Supplementary material

Contents

Data collection

We collected station-observed particulate matter with diameters ≤2.5 µm ($PM_{2.5}$) from 5446 monitoring stations in 2000-2019. Information regarding the distribution of included monitoring stations and the sources of data can be found in the previous study.[1] To ensure the comparability of health risks estimated from observed and estimated $PM_{2.5}$ sources, our study was limited to Multi-City Multi-Country (MCC) cities where both station-observed $PM_{2.5}$ and corresponding model-estimated values were available during the study period. We disregarded the data from monitoring stations located beyond the boundaries of the MCC cities or those whose data fell outside the recording period. Finally, 1710 stations were involved in 347 MCC cities. We excluded the extreme outliers above 99.9th quantiles of the collected $PM_{2.5}$ monitoring dataset. In addition, we gathered data on the daily mean temperature and daily mean relative humidity in the 347 MCC cities from the EAR5 dataset (the fifth-generation European Centre for Medium-Range Weather Forecasts Reanalysis). [2] For the grid-based model-estimated $PM_{2.5}$ exposure, comprehensive details regarding the validation of the global daily $PM_{2.5}$ concentrations can be found in our previous study[1].

Sensitivity analysis method

Several sensitivity analyses were conducted to test the robustness of the exposure-response (E-R) relationship estimations. We examined potential non-linearity in the E-R associations between short-term $PM_{2.5}$ exposure and mortality from both observed and estimated $PM_{2.5}$ concentrations. Specifically, a B-spline function with two knots of mean $PM_{2.5}$ concentration was used for all 347 MCC cities, and the overall non-linear E-R relationship curves were pooled and compared. A multivariate meta-regression method was employed to examine the statistical differences in the E-R relationships from observed and estimated daily $PM_{2.5}$ data. Furthermore, we used different knots and degree of freedom for temperature and $PM_{2.5}$ concentrations, as well as extending the maximum lag days from two to five days to examine the robustness of our estimations. To examine the applicability of the model-estimated $PM_{2.5}$ in health risk assessment outside the 5446 monitoring stations, we examine the disparities in model-estimated $PM_{2.5}$ for mortality risk assessment by comparing them with another external MCC monitor station data sources. Specifically, we selected MCC cities where the monitoring stations were not included in the Deep Ensemble Machine Learning model training. We then compared the disparities in E-R estimates derived from both model-estimated exposure and station-observed $PM_{2.5}$ data. Ultimately, our validation analysis encompasses 81 MCC cities across 11 countries, with a cumulative total of over 4.4 million all-cause deaths. The details regarding the included MCC cities and countries can be found in Table S6.

All statistical analyses were performed using R software (version 4.0.1). The Spearman correlation analysis was conducted to test the correlation between monitoring station-observed and model-estimated daily $PM_{2.5}$ concentrations at city and country levels.

Meta-regression method

We used the multivariate meta-regression method to examine the statistical differences in the E-R relationships from station-observed and model-estimated daily $PM_{2.5}$ data. Here, we outlined a procedure for conducting the meta-regression approach. Initially, we computed the effect size (Relative Risk Increase, RRI) and its corresponding standard error for each city. Subsequently, a binary indicator (x) was introduced, where '1' signifies RRI based on station-observed $PM_{2.5}$ data and '0' indicates those relying on model-estimated data. The ‘mixmeta’ R function was employed to develop a meta-regression model to examine if the effect size varies depending on whether $PM_{2.5}$ data is observed or estimated. Finally, by examining the coefficient of 'x' and its associated *P*-value from the meta-regression output, we ascertained the statistical differences in the E-R relationships from observed and estimated daily $PM_{2.5}$ exposure. We provided an example data (see Table S1) and the R code to illustrate how to conduct meta-regression model to examine the statistical differences in the E-R relationships from station-observed and model-estimated daily $PM_{2.5}$ data.

