The Effect of Environmental Factors on the Association between Airborne Particulate Matter and Mortality in East Asia

Satbyul Estella Kim

A Dissertation Submitted in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Public Health

February, 2017

Seoul National University

The Effect of Environmental Factors on the Association between Airborne Particulate Matter and Mortality in East Asia

Satbyul Estella Kim

A Dissertation Submitted to the Faculty of Seoul National University in Partial Fulfillment of the Requirements for the Degree of Doctor of Philosophy in Public Health

February, 2017

Read and Approved by:

Seung-Muk Yi ____________

Sung-il Cho ____________

Yun-Chul Hong ____________

Hae-Kwan Cheong ____________

Ho Kim ____________

The Effect of Environmental Factors on the Association between Airborne Particulate Matter and Mortality in East Asia

지도교수 김 호

이 논문을 보건학 박사학위논문으로 제출함
2017년 02월

서울대학교 보건대학원
보건학과 보건학전공
김 샛 별

김샛별의 박사학위논문을 인준함
2017년 02월

위 원 장 ______ 이 승 묵

부위원장 ______ 조 성 일

위 원 ______ 홍 윤 철

위 원 ______ 정 해 관

위 원 ______ 김 호

Abstract

The Effect of Environmental Factors on the Association between Airborne Particulate Matter and Mortality in East Asia

Satbyul E. Kim

Department of Biostatistics and Epidemiology

Graduate School of Public Health

Seoul National University

Background: Worldwide, air pollution is responsible for large numbers of deaths, and substantial epidemiological research has provided evidence for the association between air pollution and mortality. There has been growing demand from policymakers for a better understanding of the relationship between air pollution and adverse health effects, including mortality.

Methods: First, we examined seasonal patterns in the short-term association of airborne particulate matter (PM) smaller than 10 μm (PM_{10}) with daily mortality in 29 cities in three East Asian countries. Stratified time-series models were used to determine whether seasons alter the effect of PM_{10} on

mortality. Furthermore, this effect was first quantified for each season and at each location using a time-series model, after which city-specific estimates were pooled using a hierarchical Bayesian model.

Second, we investigated the effects of temperature on the relationship between PM_{10} and mortality due to non-accidental, cardiovascular, and respiratory death in seven cities in South Korea. We applied stratified time-series models to the datasets in order to examine whether the effects of PM_{10} on mortality were modified by temperature. The effect of PM_{10} on daily mortality was estimated for different temperature ranges at each location using a time-series model, then the estimates were pooled through a random-effects meta-analysis using the maximum likelihood method. Lastly, we estimated the durational effect on mortality of consecutive days with a daily mean PM_{10} concentration of $\geq 75\ \mu g/m^3$. A standard time-series Poisson model was fitted in each location with duration as the main variable of interest while controlling for daily mean PM_{10} concentration, meteorological variables, seasonal trend, and day of the week. Moreover, the duration-mortality relationships were estimated and then a meta-analysis of the country-specific estimates was performed using the maximum likelihood method. In addition, the additional percent increase in deaths were calculated considering the consecutive days of elevated PM_{10} levels for each country.

Findings: For seasonal analysis, a 10 μg/m^3 increase in PM_{10} was significantly associated with increases in non-accidental mortality of 0.44% (95% confidence interval [CI]: 0.03%, 0.8%) in spring and 0.42% (95% CI: 0.02%, 0.82%) in the fall for Japan. In South Korea, a 10 μg/m^3 increase in PM_{10} was significantly associated with increases in non-accidental mortality of 0.51% (95% CI: 0.01%, 1.01%) in summer and 0.45% (95% CI: 0.03%, 0.87%) in the fall, in cardiovascular disease mortality of 0.96% (95% CI: 0.29%, 1.63%) in the fall, and in respiratory disease mortality of 1.57% (95% CI: 0.40%, 2.75%) in the fall. In China, a 10 μg/m^3 increase in PM_{10} was associated with increases in non-accidental mortality of 0.33% (95% CI: 0.01%, 0.66%) in summer and 0.41% (95% CI: 0.09%, 0.73%) in winter, in cardiovascular disease mortality of 0.41% (95% CI: 0.08%, 0.74%) in spring and 0.33% (95% CI: 0.02%, 0.64%) in winter, and in respiratory diseases mortality of 0.78% (95% CI: 0.27%, 1.30%) in winter.

For the modifying effect of temperature, a total of 828,787 non-accidental deaths were registered from 2000-2009 from 7 cities in South Korea. The highest overall risk between PM_{10} and non-accidental or cardiovascular mortality was observed on extremely hot days (daily mean temperature: > 99th percentile) in individuals aged < 65 years. In those aged ≥ 65 years, the highest overall risk between PM_{10} and non-accidental or cardiovascular mortality was observed on very hot days (daily mean temperature: 95-99th percentile) but not on extremely hot days. There were strong harmful effects from PM_{10} on non-accidental mortality with the highest temperature range (> 99th percentile) in men and a very high temperature range (95-99th percentile) in women.

For the durational effect, the mortality risk is significantly higher overall when the elevated PM_{10} concentration lasts multiple days in all three countries. Estimated non-accidental mortality was increased by 0.68% (95% CI: 0.35, 1.01) for Japan, 0.48% (95% CI: 0.30, 0.66) for South Korea, and 0.24% (95% CI: 0.14, 0.33) for China for an additional consecutive day of $PM_{10} \geq 75$ μg/m^3. For the annual maximum duration of high PM_{10} (≥ 75 μg/m^3) in Japan (2.40 days), South Korea (6.96 days), and China (42.26 days) corresponded to increases in non-accidental death of 1.64% (95% CI: 1.31, 1.98), 3.37% (95% CI: 3.19, 3.56) and 10.43% (95% CI: 10.33, 10.54), respectively.

Interpretation: Our analyses suggest that the acute effect of particulate air pollution varies seasonally and geographically, temperature affects the relationship between the PM_{10} levels and cause-specific mortality, and there

are additional mortality effects when high PM_{10} levels last for several days while accounting for the effect of each day's PM_{10} concentration. These findings have important implications for the planning of public health interventions to minimize the health burden of air pollution.

Keywords: Air pollution, Particulate matter, Mortality, Time-series analysis, Seasonality, Effect modification, Temperature, East Asia.

Student Number*: 2011-30692*

Contents

List of Tables

List of Figures

Appendices

Chapter 1

Introduction

Outdoor air pollution is a major environment-related health risk to human beings and the adverse health effects of air pollution have been subject to intense study in recent years (Brunekreef and Holgate, 2002; Kampa and Castanas, 2008; World Health Organization, 2006). Over 3.5 million people die each year from outdoor air pollution (UNEP Year Book, 2014). Between 2005 and 2010, the death rate rose by 4% worldwide, by 5% in China, and by 12% in India (UNEP Year Book, 2014). Especially ambient particulate air pollution is one of the major contributors to the global burden of disease, and the International Agency for Research on Cancer (IARC) and the WHO designate airborne particulates a Group 1 carcinogen (International Agency for Research on Cancer, 2013; Straif et al., 2013).

Particulate air pollution is a mixture of solid, liquid, or solid and liquid particles suspended in the air (Steenland and Savitz, 1997). The size of the suspended particles varies, from a few nanometers to tens of micrometers (Zereini and Wiseman, 2010). Particulate matter with a diameter of 10 μm or smaller is called PM_{10}. It is able to penetrate deep into the lungs and blood stream unfiltered, causing permanent DNA mutations, heart attacks, increased blood pressure, and premature death (Anderson et al., 2012; Auchincloss et al., 2008; Bell et al., 2004; Nel, 2005; World Health Organization, 2006; Yauk et al., 2008). A large body of epidemiological evidence suggests an association between particulate matter and mortality, and there is no safe level of particulates (Crouse et al., 2015; Daniels et al., 2000). Certain groups of people are more susceptible to suffering adverse health effects due to ambient particulate matter (Sacks et al., 2011), including the elderly, children, and people with pre-existing heart and lung disease, asthmatics, and the socially disadvantaged and poorly educated (Anderson et al., 2012; Theophanides et al., 2011; World Health Organization, 2003).

Exposure to PM_{10} is beyond the control of individuals and needs action by public authorities at the national, regional, and even international level to tackle the problem. For future public health interventions, we need to gain a better understanding of the association between particulate matter and its negative effect on health. Although many relevant studies have been carried out, there is limited interpretation of the results, and they do not cover all the spectra of an emergent specific public health problem:

(1) The constituents and concentrations of pollutants, and individuals'

exposure and biological responses to air pollution may vary by season and meteorological conditions. However, evidence regarding seasonality of the acute effects of air pollution on mortality is limited and inconsistent.

(2) There is inconsistent evidence regarding the modifying effect of temperature on acute mortality due to air pollution.

(3) While previous epidemiological studies on the effect of air pollution on health usually consider its concentration as a risk factor, none so far has offered the negative synergetic effect on health when the elevated air pollution level lasts for several days, beyond the summed effects of single days at high levels.

Therefore, our primary goals are (1) to examine seasonal and geographical variation on the short-term association of PM_{10} with daily mortality, (2) to investigate the modification effects of temperature on the relationship between PM_{10} and mortality due to non-accidental, cardiovascular, and respiratory death, and (3) to observe the association between mortality and duration (consecutive days of elevated PM_{10}), and quantify durational effect estimates while considering the adverse health effects from the PM_{10} level itself as well.

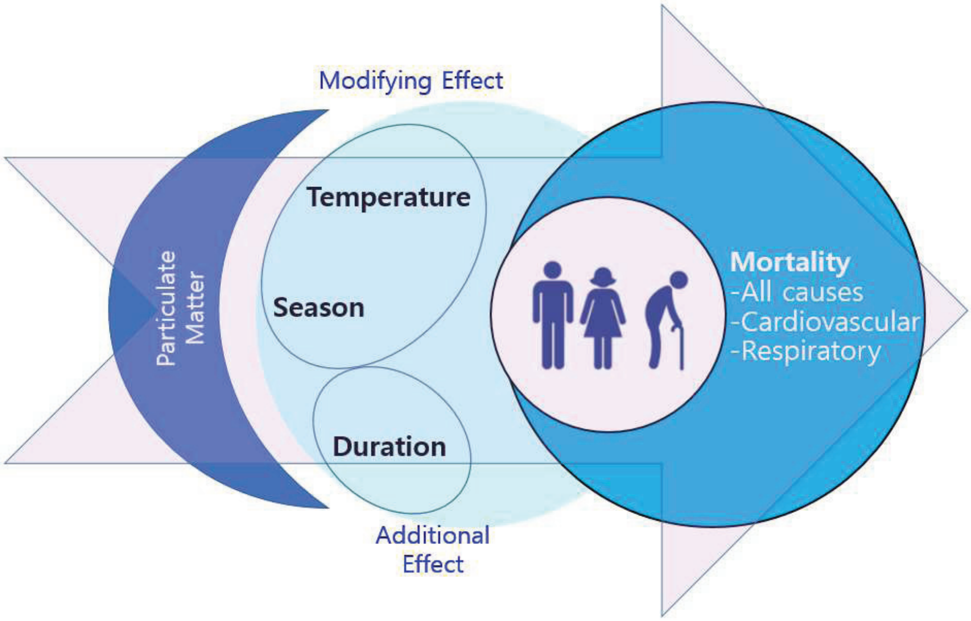


Figure 1. The effect of particulate matter on mortality: Some questions for better understanding

These findings have important implications for the planning of public health interventions to minimize the health burden of air pollution.

Chapter 2

Seasonal analysis of the short-term effects of air pollution on daily mortality in Northeast Asia

2.1 Introduction

Several time series studies of air pollution and daily mortality have typically assumed that the effects of air pollution on mortality remained constant over the study period. However, the short-term effects of air pollution on mortality might vary seasonally. Annual variations in meteorological conditions and sources of air pollution could lead to variations in the mixtures and concentrations of air pollution components; in addition, seasonal exposure patterns have been observed. Human behavior patterns also differ from season to season, and could lead to seasonal differences in personal exposure. Therefore, season should be considered an important modifying factor when investigating the acute health effects of air pollution. Hence, it is conceivable that the short-term associations of air pollution with daily mortality might differ from season to season (Peng et al., 2005). The particulate matter (PM) composition also varies by geographic region, suggesting that seasonal patterns should be examined according to location. For example, in China, coal is a greater source of PM in the summer and winter seasons, during which more energy is used than in the spring and fall seasons. In South Korea, the PM mixture during spring contains a large proportion of wind-blown dust from Asian dust storms that are less hazardous to health than combustion-related particles. A few multi- and single-city studies have provided evidence of seasonality with respect to the short-term health effects of PM, although this evidence has been inconsistent (Bell et al., 2008; Kan et al., 2008; Peng et al., 2005; Pope III and Dockery, 2006; Qian et al., 2010). Therefore, a multi-city study conducted using common methodology is needed to clarify the effect of seasonality on the health impacts of air pollution. To address this need, this study examined the seasonal significance of the acute effect of air pollution on cause-specific mortality in northeast Asia, including 29 cities in Japan, South Korea, and China since these three countries are located in proximity to each other and are similar in many socioeconomic and cultural aspects, but are exposed to different air pollution conditions.

