending on their emission sources.[26,27] Reductions in ambient PM_{10} concentrations changing PM chemical composition could affect PM toxicity and thereby influence mortality; however, confirming this hypothesis will require studies incorporating detailed compositional data.

These findings could relate to the dose–response relationship between PM_{10} and mortality. The mortality effects of $PM_{2·5}$ are reported as supralinear, characterised by a steep slope at low concentrations, followed by a decrease in the slope at higher concentrations.[28,29] A reduction in PM_{10} concentration over time might have resulted in lower mortality effects, in line with the supralinear dose–response association.

This study has some limitations. This is a multicountry analysis; however, the geographical distribution is skewed towards the northern hemisphere, and data remain insufficient for regions such as Australia, Africa, South America, and central and west Asia. Additionally, the included study areas were predominantly urban and located in high-income or middle-income countries. The temporal trend of health risks from PM may differ in non-urban environments and low-income countries. Likewise, differences in temporal trends based on individual characteristics, such as age, sex, and socioeconomic position, could not be investigated because of the scarcity of data. Future research is needed to investigate temporal trends in PM_{10} risks for other populations and parts of the world, possibly with daily modelled pollution estimates, which introduce uncertainty

Modelling Lab, London School of Hygiene & Tropical Medicine, London, UK (Prof A Gasparrini PhD, Prof P Masselot PhD, M Mistry PhD)**; Department of Economics, Ca' Foscari University of Venice, Venice, Italy** (M Mistry)**; Department of Environmental Health, Harvard TH Chan School of Public Health, Boston, MA, USA** (A Zanobetti PhD, Prof J Schwartz PhD)

Correspondence to: Dr Yongsoo Choi, School of the Environment, Yale University, New Haven, CT 06511, USA **yongsoo.choi@yale.edu**