Table S1. Example data for meta regression

City	ISO3	coef	vcov	type
Winston	USA	0.025689	2.89E-05	model
Winston	USA	0.012943	1.82E-05	station
Worcester	USA	0.029642	1.53E-05	model
Worcester	USA	0.020381	1.03E-05	station
Warrington	GBR	0.002961	3.29E-05	model
Warrington	GBR	0.013875	2.36E-05	station

WDC	USA	0.034593	1.18E-05	model
WDC	USA	0.02491	8.39E-06	station
Washington	USA	0.003676	3.50E-05	model
Washington	USA	0.006518	2.11E-05	station
West Midlands	GBR	-0.00591	1.89E-06	model
West Midlands	GBR	-0.00476	1.55E-06	station
West Yorkshire	GBR	-0.00016	2.90E-06	model
West Yorkshire	GBR	-0.0006	2.15E-06	station
Youngstown	USA	0.010351	1.57E-05	model
Youngstown	USA	0.005055	1.06E-05	station
Yorktown	GBR	-0.01519	4.00E-05	model
Yorktown	GBR	-0.00467	3.03E-05	station
york	USA	0.004386	1.86E-05	model
york	USA	-0.01022	9.18E-06	station

Notes: The coef and vcov are the coefficient and variance-covariance matrix for each city obtained by the first stage city-specific daily fine particulate matter ($PM_{2.5}$) E-R associations using a quasi-Poisson regression.

R code for meta-regression

```
model_test_example <- mixmeta(coef~ 1+type, vcov, data=df, method="ml")

p <- summary(model_test_example)$coefficients[,4][2]
```

Study strengths

This study has several strengths. To the best of our knowledge, our study is the first to estimate the mortality effect of short-term $PM_{2.5}$ exposure from both station-observed and model-estimated daily $PM_{2.5}$ observations from 347 cities worldwide. We used a large dataset of over 15.8 million deaths over a long period of approximately 20 years to estimate the mortality associations with $PM_{2.5}$ short-term daily exposure. Moreover, we examined the global daily $PM_{2.5}$ model estimations with a high spatial resolution of $0.1°\times0.1°$ to evaluate the association between mortality risks and short-term $PM_{2.5}$ exposure. The E-R estimates using model-estimated data were consistent with that from station-observed data. These comparative analyses offer compelling evidence for the use of the estimated global $PM_{2.5}$ data in future epidemiological health risk assessments. Furthermore, we employed external MCC monitoring stations to further validate our model-estimated exposure-mortality risk assessment, yielding robust results. It should be noted that utilizing model-estimated $PM_{2.5}$ in conjunction with data from more monitoring stations globally could potentially lead to even more unbiased estimates, making it a promising area for future exploration.

Supplementary results

Figure S1. The correlation between station-observed and model-estimated daily $PM_{2.5}$ in the study period in 2000-2019

Notes: $PM_{2.5}$: particulate matter with a diameter of < 2.5 μm; Correlation coefficient was based on Spearman correlation analysis.