2.2 Materials and Methods

2.2.1 Data collection

The collected data included meteorological variables, air pollution values, and daily information about health outcomes in six Japanese cities (1993–2008), Sapporo, Sendai, Tokyo, Nagoya, Osaka, and Kitakyushu; seven South Korean cities (2000–2009): Seoul, Incheon, Daejeon, Daegu, Gwangju, Busan, and Ulsan; and 16 Chinese cities (study period for each city can be found in Table 1): Anshan, Beijing, Fuzhou, Guangzhou, Hangzhou, Hong Kong, Lanzhou, Shanghai, Shenyang, Suzhou, Taiyuan, Tangshan, Tianjin, Wuhan, Urumqi, and Xian (Figure 2). Lanzhou was excluded from the cardiovascular diseases (CVD) and respiratory diseases (RD) analysis because of a lack of available data. Daily mortality counts were obtained from the Ministry of Health and Welfare of Japan, the Korea National Statistics Office, and the Center for Disease Prevention and Control of China. All diseases were classified according to the International Classification of Diseases, version 10 (World Health Organization, 1996). For analysis, deaths due to injuries or accidents were not considered because these were not thought to associate with air pollution; therefore, we examined non-accidental, cardiovascular, and respiratory mortality (codes A00–R99 for total non-accidental mortality, I00–I99 CVD, and J00–J99 for RD).

Information about weather variables was supplied by the Japan Meteorological Agency, the Korea Meteorological Office, and the China Meteorological Data Sharing Service System; these included data on daily mean temperature (°C), daily mean relative humidity (%), and daily mean atmospheric pressure (hPa; Japan and South Korea only). For air pollution, we collected data on PM with an aerodynamic diameter <10μm (PM_{10}). We calculated the daily representative concentration value of PM_{10} for each metropolitan city by averaging the hourly values of all monitoring stations per metropolitan city to yield 24-h average PM_{10} concentrations. PM_{10} data were provided by the Japan National Institute for Environmental Studies, the Korea Research Institute of Public Health, and the Environmental Monitoring Center of China.

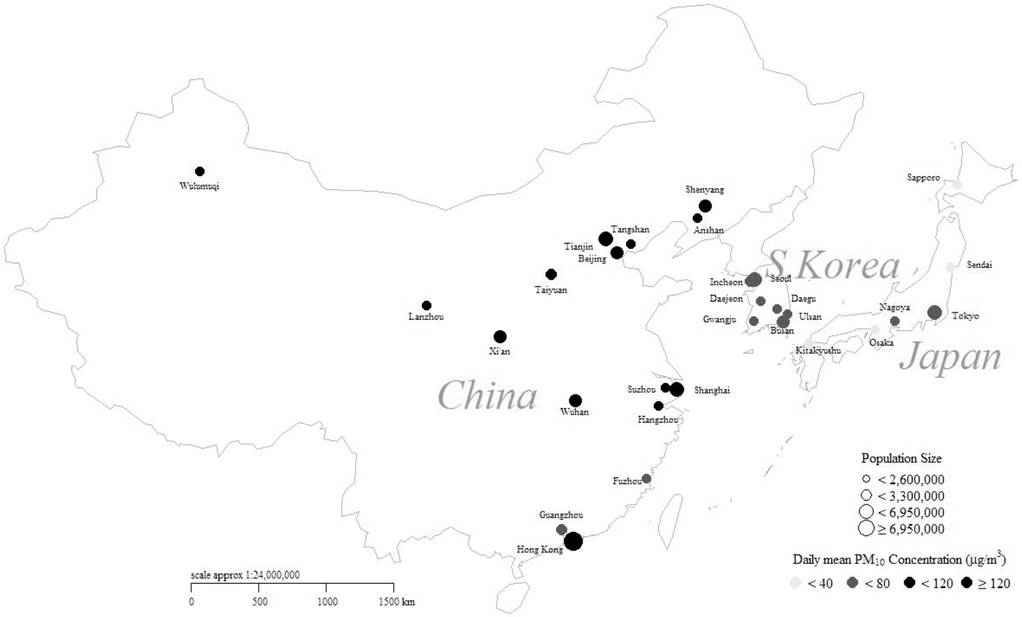


Figure 2. Locations of the study areas: 29 cities in Japan, South Korea, and China. Circle sizes represent the city populations; circle shading indicates the daily mean PM_{10} concentrations.

2.2.2 Statistical analysis

We applied two-stage Bayesian hierarchical statistical models to estimate the average associations of PM_{10} with daily mortality (Bell et al., 2008). In the first stage, we obtained city-specific estimates; in the second stage, we combined these estimates to generate national average estimates and account for their statistical uncertainty.

We investigated the potential patterns of interactions between PM_{10} and season on daily mortality while adjusting for other covariates. The shape of the dose-response relationship between PM air pollution and mortality is critical to this assessment; therefore, a smoothing spline function was adopted to capture the shape of the PM–mortality association. City-specific plots are presented in the supplementary material (Appendix 1). It was concluded that the relationship could be described using a linear model. Therefore, a linear model was used to assess the effect of PM_{10} on daily mortality.

We applied stratified time-series models to the data sets to examine whether the effects of PM_{10} on mortality were modified by the four seasons: spring, summer, fall, and winter. The effect of PM_{10} on daily mortality was first quantified within each season and at each location using a time-series model.

We stratified the effect of PM_{10} on mortality according to the four seasons in each city. This approach allowed us to examine heterogeneity of the effects of PM_{10} across the season strata and provided a simple, quantitative comparison of the effect of mortality on PM_{10} in the different season strata. To analyze the effects of PM_{10} in these different season strata, we used a Poisson log-linear model and included the season strata for which it was assumed that the effect of PM_{10} on mortality was purely additive. Model [1] is described as follows:

$$\begin{aligned}\mathbf{ln}\left(\boldsymbol{E}(\boldsymbol{y}_{\boldsymbol{t}^{\boldsymbol{c}}})\right) = \boldsymbol{\alpha}_{\boldsymbol{c}} \\ &+ \boldsymbol{factor}(\boldsymbol{season}_{\boldsymbol{t}-\boldsymbol{i}^{\boldsymbol{c}}}) \\ &+ \boldsymbol{PM}_{\mathbf{10}\,\boldsymbol{t}-\boldsymbol{i}^{\boldsymbol{c}}}\!:\!\boldsymbol{factor}(\boldsymbol{season}_{\boldsymbol{t}-\boldsymbol{i}^{\boldsymbol{c}}}) + \boldsymbol{s}(\boldsymbol{temp}_{\boldsymbol{t}-\boldsymbol{i}^{\boldsymbol{c}}}, \boldsymbol{df}) \\ &+ \boldsymbol{s}(\boldsymbol{time}_{\boldsymbol{t}}, \boldsymbol{df}) + \boldsymbol{factor}(\boldsymbol{DOW}_{\boldsymbol{t}}) + \boldsymbol{s}(\boldsymbol{humid}_{\boldsymbol{t}-\boldsymbol{i}^{\boldsymbol{c}}}) \\ &+ \boldsymbol{s}(\boldsymbol{press}_{\boldsymbol{t}-\boldsymbol{i}^{\boldsymbol{c}}})\ [\mathbf{1}]\end{aligned}$$

where **t** refers to the day of the observation; **c** is the city; **i** is the lag, $[\mathbf{E}(\mathbf{Y}_t^{\mathbf{c}})]$ is the estimated daily case counts on day t in city c; **s(•)** is the smoothing functions; **df** is the degrees of freedom; $\boldsymbol{\alpha}_{\boldsymbol{c}}$ is the intercept term of city c; $\mathbf{season}_{t\text{-}i}^{\mathbf{c}}$ is the season strata for city c on day t-i; $\mathbf{season}_{t\text{-}i}^{\mathbf{c}}\mathbf{:PM}_{10t\text{-}i}^{\mathbf{c}}$ is the mean PM_{10} level on day t-i within a season stratum; $\mathbf{temp}_{t\text{-}i}^{\mathbf{c}}$ is the mean temperature on day t-i in city c; $\mathbf{time}_t$ is seasonality according to calendar days; and $\mathbf{humid}_{t\text{-}i}^{\mathbf{c}}$ and $\mathbf{press}_{t\text{-}i}^{\mathbf{c}}$ are the humidity and pressure on day t-i in city c, respectively. Day of the week (DOW) was also included in the model as a categorical variable to control for systematic variation within a week (Katsouyanni et al., 1996; Schwartz et al., 1996). This model allowed us to explore potential interactive effects between PM_{10} and season on mortality while accounting for potential confounders such as DOW, seasonality, temperature, and other weather variables.

A lag effect is known to exist in the association between PM_{10} and mortality (Braga et al., 2001b; Schwartz, 2000), and single-day lag models have been reported to underestimate the cumulative health effects of air pollution (Wong et al., 2008). Therefore, we examined the PM_{10} effects from different multiday lag (lag 01 to lag 05) structures for each city as part of the sensitivity analysis. For each country, we focused on the results of the lag model that yielded maximum effects.

Finally, we pooled the city-specific effect estimates to generate an overall estimate for each country using Bayesian hierarchical modeling. For the hierarchical model, we used the computational Two-Level Normal Independent Sampling Estimation (TLNISE) algorithm derived by Everson and Morris (Everson and Morris, 2000) to approximate separately the posterior distributions of all unknown parameters within each country.

We used R version 3.2.2 and the *gam* function in the mgcv package (R Foundation for Statistical Computing, Vienna, Austria) and *tlnise* in the tlnise package for our analyses. The results are expressed in terms of percentage changes (excess relative risk, ERR [%]) in the daily mortality counts for each 10-μg/m^3 incremental increase in pollutant concentration, along with respective 95% confidence intervals (CI).

2.3 Results

2.3.1 Summary statistics

Table 1 summarizes data from each city, including the study periods, average temperatures, PM concentrations, and numbers of deaths. The data set included 1,858,521 deaths from Japan, 838,955 deaths from South Korea, and 3,675,348 deaths from China. The number of natural deaths per day ranged from 9 in Ulsan to 155 in Tokyo. The daily mean PM_{10} values were 32.35 $\mu g/m^3$ in Japan, 55.45 $\mu g/m^3$ in South Korea, and 110.43 $\mu g/m^3$ in China. Daily PM_{10} levels varied considerably among seasons. Regarding season-specific levels, the highest daily mean PM_{10} values were 35.43 $\mu g/m^3$ in summer in Japan, 69.98 $\mu g/m^3$ in spring in South Korea, and 136.58 $\mu g/m^3$ in winter in China. The average temperature ranged from 7°C to 24° C and depended on the distinct climatic characteristics among these cities.