See **Online** for appendix

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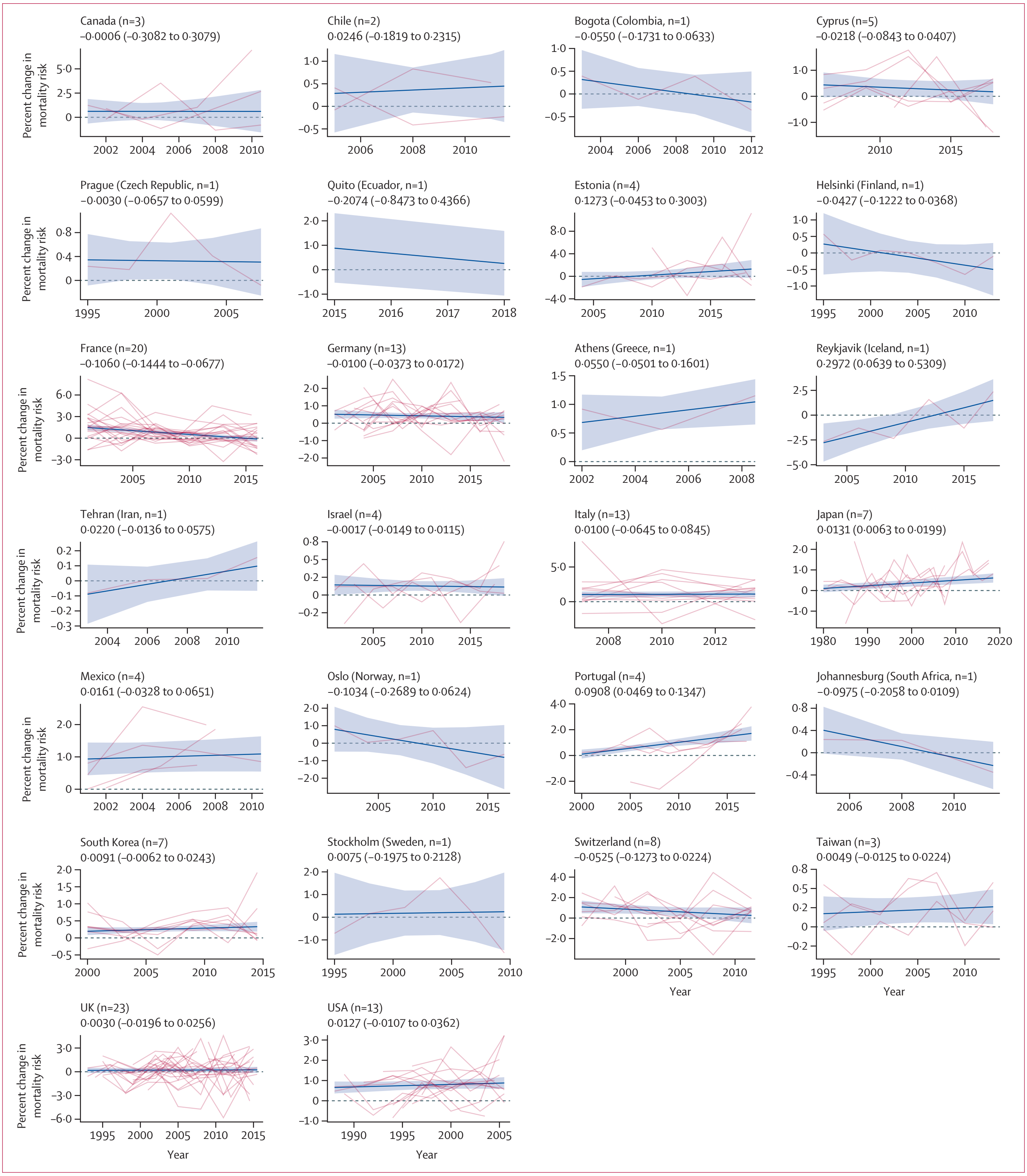
Canada (n=3)
−0·0006 (−0·3082 to 0·3079)
Chile (n=2)
0·0246 (−0·1819 to 0·2315)
Bogota (Colombia, n=1)
−0·0550 (−0·1731 to 0·0633)
Cyprus (n=5)
−0·0218 (−0·0843 to 0·0407)
Prague (Czech Republic, n=1)
−0·0030 (−0·0657 to 0·0599)
Quito (Ecuador, n=1)
−0·2074 (−0·8473 to 0·4366)
Estonia (n=4)
0·1273 (−0·0453 to 0·3003)
Helsinki (Finland, n=1)
−0·0427 (−0·1222 to 0·0368)
France (n=20)
−0·1060 (−0·1444 to −0·0677)
Germany (n=13)
−0·0100 (−0·0373 to 0·0172)
Athens (Greece, n=1)
0·0550 (−0·0501 to 0·1601)
Reykjavik (Iceland, n=1)
0·2972 (0·0639 to 0·5309)
Tehran (Iran, n=1)
0·0220 (−0·0136 to 0·0575)
Israel (n=4)
−0·0017 (−0·0149 to 0·0115)
Italy (n=13)
0·0100 (−0·0645 to 0·0845)
Japan (n=7)
0·0131 (0·0063 to 0·0199)
Mexico (n=4)
0·0161 (−0·0328 to 0·0651)
Oslo (Norway, n=1)
−0·1034 (−0·2689 to 0·0624)
Portugal (n=4)
0·0908 (0·0469 to 0·1347)
Johannesburg (South Africa, n=1)
−0·0975 (−0·2058 to 0·0109)
South Korea (n=7)
0·0091 (−0·0062 to 0·0243)
Stockholm (Sweden, n=1)
0·0075 (−0·1975 to 0·2128)
Switzerland (n=8)
−0·0525 (−0·1273 to 0·0224)
Taiwan (n=3)
0·0049 (−0·0125 to 0·0224)
UK (n=23)
0·0030 (−0·0196 to 0·0256)
USA (n=13)
0·0127 (−0·0107 to 0·0362)
Percent change in mortality risk
Year