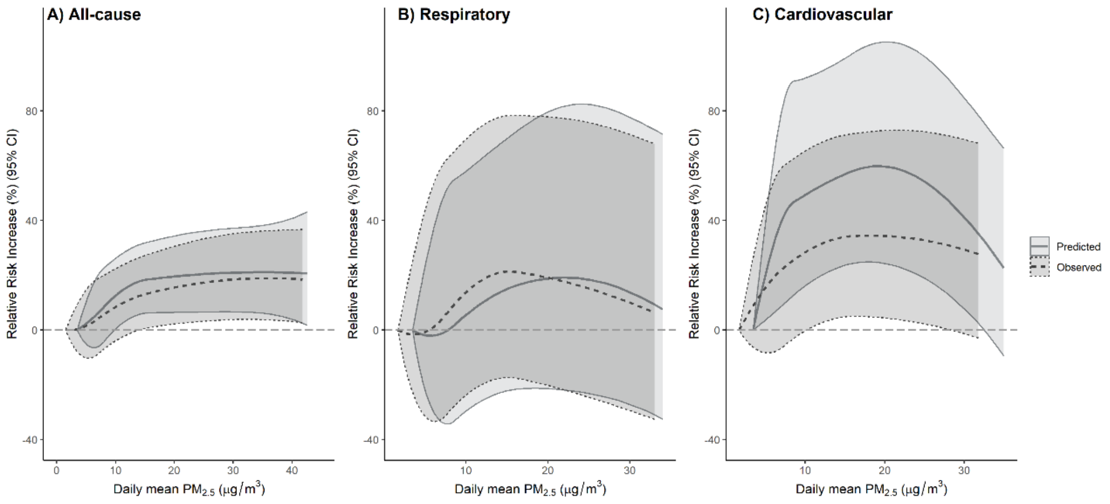

Figure S2. The non-linear exposure-response relationships of station-observed and model-predicted $PM_{2.5}$ with all-cause, respiratory, and cardiovascular mortality

Notes: $PM_{2.5}$: particulate matter with a diameter of < 2.5 µm.

Table S2. The summary of the included cities and the consistency between station-observed and model-estimated daily fine particulate matter ($PM_{2.5}$) in the study period

Country & region	No. of cities	Start date	End date	Study period (year)	R^2	RMSE
Australia	40	1/01/2009	31/12/2017	9	0.53	3.26
China	3	27/11/2013	31/12/2015	2.1	0.98	6.74
Czechia	4	1/01/2004	31/12/2015	12	0.76	9.98
Finland	1	1/01/2001	31/12/2014	14	0.74	2.80
France	19	1/01/2011	31/12/2015	5	0.82	4.94
Germany	8	1/01/2003	31/12/2015	13	0.85	4.39
Italy	3	1/01/2013	31/12/2015	2.7	0.64	8.70
Netherlands	5	1/01/2013	31/12/2016	4	0.96	1.86
Norway	1	1/01/2003	31/12/2018	16	0.79	2.80
Portugal	2	9/03/2002	31/12/2018	16.8	0.66	7.40
Spain	16	1/01/2004	31/12/2014	11	0.64	4.63
Sweden	3	8/01/2002	31/12/2016	15	0.74	3.32
Taiwan	6	21/12/2016	31/12/2018	2	0.84	4.88
United Kingdom	30	12/01/2000	31/12/2016	17	0.82	3.88
USA	206	1/01/2000	31/12/2006	7	0.79	3.89
Total	347	1/01/2000	31/12/2018	8.3	0.82	4.31

Notes: R^2: coefficients of determination; RMSE: Root Mean Square Error.

Table S3. The comparison of pooled RRIs (%) for all-cause, respiratory, and cardiovascular mortality associated with a 10 μg/m^3 increase in station-observed and model-estimated daily mean fine particulate matter (PM$_{2.5}$) by country