Table 1. Descriptive data from the study period, including air pollutant concentrations (PM_{10}), temperature, and daily total deaths in 29 cities

Country	City	Approx. population in millions [a]	Years of data	Mean temperature (°C)	PM_{10} concentrations [b] (μg/m^3) (5th-95th percentile range)					Daily mean number of deaths [c]		
					All year	Spring	Summer	Fall	Winter	Non-accidental	CVD	RD
Japan	Sapporo	1.88	1993-2008	9.09 (-5.3, 23.1)	15.19 (6.25, 31.45)	17.19 (6.77, 36.84)	16.35 (6.31, 32.51)	13.61 (6.18, 26.75)	13.54 (5.97, 26.93)	28.55	9.44	4.02
	Sendai	1.06	1993-2008	12.62 (0.5, 25.4)	24.88 (8.61, 53.21)	26.43 (9.98, 53.05)	31.52 (13.06, 63.7)	24.59 (9.58, 48.63)	16.83 (6.82, 36.01)	14.09	4.75	1.85
	Tokyo	8.34	1993-2008	16.57 (5.1, 28.9)	41.02 (13.6, 87.51)	38.43 (15.29, 75.08)	44.84 (19.42, 90.28)	42.65 (15.46, 92.74)	38.11 (9.39, 92.51)	154.95	51.29	22.36
	Nagoya	2.19	1993-2008	16.07 (3.4, 29)	42.52 (15.45, 82.47)	42.93 (16.65, 77.48)	45.15 (21.86, 78.74)	45.12 (17.33, 90.95)	36.8 (12.32, 84.87)	39.76	13.54	5.58

	Osaka	2.59	1993-2008	17.16 (4.8, 29.9)	38.71 (13.52, 77.61)	41.25 (15.42, 77.65)	40.07 (17.68, 72.78)	36.77 (13.95, 77.0)	36.7 (10.66, 84.05)	58.6	17.71	9.01
	Kitakyushu	1	1993-2008	17.25 (5.42, 29.4)	31.78 (11.8, 63.67)	37.55 (14.88, 73.96)	34.67 (14.3, 67.16)	29.17 (11.56, 58.93)	25.6 (9.6, 52.5)	22.08	6.9	3.4
South Korea	Seoul	10.35	2000-2009	12.89 (-3.98, 26.53)	63.67 (20.06, 129.79)	80.91 (31.83, 157.1)	50.88 (16.42, 104.78)	54.28 (17.83, 119.83)	68.6 (30.47, 133.02)	93.02	25.02	5.42
	Incheon	2.63	2000-2009	12.72 (-3.19, 25.86)	59.82 (23.86, 116.54)	73.65 (33.38, 136.62)	49.12 (20.92, 96.71)	54.36 (21.41, 110.69)	61.93 (28.32, 121.07)	26.22	7.61	1.74
	Daejeon	1.48	2000-2009	13.08 (-2.6, 26.69)	47.96 (18.15, 94.2)	62.25 (24.39, 117.12)	36.76 (15.12, 75.32)	41.08 (16.93, 78.04)	51.51 (24.35, 95.98)	13.86	3.73	1.04
	Daegu	2.57	2000-2009	14.55 (-0.5, 28.08)	57.63 (24.96, 104.41)	71.19 (32.89, 127.78)	46.82 (22.29, 80.8)	50.95 (23.03, 95.84)	61.37 (31.2, 110.95)	27.5	7.39	1.81
	Ulsan	0.96	2000-2009	14.55 (0.93, 27.35)	51 (24.07, 91.72)	65.29 (28.62, 114.57)	44.95 (22.2, 78.86)	44.38 (22.85, 79.41)	49.05 (25.65, 87.28)	9.56	3.36	0.93
	Busan	3.68	2000-2009	14.84 (1.42, 26.69)	57.88 (28.21, 105.67)	72.06 (32.33, 130.87)	51.91 (27.59, 91.5)	51.77 (26.8, 91.43)	55.47 (28.27, 98.44)	45.38	14.08	2.76

	Gwangju	1.42	2000-2009	14.11 (-0.74, 27.4)	50.2 (19.87, 100.7)	64.5 (25.23, 129.01)	40.81 (16.02, 87.23)	44.6 (20.28, 87.39)	50.65 (23.81, 99.68)	14.11	2.65	0.69
China	Urumqi	3.03	2006-2007	17.9 (2.78, 31.9)	129.77 (54, 234)	129.41 (59.5, 203.1)	96.06 (47.65, 174.36)	137.55 (51.19, 232.9)	156.89 (72, 272.2)	57.51	4.26	2.2
	Shenyang	6.26	2005-2008	8.17 (-14, 25)	114.22 (52.63, 214.75)	116.3 (55.59, 196.28)	100.15 (48.67, 148.21)	104.92 (49.64, 150.74)	135.83 (57.5, 249.38)	66.65	31.69	6.4
	Anshan	1.2	2004-2006	11.36 (-10.23, 27.5)	110.88 (42.75, 221.5)	116.14 (44.75, 230.75)	92.75 (34.75, 173.75)	115.33 (44, 241.4)	119.52 (51, 258)	27.62	14.14	1.91
	Tianjin	11.09	2005-2008	13.29 (-4.3, 28.3)	100.84 (36, 212.6)	109.31 (43.67, 216.36)	83.25 (37.25, 139.74)	103.52 (33.61, 227.31)	107.46 (32.63, 254.25)	10.92	6.4	0.66
	Beijing	11.72	2007.1-2008.9	14.76 (-2.31, 28.5)	138.9 (34, 298.8)	161.42 (44, 333.6)	124.58 (33.8, 242.8)	116.22 (21, 292)	146.83 (45.45, 306.6)	117.74	54.16	14.06
	Xian	6.5	2004-2008	13.42 (-2, 28)	132.09 (64, 244)	129.28 (70, 232)	105.56 (60, 150.3)	129.38 (55.3, 240)	164.55 (74, 296.9)	26.18	12.07	7.24
	Taiyuan	3.43	2004-2008	11.23 (-6, 26.07)	132.13 (46.06, 251.16)	148.04 (53.3, 310.5)	112.13 (46.86, 178.06)	127.13 (47.59, 221.45)	141.32 (42.66, 300.05)	24.15	8.93	1.9

Lanzhou	2.63	2004-2008	7.43 (-9, 21)	156.41 (52.5, 368.38)	166.62 (52.5, 386.2)	103.31 (51, 173)	136.84 (50.65, 272.7)	220.24 (60.35, 437.3)	18.66	NA	NA
Tangshan	3.37	2006-2008	12.57 (-4.93, 27.3)	97.53 (48, 189.05)	99.57 (52, 163)	80.03 (48, 123)	91.8 (44, 193.6)	118.17 (49.5, 233)	18.94	8.33	2.93
Suzhu	5.35	2005-2008	17.18 (2, 30.2)	89.82 (32, 184)	100.32 (39.35, 180)	73.18 (32, 131.65)	92.47 (34, 188)	93.39 (26, 216)	34.21	12.68	4.63
Shanghai	22.32	2001-2004	17.72 (4.03, 30.68)	102.01 (36.6, 225.67)	114.35 (41.6, 262.77)	80.93 (33.35, 156.33)	96.94 (38.69, 209.8)	116.03 (33.67, 259)	119.04	44.21	14.29
Wuhan	9.79	2003-2005	8.6 (-12.6, 26.46)	144.11 (36, 438.55)	108.01 (40.15, 254)	56.29 (31, 90.85)	121.17 (45.05, 282.5)	293.97 (89.95, 604.3)	17.26	32.69	6.95
Hangzhou	6.24	2002-2004	17.94 (4.2, 30.7)	120.46 (47.85, 232)	121.3 (49, 244.2)	98.36 (46.6, 168)	125.11 (45.2, 219)	137.61 (41, 268.1)	20.11	6.84	3.82
Fuzhou	1.18	2004-2006	20.66 (8.48, 30.6)	72.33 (26, 144.5)	88.26 (31, 162)	56.04 (26.75, 95)	72.16 (30, 138)	72.88 (20, 147)	15.86	6.73	1.5
Guangzhou	11.07	2007-2008	22.84 (11.75, 31.2)	73.79 (24.77, 160.73)	73.6 (24.85, 151.18)	50.08 (22.28, 83.38)	76.28 (33.82, 132.6)	95.26 (21.93, 185.77)	79.45	29.35	14.99

Hong Kong	7.24	1996-2002	23.65 (15, 29.9)	51.62 (21.46, 98.37)	50.64 (24.37, 97.72)	33.22 (19.19, 67.28)	57.66 (25.77, 95.3)	65.26 (26.89, 109.35)	84.18	23.77	16.17

[a] Source: World Population Prospects 2015

[b] PM_{10}: particulate matter <10 µm

[c] All-cause mortality excluding external causes. Causes of death were based on ICD codes.

2.3.2 Lag effects

Figure 3 shows the quantitative effects of PM_{10} on non-accidental mortality and its moving average lag structure for each country. The largest effects were observed at lag01 (2-day moving average of current and previous day concentrations of PM_{10}) in Japan, lag04 in South Korea, and lag03 in China (Figure 3).

2.3.3 Overall effects

The overall effects of PM_{10} on non-accidental mortality for each city are shown in the supplementary material (Appendix 2). The largest effect of PM_{10} was observed in Guangzhou (China), with a 1.80% (95% CI: 1.44%, 2.16%) increase in mortality for every 10-$\mu g/m^3$ increase in PM_{10}, followed by 0.82% (0.09%, 1.55%) in Fuzhou (China) and 0.81% (0.01%, 1.61%) in Sendai (Japan).

2.3.4 Effects by season Associations of PM_{10} and mortality from non-accidental, CVD, and RD were evaluated by season. The seasonal effects of PM_{10} on non-accidental mortality for each city are shown in Figure 4. Significant mortality effects of the PM_{10} were observed in Seoul and Nagoya in summer, and in Busan, Tokyo, Tianjin, Xian, and Fuzhou in fall. In addition, significant associations were observed in spring and fall in Osaka, summer and winter in Suzhou, spring and summer in Wuhan, fall in Fuzhou, spring, summer, and winter in Guangzhou, and winter in Hong Kong. Regarding CVD, significant associations were observed in Osaka and Fuzhou in spring, Sendai, Tokyo, Suzhou, and Wuhan in summer, Seoul and Tianjin in fall, and Hong Kong in winter. Significant associations were observed in Shanghai for all seasons except spring, and in Guangzhou in spring and winter (Appendix 3). Regarding RD, significant associations were only observed in cooler seasons, with the exception of Guangzhou. Such associations were observed in Busan in fall, and in Suzhu, Shanghai, Wuhan, and Hong Kong in winter. Notably, significant associations were observed in spring, summer, and winter in Guangzhou (Appendix 4).

Nationally, the seasonal effects of PM_{10} on mortality varied by cause of death and country. Japan exhibited significant associations with non-accidental mortality in spring and fall. In South Korea, significant effects were observed for non-accidental death in summer and fall, and for CVD and RD in fall. In contrast, in China, significant seasonal effects were observed non-accidental death in summer and winter, for CVD in spring and winter, and for RD only in winter (Table 2).

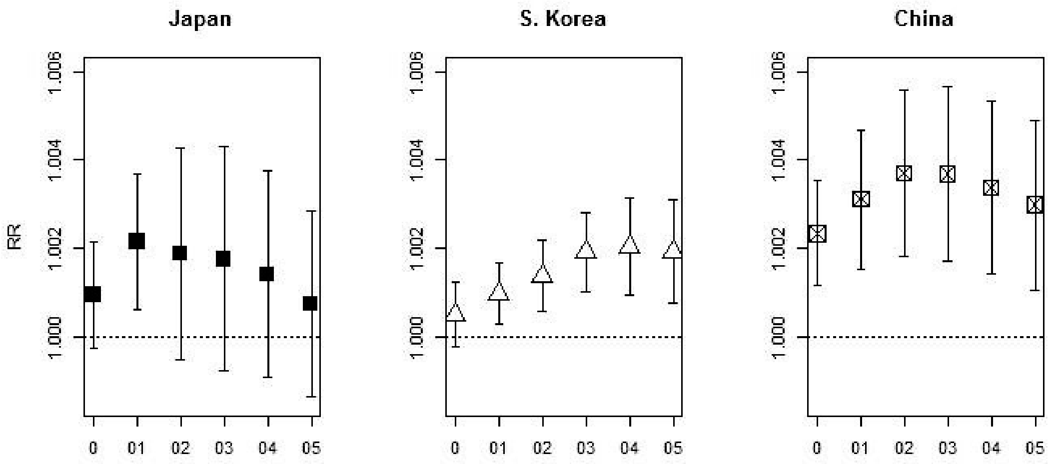
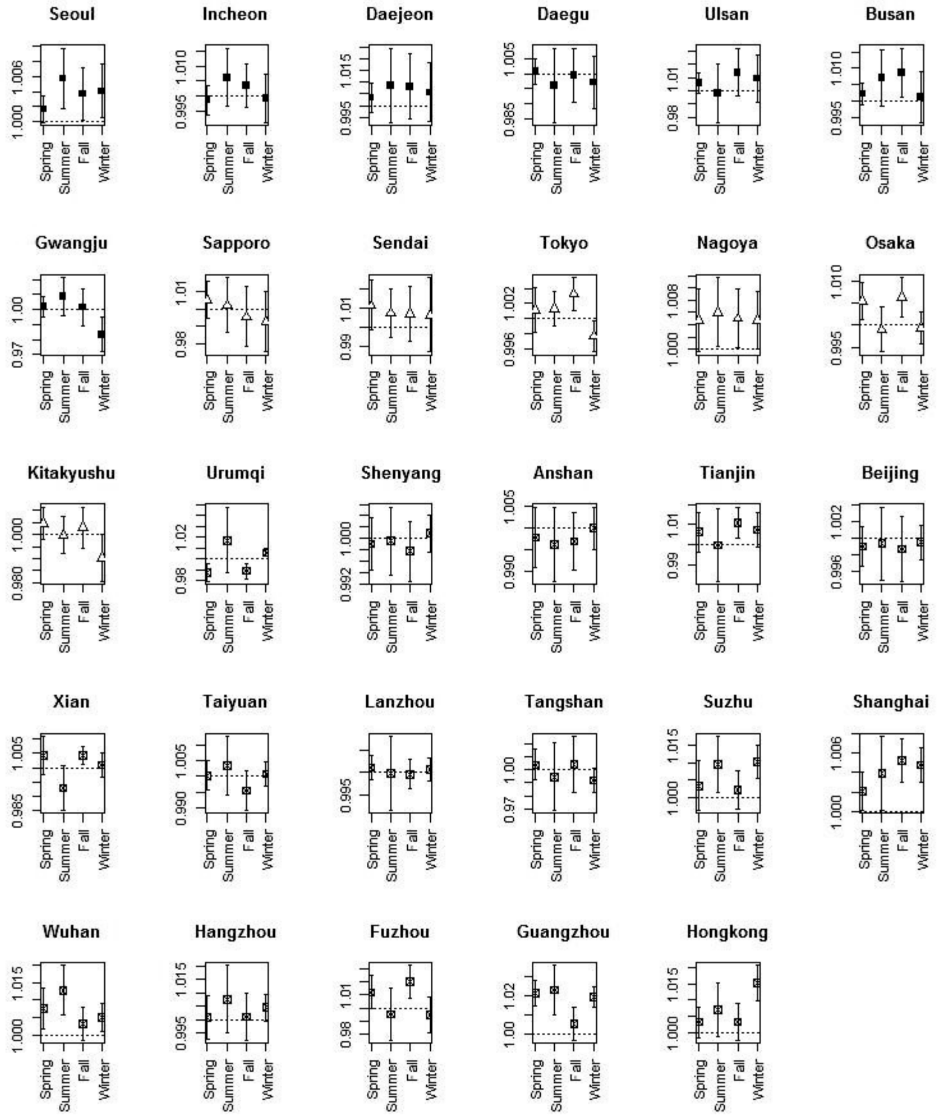