Figure 2: **Country-specific temporal trend of the association between PM_{10} and all-cause mortality across 143 cities in 26 countries from 1979 to 2019**
The x-axis scale differs across the panels because the study period differs for all countries. The blue line shows the overall temporal trend, and the red lines indicate temporal trend for individual cities. The x-axis represents calendar year, and the y-axis shows the percent change in all-cause mortality risk per 10-μg/m^3 increase in PM_{10}. Panels are ordered alphabetically by country name. For countries represented by only one city, the city name appears in the panel label. *n* denotes the number of available cities, and the numbers beneath each country name indicate the percent change in the PM_{10}–mortality risk per year, along with their 95% CIs. PM=particulate matter.

	Percent change in PM_{10}–mortality risk (95% CI)		p value‡
	Calendar year*	Second variable†	
Calendar year	0·0069% (0·0022 to 0·117)	··	Ref
Calendar year + per capita GDP	0·0027% (–0·0040 to 0·0093)	0·047% (–0·005 to 0·098)	0·086
Calendar year + population number	0·0067% (0·0020 to 0·0115)	0·014% (–0·002 to 0·029)	0·084
Calendar year + percentage of population aged ≥65 years	0·0011 (–0·0053 to 0·0076)	0·112% (0·026 to 0·198)	0·013
Calendar year + PM_{10} concentration	0·0041% (–0·0013 to 0·0094)	–0·067% (–0·127 to –0·007)	0·034
Calendar year + temperature	0·0069% (0·0021 to 0·0117)	0·010% (–0·101 to 0·122)	0·857
Calendar year + EVI	0·0059% (0·0009 to 0·0109)	–0·045% (–0·106 to 0·016)	0·157

EVI=enhanced vegetation index. GDP=gross domestic product. Ref=reference. *Percent change in PM_{10}–mortality risk by 1 year. †Percent change in PM_{10}–mortality risk per IQR increase. The IQR values are as follows: per capita GDP: US$21 629; population number: 1 824 096; percentage of the population aged 65 years and older: 5·9%; PM_{10} concentration: 16·7 μg/m^3; temperature: 4·9°C; EVI: 0·10. ‡p value for likelihood ratio test.

Table 2: **Results of longitudinal random-effects meta-regression of PM_{10}–mortality risk per IQR increase in each explanatory variable**

but may allow analysis in locations without monitoring data. Additionally, our data show high variability across countries. In some countries, data were available for dozens of cities, whereas in others, only one or two cities were covered. Caution should be exercised when extrapolating results from a few cities to the country level and when comparing results among countries. As our data cover an extended time period, improvements in death registration systems and in environmental monitoring over time may have affected data comparability and introduced additional uncertainty into our estimates.

Although the temporal trends in PM_{10} effects were highly heterogeneous across countries and cities, we were not able to fully explain these differences. We accounted for some variation using a small set of socioeconomic variables; however, many potentially important influences could not be incorporated because of data constraints. For example, changes in PM chemical composition, improvements in medical infrastructure, public health interventions, and patterns of urbanisation could all modify the health impacts of PM_{10} over time. Future studies with more comprehensive data, including $PM_{2.5}$ and detailed information on its chemical composition, are needed to better understand these temporal trends. In addition, for some explanatory variables, city-specific information was unavailable; therefore, we used data from larger administrative units as proxies, which may have introduced misclassification. Further work should investigate how temporal trends in the concentration–response function interact with other determinants of overall health burden, including shifts in population demographics (eg, age distribution), subpopulation-specific responses, pollution levels, urbanicity, and other time-variant factors.

The ambient PM_{10} concentrations and temperature measurements were obtained from fixed-site environmental monitors rather than personal exposure and, therefore, do not account for indoor or outdoor activity patterns, which can lead to exposure misclassifications. Although such detailed exposure assessment is not feasible at this scale of population and over long timeframes, more focused studies are warranted.