Country & Region	All-cause		Respiratory		Cardiovascular	
	Observed PM$_{2.5}$	Estimated PM$_{2.5}$	Observed PM$_{2.5}$	Estimated PM$_{2.5}$	Observed PM$_{2.5}$	Estimated PM$_{2.5}$
Australia	1.17 (-1.36, 3.77)	-0.72 (-6.27, 5.15)	4.28 (-4.66, 14.05)	3.10 (-18.50, 30.44)	3.31 (-3.55, 10.65)	4.22 (-7.37, 17.26)
China	0.39 (0.04, 0.74)	0.42 (0.06, 0.78)	0.61 (-0.26, 1.49)	0.71 (-0.30, 1.73)	0.23 (-0.09, 0.56)	0.25 (-0.10, 0.59)
Czechia	0.18 (-0.01, 0.37)	-0.02 (-0.21, 0.18)	0.51 (-0.20, 1.23)	0.53 (-1.04, 2.13)	-0.08 (-0.38, 0.22)	-0.42 (-0.85, 0.01)
Finland	0.98 (0.48, 1.48)	0.93 (0.37, 1.50)	1.33 (-0.79, 3.51)	1.40 (-1.04, 3.89)	0.89 (0.08, 1.70)	0.35 (-0.57, 1.27)
France	0.59 (-0.07, 1.25)	0.45 (-0.38, 1.29)	0.86 (-0.54, 2.27)	0.68 (-1.23, 2.63)	NA	NA
Germany	0.22 (-0.05, 0.48)	0.24 (0.06, 0.43)	NA	NA	NA	NA
Italy	2.07 (-0.38, 4.58)	1.59 (0.37, 2.83)	NA	NA	NA	NA
Netherlands	-0.08 (-0.81, 0.65)	-0.32 (-1.23, 0.60)	NA	NA	NA	NA
Norway	-1.06 (-1.61, -0.52)	-1.16 (-1.88, -0.43)	-1.57 (-3.35, 0.24)	-3.90 (-6.36, -1.38)	-0.78 (-1.79, 0.25)	-1.05 (-2.50, 0.42)
Portugal	0.11 (-0.07, 0.30)	0.53 (0.23, 0.83)	-0.15 (-0.83, 0.54)	-0.59 (-1.09, -0.08)	0.06 (-0.13, 0.24)	0.26 (-0.03, 0.55)
Spain	-0.97 (-2.55, 0.64)	-0.48 (-1.84, 0.89)	-0.19 (-4.26, 4.05)	-0.94 (-4.97, 3.25)	-2.29 (-4.94, 0.43)	-0.84 (-3.59, 1.99)
Sweden	-0.05 (-1.27, 1.19)	0.42 (0.02, 0.83)	-0.22 (-4.56, 4.33)	-1.23 (-5.10, 2.80)	0.45 (-0.23, 1.13)	0.49 (-0.18, 1.16)
Taiwan	0.11 (-0.75, 0.99)	-0.27 (-1.50, 0.98)	0.10 (-3.19, 3.51)	0.38 (-3.57, 4.50)	-1.39 (-2.99, 0.24)	-1.68 (-4.08, 0.78)
United Kingdom	0.49 (0.12, 0.86)	0.57 (0.07, 1.07)	0.47 (-0.63, 1.59)	0.51 (-0.91, 1.96)	0.75 (-0.02, 1.53)	0.78 (-0.21, 1.77)
USA	0.86 (0.68, 1.04)	1.17 (0.92, 1.43)	0.68 (-0.03, 1.40)	1.08 (0.11, 2.06)	0.56 (0.23, 0.89)	0.89 (0.45, 1.33)

Notes: PM$_{2.5}$: particulate matter with a diameter of < 2.5 μm; RRI: relative risk increase; Values in brackets are 95% confidence interval.

Table S4. The pooled RRIs (%) for all-cause mortality associated with a 10 μg/m^3 increase in station-observed and model-predicted daily mean fine particulate matter ($PM_{2.5}$) with different degree of freedom for temperature and relative humidity

df	$PM_{2.5}$ sources	RRI (%)	95% CI
3	Model-predicted	0.86	0.65 to 1.07
3	Station-observed	0.67	0.51 to 0.83
4	Model-predicted	0.87	0.66 to 1.08
4	Station-observed	0.68	0.52 to 0.83
5	Model-predicted	0.86	0.66 to 1.07
5	Station-observed	0.68	0.52 to 0.83

Notes: $PM_{2.5}$: particulate matter with a diameter of < 2.5 μm; df: degree of freedom; RRI: relative risk increase; 95% CI: 95% confidence interval.

Table S5. The pooled RRIs (%) for all-cause mortality associated with a 10 μg/m^3 increase in station-observed and model-predicted daily mean fine particulate matter ($PM_{2.5}$) with different sets of knots for spline functions for temperature and relative humidity

Knot	$PM_{2.5}$ sources	RRI (%)	95% CI
Type1	Model-predicted	0.86	0.65 to 1.07
Type1	Station-observed	0.67	0.51 to 0.82
Type2	Model-predicted	0.86	0.66 to 1.07
Type2	Station-observed	0.67	0.52 to 0.83
Type3	Model-predicted	0.87	0.66 to 1.08
Type3	Station-observed	0.67	0.52 to 0.83

Notes: $PM_{2.5}$: particulate matter with a diameter of < 2.5 μm; Type1: setting knot of the 25th, 50th, and 75th percentiles of temperature for its spline function; Type2: setting knot of the 10th and 90th percentiles of temperature for its spline function; Type3: setting knot of the 25th and 75th percentiles of temperature for its spline function; RRI: relative risk increase; 95% CI: 95% confidence interval.