Figure 3. Relative risk in mortality associated with a 10 μg/m^3 increase in PM_{10} with different lag structures. Bars represent 95% confidence intervals.



`

Figure 4. City-specific seasonal effects of PM_{10} on non-accidental mortality.

Table 2. Pooled results for the percent changes in daily non-accidental mortality by season, along with 95% confidence intervals, for 10μg/m^3 increments in PM_{10} and mean daily PM_{10} concentrations by season.

Country	Season	Non accidental	CVD	RD	Daily PM_{10} (μg/m^3)
Japan	Spring	0.44(0.03, 0.86)*	0.38(-0.14, 0.91)	0.56(-0.31, 1.44)	33.96
	Summer	0.2(-0.23, 0.64)	0.53(-0.18, 1.23)	0.4(-0.52, 1.34)	35.43
	Fall	0.42(0.02, 0.82)*	0.19(-0.37, 0.76)	0.54(-0.17, 1.24)	31.99
	Winter	-0.13(-0.69, 0.44)	-0.19(-0.77, 0.39)	-0.5(-1.41, 0.42)	27.93
South Korea	Spring	0.18(-0.17, 0.52)	0.1(-0.34, 0.53)	0.13(-0.71, 0.98)	69.98
	Summer	0.51(0.01, 1.01)*	0.08(-0.77, 0.93)	0.16(-1.32, 1.67)	45.89
	Fall	0.45(0.03, 0.87)*	0.96(0.29, 1.63)*	1.57(0.4, 2.75)*	48.77
	Winter	-0.02(-0.57, 0.54)	-0.18(-0.87, 0.5)	0.59(-0.68, 1.87)	56.94
China	Spring	0.25 (-0.01, 0.51)	0.41(0.08, 0.74)*	0.46(-0.12, 1.05)	114.54
	Summer	0.33 (0.01, 0.66)*	0.47(-0.02, 0.96)	0.71(-0.03, 1.47)	84.12
	Fall	0.16 (-0.09, 0.4)	0.18(-0.15, 0.51)	0.28(-0.2, 0.76)	106.53
	Winter	0.41 (0.09, 0.73)*	0.33(0.02, 0.64)*	0.78(0.27, 1.3)*	136.58

2.4 Discussion

We explored the relationships of air pollution-related mortality with the cause of death and season in 29 Northeast Asian cities to further characterize the seasonal patterns of the air pollution–mortality relationship across a broad region, using a time-series model with stratification and a hierarchical Bayesian model. Previous studies have reported inconsistent results. The suggested evidence of seasonality in the present study was generally consistent within countries. In particular, we observed significant associations of the acute effects of PM_{10} on non-accidental mortality, with the highest effects observed in transitional seasons (spring and fall) in Japan, in summer and fall in South Korea, and in summer and winter in China. Regarding CVD, no significant seasonal associations were observed in Japan, whereas significant associations were observed in fall in South Korea and in spring and winter in China. Similarly, no significant associations between seasons and RD were observed in Japan, whereas significant associations were observed in fall in South Korea and spring and winter in China.

An early analysis of multicity season-specific approaches, conducted by Moolgavkar and Luebeck, indicated that the adverse effects of air pollution were more apparent in summer (Moolgavkar and Luebeck, 1996). In addition, Peng at al. analyzed data from 100 northeastern United States cities included in the National Morbidity, Mortality, and Air Pollution Study and found a significant association between PM_{10} and mortality only in the summer (lag 0) and spring (lag 1) (Peng et al., 2005). Studies conducted in European countries have also identified a higher effect of PM_{10} on mortality in summer (Katsouyanni et al., 1997; Nawrot et al., 2007; Stafoggia et al., 2008). Several Asian single-city studies conducted in Shenyang, China (Ma et al., 2011); Bangkok, Thailand (Wong et al., 2008); and Seoul, South Korea (Kim et al., 2015; Park et al., 2011; Yi et al., 2010) estimated the largest effects in summer or the warmer months. Moreover, a recent study of 17 Chinese cities confirmed such effects in summer and winter (Chen et al., 2013), consistent with our current results from China. Furthermore, other studies have reported stronger effects in transitional seasons (spring and fall) (Levy et al., 2001; Zanobetti and Schwartz, 2009; Zeka et al., 2006), consistent with our current results from Japan.

Substantial variations have been observed across locations, and previous results might have varied according to the mixture and concentration levels of PM components, climate conditions, exposure patterns of local populations, socioeconomic status, and analytical methods. For instance, in South Korea and China, PM_{10} concentrations tend to be higher in winter and spring months than in summer and fall months. Although a dose-response relationship between PM_{10} concentrations and mortality was apparent from the previous studies (Bell et al., 2004; Dominici et al., 2004), the strongest effect was observed in summer in South Korea even though the PM_{10} concentration was lowest in summer. Similarly, a previous study of the seasonal effects of PM_{10} in Seoul also noted more adverse health effects of air pollution in summer (Kim et al., 2015; Park et al., 2011; Yi et al., 2010). Likewise, a two-peak pattern in the effect of PM_{10} on mortality was observed in China, with the strongest effects occurring in summer and winter; PM_{10} concentrations were lowest in summer and highest in winter. This suggests that the estimated strong effects of PM_{10} on mortality might indicate the presence of a toxic component in the PM mixture. In China, the highest levels of toxic particles observed during summer or winter seasons might be attributable to the increased use of energy, as coal combustion is a major energy source. This speculation is supported by evidence of an association between combustion species and an increased risk of mortality (Huang et al., 2012).

In South Korea, the highest PM_{10} level was observed during spring (69.98

μg/m^3); however, the effects on mortality were lower in spring than in summer and fall, possibly as a result of the Asian dust storms that mainly originate in the Taklamakan and Gobi deserts of western China and Mongolia (Tanaka and Chiba, 2006) and affect South Korea during the spring; these storms constitute one of the major sources of PM in spring in South Korea. The elements of wind-blown dust from desert soil pose a weaker health hazard than do combustion particles and might lead to an underestimation of PM-related mortality by reducing the apparent particle toxicity (Laden et al., 2000; Lee et al., 2007). As local PM mixtures may differ, a detailed analysis of the regional and seasonal variation in PM constituents warrants further investigations. In addition, it is interesting to know whether the seasonal patterns are different between specific-cause mortality.

Moreover, the pattern of exposure to ambient PM may also contribute to seasonal variations in the effects of PM_{10} on mortality. Japan showed exhibited the lowest seasonal variations in PM_{10} concentrations (highest: summer, 35.43 μg/m^3; lowest: winter, 27.93 μg/m^3) and the highest levels of mortality in spring and fall, when the weather conditions are not extreme and permit more outdoor activity; in contrast, people are more likely to stay inside on hot or cold days, thus limiting exposure to air pollutants. Thus, seasonal effects might be related to different patterns of behavior rather than to PM constituents and concentrations.

To our knowledge, this is the first multi-country, multi-city study in Asia to analyze seasonal variations in PM-related health effects. All 29 cities from the three countries exhibited distinct PM_{10} distributions. Chinese cities and Japanese cities had the highest and lowest PM_{10} levels, respectively, despite that these countries are located adjacent to each other and are geographically similar (Figure 2). Therefore, our findings provide new data regarding seasonal variations in the health effects of air pollution.

Although our study had several strengths, it is important to note several limitations. First, the outdoor levels of air pollution might not reflect individual exposures to PM_{10}. Second, data on PM compositions were unavailable. A seasonal constituent analysis might help to address why seasonal variations in the effects on mortality exist. Third, emergency visit data, rather than mortality data, might represent more immediate responses to PM_{10} levels. Thus, further studies on morbidity would strengthen findings regarding the biological plausibility of these effects on mortality, temperature, and air pollution. Fourth, the study period durations varied among cities, resulting in uncertainty when the city-specific results were combined to determine national-level data (Dominici et al., 2007). Finally, our findings require further validation, especially in areas with different weather patterns. However, if substantiated, these findings will provide meaningful insights into the impact of air pollution on local population health.

2.5 Conclusion

In conclusion, our study has confirmed that the relationship between PM_{10} and mortality varies by season and location. Moreover, our findings have clear implications for the planning public health interventions and estimations of the future burdens of air pollution-related deaths under predicted climate change scenarios.

Chapter 3

Temperature modifies the association between particulate air pollution and mortality: a multi-city study in South Korea

3.1 Introduction

Many epidemiologic studies have shown that ambient air pollution has adverse effects on mortality (Chen et al., 2004; Dockery et al., 1993; Mar et al., 2000; Samet et al., 2000; Wong et al., 2008). Temperature also has an effect on daily mortality (Curriero et al., 2002; McMichael et al., 2008), and a strong association between temperature and mortality has been detected with a generally nonlinear relationship of J-, U-, or V-shaped exposure responses in different countries (Baccini et al., 2008; Basu and Samet, 2002; Braga et al., 2001a; Guo et al., 2011).

Temperature is usually considered as a confounder in the study of air pollution. Therefore, when estimating the unconfounded effects of air pollution on mortality, an adjustment for temperature is typically warranted. However, the interactions between temperature and air pollution have received less attention.

Temperature may act as an effect modifier, but this idea remains controversial (Hales et al., 2000; Katsouyanni et al., 1993; Roberts, 2004; Samet et al., 1998). However, in several recent studies, a significant interaction was detected (Park et al., 2011; Qian et al., 2008; Ren and Tong, 2006; Stafoggia et al., 2008). Season-specific approaches have also shown that the adverse effects of air pollution are more apparent in the warm season, although substantial variations have been observed across locations (Nawrot et al., 2007; Peng et al., 2005).

It is thought that air pollution affects certain subgroups of the population to a greater extent (World Health Organization, 2004). According to consistent findings from many countries, vulnerability to the effects of air pollution may be affected by population demographic characteristics such as age and sex on the relationship between air pollution and daily mortality (Atkinson et al., 2001; Bateson and Schwartz, 2004; Cakmak et al., 2006; Gouveia and Fletcher, 2000; Kan et al., 2008; Katsouyanni et al., 2001). Additionally, people with pre-existing health problems such as cardiovascular and respiratory diseases seem to be more susceptible (Anderson et al., 2003; Basu, 2009; Bateson and Schwartz, 2004; Gasparrini et al., 2012; Goldberg et al., 2001; Katsouyanni et al., 2001).

In the present study, we investigated the modification effects of temperature on the relationship between air pollution and the different causes of mortality in seven cities in South Korea. Moreover, we investigated the temperature modification effect on the PM-mortality relationship by age and sex.