Lastly, in our two-stage design, the number of time-window estimates available for each city in the second-stage analysis was relatively small, limiting the statistical power to estimate temporal trends and to fit models with multiple explanatory variables. In addition, the proportions of the population aged 65 years or older and the annual PM_{10} concentration were moderately correlated over time, leading to imprecise estimates when both variables were included in the same model.

Understanding temporal heterogeneity in PM_{10} health effects is essential, as such insights can inform evidence-based policy making and help to implement effective and efficient strategies to reduce the health burden of PM. Many air quality policies are currently established on the assumption that the health effects of PM remain constant, focusing solely on changes in PM concentrations. However, our findings call this assumption into question by providing evidence that the relationship between PM_{10} and mortality can also shift over time.

The health effects of PM have been extensively researched for nearly seven decades. Previous studies have shown that the effects of PM can differ based on population characteristics, geographical location, and PM composition or source.[30,31] However, it is unclear how these risks can evolve over time. Additionally, questions remain about whether risk estimates from past decades are still applicable today. Our study addresses this gap by revealing that reliance on historical estimates can lead to biased conclusions, undermining the accuracy of evidence-based decisions. Moreover, our findings indicate that the effects of PM_{10} on mortality have increased over time, suggesting that using historical risk estimates might underestimate the current disease burden attributable to PM; however, the overall burden is also a function of other factors that change over time, such as pollutant concentration and the shifts in demographics patterns related to vulnerability (eg, age distribution). Our results suggest that even in places where air pollution levels have improved, the actual health burden attributable to PM may not have diminished as expected because of an increase in the health effects of PM.

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The world is changing rapidly. Climate change is altering our environment, and the population is ageing and becoming more urbanised.[32] In this context, future risks associated with PM are likely to differ from those observed today. Accurately predicting the future health burden is therefore crucial, and understanding the temporal changes in PM–mortality risk would provide valuable information for more accurately predicting future risk.

In conclusion, this study provides evidence that the association between PM_{10} and mortality changes over time, with the effects of PM_{10} on mortality becoming more pronounced. Population ageing and changes in ambient PM_{10} concentrations partly explain this trend. These findings suggest that current policy estimates of air quality might underestimate the actual health burden attributable to PM_{10} if they rely on historical risk estimates, although the overall health burden also relates to factors that vary over time (eg, pollutant levels and age distribution). Our results underscore the need to continuously update understanding of air pollution and its evolving health risks to ensure that policy interventions remain effective and responsive.

Contributors

MLB is the senior author. YC, MLB, AG, FS, J-TL, GB, and HHK designed the study. YC and GB performed the statistical analysis, and YC took the lead in drafting the manuscript. MLB, GB, HHK, RS, SH, SB, MS, FDD, VG, YG, BA, FS, AG, PM, and MMI provided substantial input in interpreting the results and in editing and revising the draft. YS, ST, EL, NVO, PMC, SO, SA, JKY, AU, DR, HO, MMA, JJKJ, NR, MP, AS, SB, KK, ES, HKC, AE, FM, RR, MS, FDD, MH, CFSN, LM, MHD, EEFA, JKL, SR, JM, VG, YG, NS, RMG, HOK, WL, BF, AMVC, MSR, YLG, S-CP, BA, FS, AG, PM, MMI, AZ, JS, and MLB provided the data. YC and MLB accessed and verified the underlying data. The corresponding author had full access to all the data in the study and had final responsibility for the decision to submit for publication. The corresponding author attests that all listed authors meet authorship criteria and that no others meeting the criteria have been omitted.

Declaration of interests

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Data sharing

Data were collected within the MCC Collaborative Research Network and are not publicly available owing to restrictions imposed by the data sharing agreement with the MCC participants of the included countries. R code and simplified synthetic example datasets are available on GitHub and archived on Zenodo. The example datasets are provided for illustrative purposes only and do not contain any information derived from the analytic dataset.

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