Table S6. The pooled RRIs (%) for all-cause mortality associated with a 10 μg/m^3 increase in station-observed and model-predicted daily mean fine particulate matter ($PM_{2.5}$) by using different lag days

Lag days	$PM_{2.5}$ sources	RRI (%)	95% CI
2	Station-observed	0.02	-0.20 to 0.24
2	Model-predicted	0.02	-0.25 to 0.30
3	Station-observed	-0.25	-0.46 to -0.04
3	Model-predicted	-0.38	-0.66 to -0.09
4	Station-observed	-0.15	-0.34 to 0.04
4	Model-predicted	-0.28	-0.53 to -0.04
5	Station-observed	-0.14	-0.33 to 0.06
5	Model-predicted	-0.27	-0.54 to 0.00

Notes: $PM_{2.5}$: particulate matter with a diameter of < 2.5 μm; RRI: relative risk increase; 95% CI: 95% confidence interval.

Table S7. The pooled RRIs (%) for all-cause mortality associated with a 10 μg/m^3 increase in station-observed and model-predicted daily mean fine particulate matter ($PM_{2.5}$) using cities with monitoring stations not included in model training

Country	No. of cities	Mortality counts in 2000-2018			RRI (%) for all-cause deaths	
		Start date	End date	All-cause	Observed $PM_{2.5}$	Estimated $PM_{2.5}$
Canada	19	1/01/2000	31/12/2015	1282938	1.21 (0.65 to 1.78)	0.28 (0.04 to 0.52)
Ecuador	1	1/01/2014	31/12/2018	41204	1.43 (0.72 to 2.15)	0.16 (-2.89 to 3.30)
Estonia	3	19/08/2008	31/12/2018	25376	1.87 (1.08 to 2.66)	0.29 (-3.38 to 4.10)
Greece	1	1/01/2007	31/12/2010	115466	1.12 (0.88 to 1.36)	0.66 (0.44 to 0.89)
Iran	2	13/04/2013	31/12/2015	84894	0.11 (-0.07 to 0.29)	-0.64 (-1.05 to -0.22)
Japan	38	1/01/2011	31/12/2015	1324405	1.00 (0.60 to 1.39)	0.60 (0.25 to 0.96)
Mexico	4	7/05/2003	31/12/2012	1016016	1.42 (0.96 to 1.89)	0.70 (0.04 to 1.37)
Portugal	2	1/01/2004	31/12/2018	57483	-0.86 (-1.93 to 0.22)	0.19 (-2.86 to 3.34)
South Africa	5	31/07/2004	31/12/2013	404505	0.56 (0.28 to 0.83)	1.18 (0.44 to 1.92)
United Kingdom	2	5/11/2008	31/12/2016	58931	-0.33 (-0.67 to 0.02)	-0.08 (-0.82 to 0.67)
USA	4	1/01/2000	31/12/2006	21959	1.50 (-0.18 to 3.21)	-0.56 (-3.12 to 2.06)
Total	81	1/01/2000	31/12/2018	4433177	0.98 (0.72 to 1.25)	0.46 (0.19 to 0.73)

Notes: $PM_{2.5}$: particulate matter with a diameter of < 2.5 µm; RRI: relative risk increase; Values in brackets are 95% confidence interval.

References

1. Yu W, Ye T, Zhang Y, et al. Global estimates of daily ambient fine particulate matter concentrations and unequal spatiotemporal distribution of population exposure: a machine learning modelling study. *The Lancet Planetary Health* 2023; **7**: e209-e18.
2. Hersbach H, Bell B, Berrisford P, et al. The ERA5 global reanalysis. *Q J R Meteorol Soc* 2020; **146**: 1999-2049.