3.2 Materials and Methods

3.2.1 Scope of the study and data collection

From January 1, 2000 through December 31, 2009, the data set used in this study consisted of meteorological variables, air pollution, and daily information on health outcomes in seven metropolitan cities in South Korea: Seoul, Incheon, Busan, Daegu, Daejeon, Gwangju, and Ulsan (Figure. 5). The information on weather variables was obtained from the Korean Meteorological Office and included data on the daily mean temperature (°C), daily mean relative humidity (%), and daily mean pressure (hPa). For air pollution, we collected data on particulate matter <10μm (PM_{10}) in aerodynamic diameter from the Korean National Institute of Environmental Research. Concentrations of the air pollutants were measured every 15 min at 88 monitoring stations (Seoul: 27, Incheon: 11, Busan: 16, Daegu: 11, Daejeon: 6, Gwangju: 5, and Ulsan: 12) during the study period. We calculated the daily representative concentration value of PM_{10} for each metropolitan city by averaging the hourly values of all the monitoring stations per metropolitan city, which comprised 24-h average concentrations of PM_{10}.

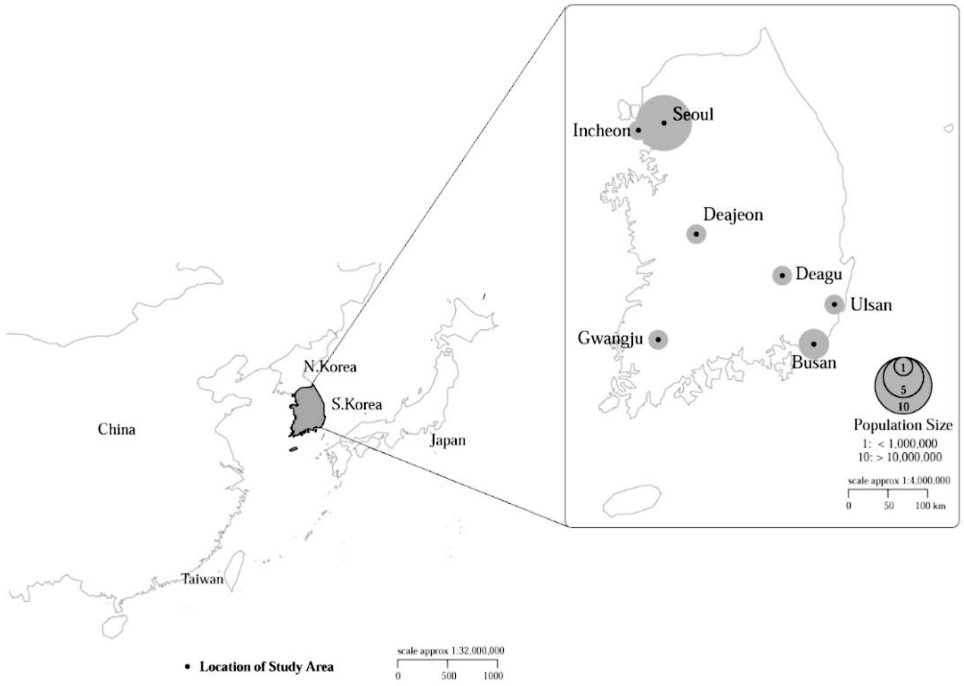


Figure 5. Location of the seven South Korean cities.

Daily mortality counts were obtained from the Korea National Statistics Office of the seven cities. All the diseases were diagnosed on discharge and were classified according to the International Classification of Disease, version 10 (World Health Organization, 1996). For analysis, we excluded mortality due to accidents and suicide; therefore, we only examined non-accidental mortality (codes A00–R99 for total non-accidental mortality, J00–J99 for respiratory diseases, and I00–I99 for cardiovascular diseases).

3.2.2 Statistical Analysis

Daily death, air pollution, and weather data were linked by date; thus, a time-series approach was used to investigate the associations between PM_{10} and mortality. Specifically, we used a generalized additive model (GAM) to analyze the relationships between daily mortality, PM_{10}, and temperature data with the assumption that the daily number of counts had an overdispersed Poisson distribution (Dominici et al., 2004). GAM allows nonparametric smoothing functions to account for smooth fluctuations of confounding factors such as seasonal variation and weather conditions on the daily number of deaths (Bell et al., 2004; Gasparrini and Armstrong, 2011; Hastie and Tibshirani, 1990; Schwartz and Zanobetti, 2000).

We performed a stage-by-stage analysis. First, we used an independent model to explore the patterns of the relationship between PM_{10} and health outcomes while controlling for temperature, prior to exploring the effect modification of temperature on the PM_{10}-mortality relationship. The Model [2] is described as follows:

$$\mathbf{ln}(\boldsymbol{E}(\boldsymbol{y}_{t,c})) = \boldsymbol{\alpha}_{c} + \boldsymbol{PM}_{\mathbf{10}\,t-i,c} + \boldsymbol{s}(\boldsymbol{temp}_{\,t-i,c}, \boldsymbol{df}) + \boldsymbol{s}(\boldsymbol{time}_{t}, \boldsymbol{df}) + \boldsymbol{factor}(\boldsymbol{DOW}_{t}) + \boldsymbol{s}(\boldsymbol{humid}_{t-i,c}, \boldsymbol{df}) + \boldsymbol{s}(\boldsymbol{press}_{t-i,c}, \boldsymbol{df}) \quad [2]$$

where $\mathbf{t}$ refers to the day of the observation; $\mathbf{c}$ refers to the cities; $\mathbf{i}$ refers to the lags, $\boldsymbol{E}(\boldsymbol{y}_{t,c})$ denotes the estimated daily case counts on day t in each city c; ***s(•)*** denotes the natural cubic spline functions; ***df*** denotes the degrees of freedom; $\boldsymbol{\alpha}_{c}$ is the intercept term of each city c; $\boldsymbol{temp}_{\,t-i,c}$ is the mean temperature on day t–i in city c; $\boldsymbol{PM}_{\mathbf{10}\,t-i,c}$ is PM_{10} on day t–i in city c; $\boldsymbol{time}_{t}$ denotes the seasonality using calendar days; $\boldsymbol{DOW}_{t}$ is the day of the week on day t; and $\boldsymbol{humid}_{t-i,c}$ and $\boldsymbol{press}_{t-i,c}$ refer to the humidity and pressure on day t–i in city c, respectively.

Numerous studies have investigated the shape of the PM-mortality exposure-response relationship. It was concluded that the shape of the PM-mortality exposure-response relationship is near linear, and a linear model without a threshold was preferred to the threshold model and to the spline model (Daniels et al., 2000; Pope, 2000; Schwartz, 1994b; Schwartz and Marcus, 1990). Therefore, linear models without a threshold were used for assessing the effect of PM_{10} on daily mortality in this study.

The sensitivity analyses were performed with adjustments for the long-term mortality trends and lag structure. First, we performed sensitivity analyses to adjust for long-term trends and seasonality in mortality. Selecting the *df* of the smooth function of time used to control for the long-term trends and seasonality is an important issue in time-series models on air pollution and mortality, because the estimates of pollution coefficients may change depending on the specification of the number of *df* (Schwartz, 1994a; Touloumi et al., 2004). We examined the model of a natural cubic spline with *df* from 1–10 per year of data. With more aggressive control for seasonality and long-term trends, the estimates appeared to be stable, and 7 *df* per year for time were selected such that only the limited information from time scales >2 months was included. This decision largely reduced the confounding seasonal factors and long-term trends (Dominici et al., 2000). We controlled for the weather covariates, which include the daily mean temperature, relative humidity, and pressure, using a natural cubic smooth function, with a *df* of 5, 4, and 3, respectively. We also controlled for the within week daily difference using the day of the week as a factor.

A lag effect exists in the association between PM_{10} and mortality (Braga et al., 2001b; Schwartz, 2000). As part of the sensitivity analysis, we also examined the PM_{10} effects from different lag structures, including both single-day lag (from lag 0 to lag 5) and multiday lag (lag 01 to lag 05). The largest effects were observed at lag 03; thus, we focused on the results of the lag 03 model and developed a second model for the study. Additional details are reported in the Appendix 5.

Second, we investigated the potential interactive patterns of PM_{10} and mean temperature on daily mortality while adjusting for other covariates. We stratified the effect of PM_{10} on mortality by the percentile of the daily mean temperature for each city. This approach allowed us to examine the heterogeneity of the effects of PM_{10} across the temperature strata, and it provided a simple, quantitative comparison of the effect of mortality on PM_{10} in the different temperature strata (Morris and Naumova, 1998; Roberts, 2004). To analyze the effects of PM_{10} in different temperature strata, we started with a Poisson log-linear model and included the temperature strata, for which it was assumed that the effect of PM_{10} on mortality was purely additive. The Model [3] is described as follows:

$$\begin{aligned}\ln\left(E\left(y_{t,c}\right)\right) = {} & \alpha_c \\ & + factor(temp\_range_{\,t-i,c}) \\ & + PM_{10\,t-i,c}{:}\,factor(temp\_ranges_{\,t-i,c}) \\ & + s\left(temp_{\,t-i,c}, df\right) + s(time_t, df) + factor(DOW_t) \\ & + s\left(humid_{t-i,c}\right) + s\left(press_{t-i,c}\right) \; [3]\end{aligned}$$

Temp_range is the indicator variable of the temperature strata, and the other definitions are the same as those in Model [2]. Using this categorical variable, Model [3] is easily extended to allow a different mortality effect on PM_{10} within the predefined temperature strata. This model allowed us to explore whether there were interactive effects between PM_{10} and temperature on mortality, while accounting for potential confounders such as the day of the week, seasonality, and other weather variables (Roberts, 2004).

The temperature cut-off points were arbitrary (Morris and Naumova, 1998; Roberts, 2004), and we defined seven strata of the daily temperatures according to city-specific percentiles of the apparent temperature distributions. Therefore, in this model, we categorized the days into seven strata according to the temperature using the percentile of the temperature for each city. Since we were interested in extreme temperature ranges, the temperature cut-offs were the 1^{st}, 5^{th}, 25^{th}, 75^{th}, 95^{th}, and 99^{th} percentile for each city: temperature $<1^{st}$ for extremely low, $1-5^{th}$ percentile for very low, $5-25^{th}$ percentile for low, $25-75^{th}$ percentile for comfort (median ± 25 percentiles), $75-95^{th}$ percentile for high, $95-99^{th}$ percentile for very high, and $>99^{th}$ percentile for extremely high. Accordingly, we explored whether the effect of PM_{10} on mortality varied by temperature strata by concentrating on extreme weather while accounting for potential confounders. All the previous analyses were repeated by considering cause-specific mortality and age- and sex-specific mortality as alternatives.

Finally, meta-analyses were performed to combine the mortality effect estimates across the cities while accounting for heterogeneity across the cities using the maximum likelihood method (Sutton et al., 2000; Van Houwelingen et al., 2002).

We used R 2.15.1 and the *gam* function in the mgcv package (version 1.7-22; R Foundation for Statistical Computing, Vienna, Austria) and *rma* in the metaphor package for all the analyses. The statistical tests were two-sided, and p-values of <0.05 were considered statistically significant. The results are expressed in terms of a percentage change (excess relative risk, ERR [%]) in the daily mortality counts for a $10\mu g/m^3$ increment in the pollutant concentrations with respective 95% confidence intervals (CI).

3.3 Results

From 2000–2009, a total of 828,787 non-accidental deaths were recorded: 230,218 due to cardiovascular disease and 51,902 due to respiratory disease. Table 3 summarizes the population and daily mortality data in the 7 South Korean cities during the study period. On average, there were approximately 33 non-accidental mortalities per day in these 7 cities, of which 9 were due to cardiovascular mortality, and 2 were due to respiratory mortality. The daily mean numbers of non-accidental, cardiovascular, and respiratory deaths varied according to the size of the city and ranged from 10–94, 3–26, and 1–6, respectively. Cardiorespiratory diseases accounted for approximately one-third of all the non-accidental deaths.

Table 3. Study populations and the number of deaths per day for non-accidental, cardiovascular, and respiratory causes in the seven South Korean cities from January 2000 to December 2009.

City	Total population	Mean number of death per day			Total number of death								
		Non-accidental	CVD	RD	Non-accidental			CVD			RD		
					Total	<65	≥65	Total	<65	≥65	Total	<65	≥65
Seoul	9,631,482	93.02	25.01	5.42	336,629	114,481	222,148	90,523	23,512	67,011	19,600	3,089	16,511
Incheon	2,632,035	26.22	7.61	1.74	94,476	32,034	62,442	27,402	6,670	20,732	6,259	1,045	5,214
Daejeon	1,490,158	13.85	3.73	1.04	49,923	15,640	34,283	13,443	3,357	10,086	3,736	518	3,218
Daegu	2,431,774	27.51	7.39	1.81	98,917	32,332	66,585	26,578	6,568	20,010	6,513	953	5,560
Gwangju	1,466,143	14.1	3.36	0.93	50,874	15,465	35,409	12,110	3,049	9,061	3,348	452	2,896
Busan	3,393,191	45.36	14.04	2.76	163,477	56,214	107,263	50,599	13,584	37,015	9,942	1,499	8,443
Ulsan	1,071,673	9.56	2.65	0.69	34,491	12,218	22,273	9,563	2,708	6,855	2,504	358	2,146

Table 4 summarizes the environmental data. The average daily concentrations of PM_{10} in the 7 South Korean cities ranged from 46.78–61.11μg/m^3, which were similar to that described in the World Health Organization Global Guidelines for ambient air quality (PM_{10} 24-h average of 50μg/m^3) (World Health Organization, 2006). The daily mean PM_{10} concentrations in the 7 strata ranged from 44.21–65.62μg/m^3 in Seoul, 35.83–64.67μg/m^3 in Incheon, 34.03–51.08μg/m^3 in Daejeon, 39.69–64.46μg/m^3 in Daegu, 29.91–53.96μg/m^3 in Gwangju, 34.57–61.12μg/m^3 in Busan, and 30.74–52.87μg/m^3 in Ulsan. The average temperature ranged from 12.78–14.88°C (Table 4).

Figure 6 shows the quantitative results of the effects of PM_{10} on non-accidental mortality, including the potential effects and its lag structure. The largest effects were observed at lag 03 where the pollution concentrations were evaluated at a 4-day moving average of pollutant concentrations on the current and previous 3 days. Additional details on the lag structure for each city are reported in the Appendix (Appendix 5).

Table 4. Summary of the environmental variables in the seven South Korean cities from January 2000 to December 2009.

City		Seoul	Incheon	Daejeon	Daegu	Gwangju	Busan	Ulsan
Latitude		37°33′N	37°29′N	36°21′N	35°52′N	35°10′N	35°06′N	35°33′N
Longitude		126°59′E	126°38′E	127°23′E	128°36′E	126°55′E	129°02′E	129°19′E
Daily mean humidity		61.68	67.28	65.66	57.7	66.45	62.9	61.18
Daily mean pressure		1016.05	1015.92	1016	1015.76	1016.17	1015.33	1015.35
Daily temperature (°C)	**Mean**	12.91	12.78	13.15	14.64	14.19	14.88	14.6
	Minimum	−15.72	−14.66	−12.60	−8.51	−8.99	−7.06	−7.36
	Median	14.46	14.09	14.49	15.84	15.49	15.87	15.62
	Maximum	30.43	30.87	30.01	31.34	30.3	30.18	30.77
	1%	−7.93	−7.02	−6.05	−3.48	−3.66	−1.90	−2.15
	5%	−3.99	−3.21	−2.62	−0.57	−0.75	1.38	0.89
	25%	4.14	4.48	4.5	6.34	5.95	8.49	7.23
	75%	21.91	21.46	21.83	22.59	22.33	21.29	21.47
	95%	26.56	25.87	26.69	28.12	27.41	26.71	27.4
	99%	28.6	27.98	28.32	30.21	28.86	28.42	29.42
Daily mean PM_{10} (μg/m^3)	**Mean**	61.11	58.39	46.78	56.26	49.22	56.44	49.75
	Maximum	89.33	88.98	74.14	83.49	77.88	80.39	71.28

Daily mean PM_{10} (μg/m^3) of each temperature stratum	**t (<1%)**	49.05	37.84	38.22	39.69	29.91	34.57	30.74
	t (1−5%)	48.6	44.8	37.77	46.38	35.89	42.03	36.55
	t (5−25%)	65.49	59.63	50.18	62.46	52.26	54.78	49.4
	t (25−75%)	65.62	64.67	51.08	58.52	53.96	61.12	52.87
	t (75−95%)	52.51	50.11	38.19	49.77	41.29	52.02	46.54
	t (95−99%)	46.59	41.35	34.03	46.65	35.79	50.19	46.96
	t (>99%)	44.21	35.83	36.29	49.44	41.86	53.35	50.96

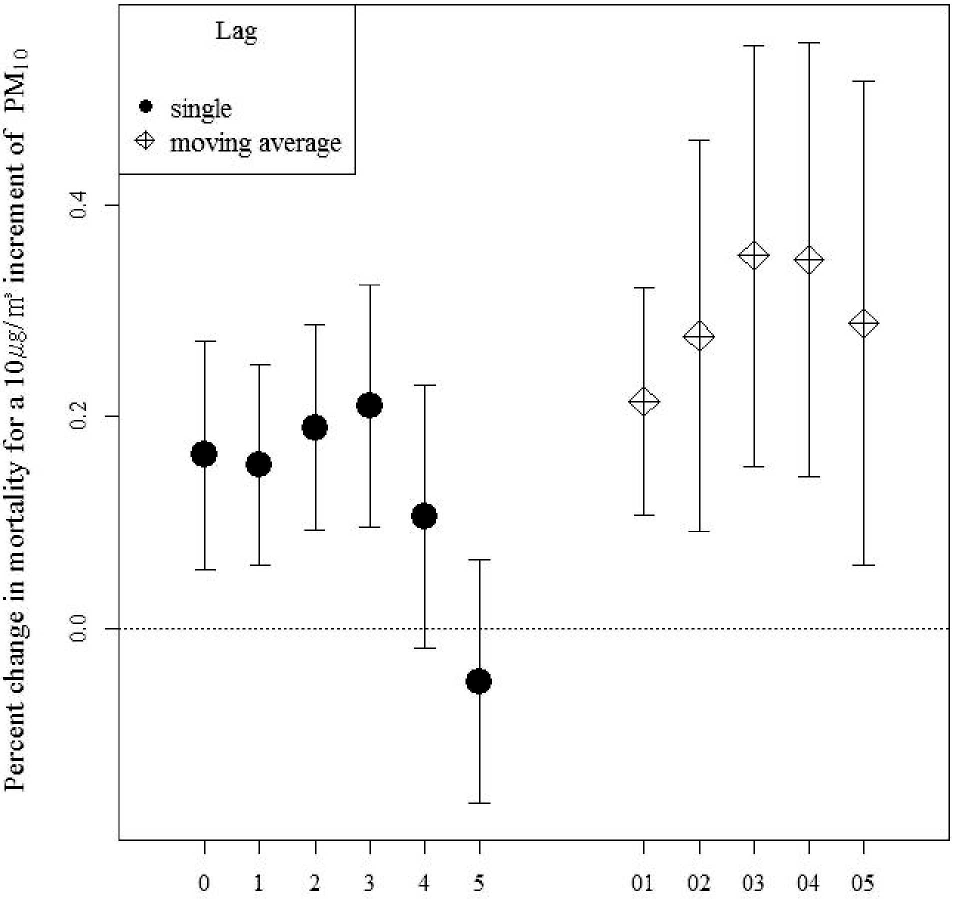


Figure 6. Pooled results of the lag structures on the effects of particulate matter <10μm (PM_{10}) in aerodynamic diameter on non-accidental mortality.

Figure 7 shows the risk of PM_{10} with the daily non-accidental, cardiovascular, and respiratory mortalities stratified by temperature (<1st, 1−5th, 5−25th, 25−75th, 75−95th, 95−99th, and >99th percentiles). The effects of PM_{10} on non-accidental mortality were the highest on days with an extremely high temperature (>99th percentile) for individuals aged <65 years; the combined analysis showed that a 10μg/m^3 increment in PM_{10} corresponded to a 4.13% (95% CI: 1.69, 6.62) increase in mortality. For individuals aged ≥65 years, the effects of PM_{10} on non-accidental mortality were the highest on days with a very high temperature (95−99th percentile); the combined analysis showed that a 10μg/m^3 increment in PM_{10} corresponded to a 1.88% (95% CI: 0.84, 2.92) increase in non-accidental mortality. The effects of PM_{10} on cardiovascular mortality were the highest on extremely hot days (>99th percentile) for individuals aged <65 years; the combined analysis showed that a 10μg/m^3 increment in PM_{10} corresponded to a 5.53% (95% CI: 0.4, 10.91) increase in cardiovascular mortality. For individuals aged ≥65 years, the effects of PM_{10} on cardiovascular mortality were the highest on days with a high temperature (95−99th percentile), but they were not significant in this temperature range. The effects of PM_{10} on respiratory mortality were the highest on days with an extremely low temperature (<1st percentile); the combined analysis showed that a 10μg/m^3 increment in PM_{10} corresponded to a 12.82% (95% CI: -5.54, 34.74) increase in respiratory mortality in individuals aged <65 years, with a 1.5% (95% CI: -6.98, 10.75) increase in mortality in those aged ≥65 years. In terms of the differences in sex groups, the effects of PM_{10} on non-accidental mortality were the highest on days with an extremely high temperature (>99th percentile) in men; the combined analysis showed that a 10μg/m^3 increment in PM_{10} corresponded to a 1.75% (95% CI: -0.14, 3.69) increase in mortality. In women, the effects of PM_{10} on non-accidental mortality were the highest on days with a very high temperature (95−99th percentile); the combined analysis showed that a 10μg/m^3 increment in PM_{10} corresponded to a 0.12% (95% CI: 0.24, 4.65) increase in non-accidental mortality. The effects of PM_{10} on cardiovascular mortality were the highest on extremely hot days (>99th percentile) in men; the combined analysis showed that a 10μg/m^3 increment in PM_{10} corresponded to a 2.51% (95% CI: -1.27, 6.44) increase in cardiovascular mortality. In women, the effects of PM_{10} on cardiovascular mortality were not significant in all the temperature ranges. The effects of PM_{10} on respiratory mortality in men and women were not significant in all the temperature ranges; however, the highest effects in women were observed on days with an extremely low temperature (<1st percentile). The combined analysis showed that a 10μg/m^3

increment in PM_{10} corresponded to an 8.06% (95% CI: -3.25, 20.68) increase in respiratory mortality (Figure 7). The city-specific results are available in the Appendix (Appendix 6-8).

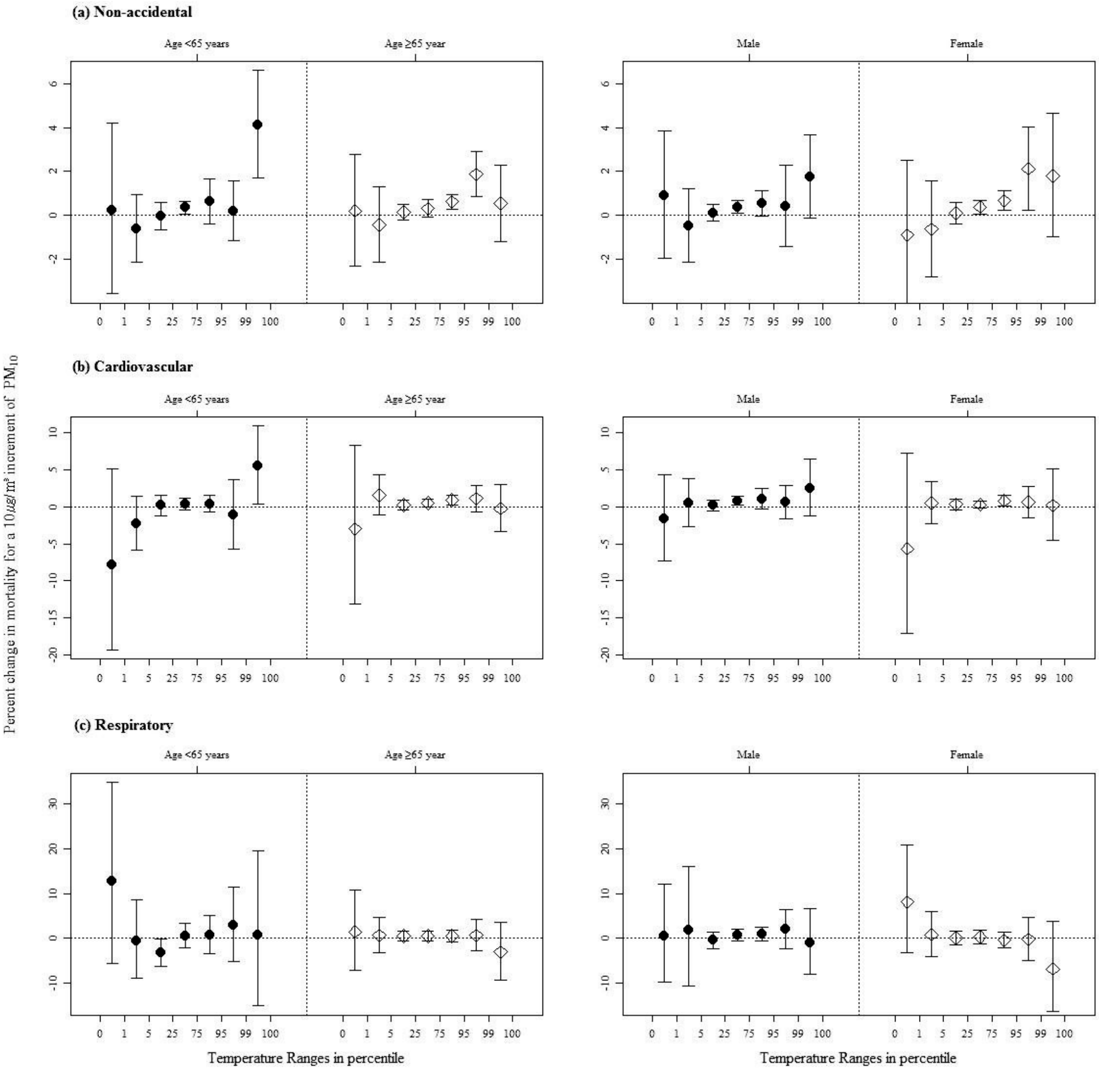


Figure 7. Pooled results of the percent change in daily (a) non-accidental mortality (b) cardiovascular mortality, and (c) respiratory mortality with a 95% confidence interval for a 10μg/m^3 increment in particulate matter <10μm in aerodynamic diameter (PM_{10}) by the temperature percentile.

3.4 Discussion

We examined the relationships between the levels of PM_{10} and death within different temperature ranges using a time-series model with stratification. Deaths due to injuries or accidents were not considered since they are not believed to be associated with air pollution, so only non-accidental, cardiovascular, and respiratory deaths were considered. In this multi-city time-series analysis, we found that temperature modified the effect of PM_{10} on mortality in seven South Korean cities. In particular, there were significantly strong harmful effects from PM_{10} on non-accidental mortality with the highest temperature range (>99th percentile) in individuals aged <65 years, with a very high temperature range (95−99th percentile) in individuals aged >65, with the highest temperature range (>99th percentile) in men, with a very high temperature range (95−99th percentile) in women. These findings are consistent with those reported by Katsouyanni et al. who found evidence of synergy between high temperatures and various air pollutants (Katsouyanni et al., 1993). In an analysis of 12 European cities, Katsouyanni et al. reported that the effects of PM_{10} were greater in warmer months (Katsouyanni et al., 1997). Similarly, by analyzing data from 100 United States cities included in the National Morbidity, Mortality, and Air Pollution Study, Peng et al. found a significant association between PM_{10} and mortality only in the summer (lag 0) and spring (lag 1) (Peng et al., 2005).

Furthermore, a dose-response relationship between the PM_{10} levels and mortality was apparent, and the mean PM_{10} levels on extremely hot days were lower than those on days with normal or low temperatures (Table 4). However, the effect of PM_{10} on mortality was found to be the highest when the temperature was very (95−99th percentile) or extremely high (>99th percentile). A previous study on the seasonal effects of PM_{10} in Seoul also noted more adverse health effects of air pollution in summer (Park et al., 2011; Yi et al., 2010). One possible interpretation for this relationship may be related to human physiology (Gordon, 2003). Temperature affects mortality through various mechanisms, and a biological interaction between air pollution and high temperatures may exist, thereby increasing the impact of pollution. Hot days can cause physiological stress and alter the physiological response to toxic agents (Gordon and Leon, 2005), which may render individuals more vulnerable to the effects of PM_{10}.

Although people living in the same city are exposed to similar levels of air pollutants, the magnitudes of the effects on health may manifest differently. For example, women, elderly, and individuals with heart or lung disease are more vulnerable to air pollution (Dominici et al., 2006; Kan et al., 2008; Peters, 2005; Plunkett et al., 1992; Pope 3rd, 2000; Wang et al., 1993). The nature of susceptibility in the air pollution-mortality relationships is complex and may be related to factors such as population, demographics, socioeconomic status, housing characteristics, and geographical factors (Makri and Stilianakis, 2008). Our findings suggested that the elderly and women are highly affected on hot days (95−99th percentile), while individuals aged <65 years and men are highly affected on extremely hot days (>99th percentile). In terms of the differences in age groups, the biological mechanism underlying the association between the exposure to PM_{10} and daily mortality can render certain subgroups more susceptible to the effects of pollutants (Pope 3rd, 2000; Sandström et al., 2003). In this study, the elderly appeared to be more susceptible to PM_{10} on hot days (95−99th percentile) than on extremely hot days (> 99%). In this regard, thermoregulation in the elderly differs from that in younger individuals (Davis and Zenser, 1985; Eržen et al., 2014; Kenney and Hodgson, 1987; Lien, 2003). Because of the deficiency of thermoregulation and other homeostatic processes in the elderly, this population may suffer more from changes in the PM_{10} levels than the general population. Therefore, a difference in the effects of PM_{10} on mortality due to the temperature between the age groups is biologically plausible. Social factors in addition to physiology can affect the susceptibility as well (Makri and Stilianakis, 2008). Behaviors of the elderly can lead to exposure that differs from younger adults (Filleul et al., 2004). There is greater awareness among the elderly on heat (Kalkstein and Sheridan, 2007; Kim et al., 2014), and confinement to indoor environments on very hot days may decrease exposure to ambient air pollutants. In addition, susceptibility of the elderly is largely attributed to a higher prevalence of underlying conditions, particularly cardiovascular and respiratory diseases (Anderson et al., 2003). In terms of the differences of results in sex groups, different physiological responses by sex are one factor. Previous studies have also reported differences by sex (Kan et al., 2008). Another possibility is that this observation may be related to different patterns of behavior or confounding social conditions (e.g., education attainment, income, poverty rate, and unemployment) (Clougherty, 2010; Krewski, 2000; O'Neill et al., 2003; Oliveira et al., 2011). Women are more likely to stay inside than men on extremely hot days since they are more aware of the heat warning system compared to men (Kim et al., 2014), which limits their exposure to air pollutants. In terms of specific causes, studies on the effects of PM_{10} on health have consistently shown exacerbations of illness in individuals with cardiovascular or respiratory diseases (Analitis et al., 2006Analitis et al., 2006; Anderson et al., 2003; Bell et al., 2004; Dominici et al., 2006; Peters et al., 1997; Peters et al., 1999; Seaton et al., 1995). Therefore, we focused on cardiovascular and respiratory death. For the former, our risk estimates due to PM_{10} were stronger on warmer days than on colder days. However, in contrast to the findings observed for cardiovascular death, an opposite trend was observed for respiratory deaths.

Although our study had several strengths, including the cause-specific death in the age and sex groups and the city-specific analysis of multiple years, it is important to note several limitations. First, the outdoor levels of air pollution may not reflect the actual exposure to PM_{10}. Second, the morbidity data rather than the mortality data may represent a more immediate response to higher temperatures and/or levels of PM_{10}, especially in the elderly. Thus, further studies on morbidity would strengthen the findings regarding the biological plausibility of the effects on mortality, temperature, and air pollution. Lastly, even though the meta-analysis can improve precision, the number of daily deaths from respiratory diseases still appears too small to be analyzed by age and sex, reducing the statistical power and resulting in wide CIs.

These findings suggest that the interaction of air pollution and climate change have an impact on health. Extreme temperature is related to global warming and other climate phenomena as well as air pollution. The possibility that extreme high temperatures intensify the health hazards of exposure to air pollution may spark new interest in the correlations between temperature, air pollution, and health. Finally, our findings require further validation, especially in areas with different weather patterns. However, if substantiated, they will provide meaningful insight into the impact of both air pollution and climate change on the general population's health. Moreover, they have clear implications on planning public health interventions and in estimating the future burden of air pollution-related deaths under predicted climate change scenarios.

3.5 Conclusions

Temperature modifies the impact of particulate pollution on death, and the risk from PM_{10} on daily mortality is increased on hot days. These findings suggest that greater consideration should be given to the role of temperature when assessing the impact of air pollution on public health.

Chapter 4

Associating mortality with prolonged high PM_{10} events in Northeast Asia

4.1 Introduction

Ambient particulate matter (PM) exposure was listed as a top-ten health risk factor, based on the global burden of disease in 2010 (Lim et al. 2013). In addition, many epidemiological studies of PM and mortality have provided evidence that daily variations in particulate air pollution concentrations are associated with daily variations in mortality counts (Katsouyanni et al. 1997; Kim et al. 2017; Samet et al. 2000; Schwartz and Dockery 1992; Ware et al. 1981; Wong et al. 2008). However, the previous time series data regarding particulate air pollution and mortality were generally analyzed using log-linear Poisson regression models for over-dispersed counts, with the daily number of deaths as the outcome, the absolute (possibly lagged) daily concentrations of pollution as the main risk factor, and smooth functions of weather variables and calendar time to adjust for time-varying confounders (Daniels et al. 2000; Schwartz and Dockery 1992). While some studies did examine the effects of cumulative days of exposure, we are not aware of any studies that have considered whether additional health risks are associated with the number of consecutive days with elevated particulate air pollution concentrations. In this context, it is important to consider both absolute daily air pollution concentrations and multi-day periods with high air pollution concentrations, as there is growing concern regarding the health effects of high air pollution concentrations in the many megacities of developing countries (Romieu I 2003). Thus, information regarding the effects of high air pollution periods (rather than the effects of single-day air pollution concentrations) might allow policy makers to address a spectrum of related public health problems, especially in the highly polluted regions of the world.

In the present study, we evaluated 28 cities in East Asia (Japan, South Korea, and China) that are relatively similar in their geography and culture, but are exposed to different air pollution conditions (Fang et al. 2009; Jeong and Park 2013; Kim et al. 2017; Lee et al. 2013; Wang and Mauzerall 2004). This approach was selected because studies with multiple locations can compare geographical areas and provide a more accurate estimation of inter-location variations using a unified analytical framework. Thus, we were able to observe the associations between mortality and the duration of multi-day periods with elevated air pollution concentrations, and to quantify the durational effect estimates while also considering the mortality effects of the absolute air pollution concentrations.

4.2 Methods

4.2.1 Study design

The present study evaluated data from 6 Japanese cities (Sapporo, Sendai, Tokyo, Nagoya, Osaka, and Kitakyushu), 7 South Korean cities (Seoul, Incheon, Daejeon, Daegu, Gwangju, Ulsan, and Busan), and 15 Chinese cities (Shenyang, Anshan, Beijing, Tangshan, Tianjin, Taiyuan, Lanzhou, Xian, Suzhou, Shanghai, Wuhan, Hangzhou, Fuzhou, Guangzhou, and Hong Kong) (Figure 8). The data collection periods varied according to location, with the earliest year being 1993 and the latest year being 2009. There may be temporal variations in the short-term effects of air pollution, although inconsistent results have left this hypothesis unconfirmed (Breitner et al. 2009; Dominici et al. 2007; Kim et al. 2015). Therefore, we did not consider the time varying effect.

4.2.2 Mortality data

Daily mortality counts were obtained from the Japanese Ministry of Health and Welfare, the Korean National Statistics Office, and the Chinese Center for Disease Prevention and Control. All causes were classified according to the 10th edition of the International Classification of Diseases (ICD-10) (World

Health Organization 2004). We excluded cases of accidental mortality and suicide, and only included non-accidental mortality in the analyses (codes A00–R99 for total non-accidental mortality, J00–J99 for respiratory diseases, and I00–I99 for cardiovascular diseases.

4.2.3 Environmental data

Data regarding weather variables were supplied by the Japanese Meteorological Agency, the Korean Meteorological Office, and the Chinese Meteorological Data Sharing Service System. The data included daily mean temperature (°C), daily mean relative humidity (%), and daily mean pressure (hPa; Japan and South Korea only). For air pollution, we collected data regarding PM_{10} (PM with an aerodynamic diameter of <10 μm), and calculated the daily representative concentrations of PM_{10} for each city by averaging the 24 hourly values from all monitoring stations in that city. Data regarding PM_{10} concentrations were provided by the Japanese National Institute for Environmental Studies, the Korean Research Institute of Public Health, and the Environmental Monitoring Center of China.

4.2.4 Statistical analysis

We calculated the additional effects of consecutive days with PM_{10}

concentrations that exceeded the threshold value after adjusting for absolute PM_{10} concentrations. The threshold value was based on the World Health Organization's Air Quality Guidelines, which recommend a 24-h average concentration of 50 μg/m^3, with interim targets of 150 μg/m^3 (IT-1), 100 μg/m^3 (IT-2), and 75 μg/m^3 (IT-3) (World Health Organization 2006). Because Japan, South Korea, and China have different ranges for PM concentrations, we defined days with elevated PM_{10} concentrations as days with concentrations of ≥75 μg/m^3. Therefore, our main variable of interest was defined as the duration of consecutive days with daily PM_{10} concentrations of ≥75 μg/m^3. For example, if the PM_{10} concentration was 36 μg/m^3 on January 1, the duration variable would be coded as "0", and if the PM_{10} concentration was 82 μg/m^3 on January 2, the duration variable would be coded as "1". If the PM_{10} concentration was 97 μg/m^3 on January 3, the duration variable would be coded as "2", and this trend would be followed until the daily mean PM_{10} concentration dropped to below 75 μg/m^3.

We performed our analysis according to city, eliminating confounding that could arise by factors varying across cities. First, we used the time series model to explore the relationships between the duration of elevated PM_{10} concentrations and mortality, while controlling for PM_{10} concentrations and temperature. For these analyses, we used a generalized additive model based on the assumption that the daily mortality counts had an over-dispersed Poisson distribution (Dominici et al. 2000; Hastie and Tibshirani 1990; Kelsall et al. 1997; Samet et al. 2000). The generalized additive model allows nonparametric smoothing functions to account for fluctuations in the confounding factors, such as seasonal variation and weather conditions, on the daily number of deaths.

To observe the mortality effect patterns over the duration variable, we applied the smoothing function to the duration variable (Appendix 9-11). We also examined the linearity hypothesis regarding the duration-mortality relation by comparing the Akaike information criterion (AIC) values from the linear and spline models. In all cases, both models gave very similar AIC values, although the linear model had a slightly better fit because, in most locations, the AIC was approximately 0.1% lower than in the spline model. Although a few Chinese cities (Fuzhou, Guangzhou, Suzhou, and Tangshan) exhibited curved patterns, most of the city-specific differences in the deviances of the two models were not statistically significant and agreed with the AIC findings. Therefore, we assumed that the duration effect was linear.

To quantify the effect estimates, the city-specific models of daily mortality counts were fitted using the duration variable as the variable of interest, while adjusting for daily mean PM_{10} concentrations, meteorological variables, and seasonal trends. Therefore, mortality risk for each additional consecutive day with PM_{10} concentrations of ≥75 μg/m^3 was calculated for each city while accounting for the effect of the PM_{10} concentrations.

$$\ln\left(E\left(y_{t,c}\right)\right) = \beta_{0c} + \beta_{1c}\, duration_{t,c} + \beta_2 PM_{10\,t-i,c} + s\left(temp_{t-i,c}\right) + s(time_t, df = 7 * number\ of\ years) + factor(DOW_t) + s(humid_{t-i,c}) + s\left(press_{t-i,c}\right) \quad [4]$$

In the above Model [4], **t** refers to the day of observation; **c** refers to the city; **i** refers to lags, $E(y_{t,c})$ denotes the estimated daily mortality counts on day t in city c; **s(•)** denotes the cubic smoothing functions; df denotes the degrees of freedom; β_{0c} is the intercept term for city c; $temp_{t-i,c}$ is the mean temperature on day t-i in city c; $PM_{10\,t-i,c}$ is the PM_{10} concentration on day t-i in city c; $time_t$ denotes seasonality using the days of calendar time; DOW_t is the day of the week on day t; and $humid_{t-i,c}$ and $press_{t-i,c}$ refer to the humidity and pressure values, respectively, on day t-i in city c. A meta-analysis of the country-specific estimates was performed using the maximum likelihood method to combine information across cities to provide health effect estimates for each country.

We multiplied the effect estimates (for each additional day) by the annual average maximum number of days with elevated PM_{10} concentrations for each country, in order to observe the mortality risk from the duration variable over the maximum period of elevated PM_{10} concentrations in each country.

$$\boldsymbol{Mortality\ Risk_{maximum\ duration}} = \boldsymbol{D_{max}} \times \left[\left(\boldsymbol{e^{\widehat{\beta}_{duration}}} - \mathbf{1}\right) \times \mathbf{100}\right]$$

Here, $\boldsymbol{D_{max}}$ is the vector of the country-specific annual average maximum numbers of days with elevated PM_{10} concentrations, and $\boldsymbol{\widehat{\beta}_{duration}}$ is the vector of the country-specific estimates. Therefore, these estimates describe the effect of prolonged elevation in PM_{10} concentrations, while accounting for the number of consecutive days with high PM_{10} concentrations.

Cause-specific and age-specific subgroups were evaluated in stratified analyses. All analyses were performed using R software (version 3.2.0) with the gam function in the mgcv package and the rma function in the metaphor package.

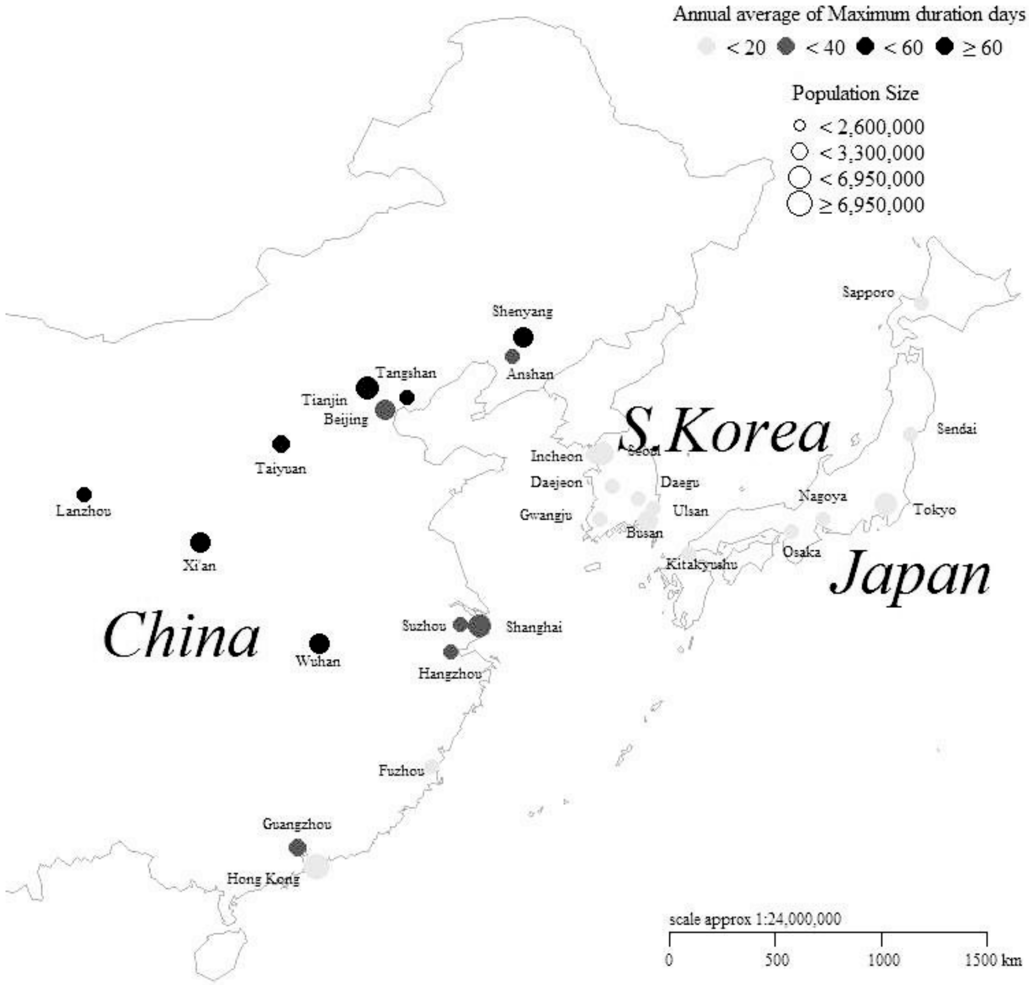


Figure 8. The locations of 28 cities in Japan (6 cities), South Korea (7 cities), and China (15 cities).

4.3 Results

Table 5 shows the mean values for the environmental variables and the daily numbers of total deaths, cardiovascular deaths, and respiratory deaths in the 28 cities. The data set included 3,662,749 deaths, with daily numbers of natural deaths ranging from 9 in Ulsan to 155 in Tokyo. Cardiovascular causes accounted for approximately 20–40% of total mortality, except in Anshan (51.2%), Tianjin (58.6%), and Wuhan (56.8%). Respiratory mortality accounted for approximately 12% of total mortality, with the lowest proportion observed in Seoul (5.8%) and the highest proportion observed in Xian (27.7%). The country-specific daily mean PM_{10} concentrations were 32.35 $\mu g/m^3$ in Japan, 55.45 $\mu g/m^3$ in South Korea, and 108.19 $\mu g/m^3$ in China. The maximum durations of consecutive days with PM_{10} concentrations of ≥75 $\mu g/m^3$ exhibited large variability, with maximum duration values ranging from 2 days in Sapporo to 125 days in Lanzhou.

The effects of prolonged elevations in PM_{10} concentrations were investigated, and the results are shown in Table 6. Each additional consecutive day with PM_{10} concentrations of ≥75 $\mu g/m^3$ was associated with a significant increase in total daily non-accidental mortality for all countries, with increases ranging from 0.68% in Japan (95% confidence interval [CI]: 0.35%, 1.01%)

to 0.24% in China (95% CI: 0.14%, 0.33%). The percent increases in cardiovascular mortality ranged from 0.96% in Japan (95% CI: 0.40%, 1.53%) to 0.27% in China (95% CI: 0.11%, 0.44%), and the increases in respiratory mortality ranged from 0.43% in Japan (95% CI: –0.45%, 1.31%) to 0.68% in China (95% CI: 0.44%, 0.93%). The durational effect of PM_{10} exposure was highest among ≥65-year-old individuals (vs. <65-year-old individuals) in Japan, although no significant difference was observed in South Korea. City-specific estimates of the effects on daily mortality according to cause of death and age are available in the Appendix (Appendix).

The annual average maximum numbers of days with elevated PM_{10} concentrations were 2.40 days for Japan, 6.96 days for South Korea, and 42.26 days for China. After adjusting for the annual average maximum number of days with elevated PM_{10} concentrations, we found increases of 1.64% (95% CI: 1.31%, 1.98%), 3.37% (95% CI: 3.19%, 3.56%), and 10.43% (95% CI: 10.33%, 10.54%) in non-accidental deaths for Japan (2.40 days), South Korea (6.96 days), and China (42.26 days), respectively. The greatest increments in mortality risk were observed for respiratory deaths, with values of 8.10% in South Korea (95% CI: 7.30%, 8.92%) and 33.40% in China (95% CI: 33.07%, 33.72%) (Figure 9). The city-specific results are available in the Appendix (Appendix 12).

Table 5. Study periods, populations, mean number of daily deaths, and the environmental variables in the 28 cities.

Country	City	Study period	Population (millions) [a]	Mortality [c]			Temperature (°C) (5th -95th percentile range)	Humidity (%) (5th -95th percentile range)	PM_{10} (μg/m³) (5th -95th percentile range)	Annual average of maximum duration [b] (days)
				Non-accidental	CVD	RD				
Japan	Sapporo	1993–2008	1.88	28.55	9.44	4.02	9.09 (–5.30, 23.10)	68.93 (51.00, 86.00)	15.19 (6.25, 31.45)	0.31
	Sendai	1993–2008	1.06	14.09	4.75	1.85	12.62 (0.50, 25.40)	71.30 (49.00, 92.85)	24.88 (8.61, 53.21)	1.38
	Tokyo	1993–2008	8.34	154.95	51.29	22.36	16.57 (5.10, 28.90)	60.81 (34.00, 85.00)	41.02 (13.60, 87.51)	3.56
	Nagoya	1993–2008	2.19	39.76	13.54	5.58	16.07 (3.40, 29.00)	66.14 (46.00, 89.00)	42.52 (15.45, 82.47)	3.56
	Osaka	1993–2008	2.59	58.6	17.71	9.01	17.16 (4.80, 29.90)	63.03 (46.00, 83.00)	38.71 (13.52, 77.61)	3.19
	Kitakyushu	1993–2008	1	22.08	6.9	3.4	17.25 (5.42, 29.40)	66.55 (48.00, 86.00)	31.78 (11.80, 63.67)	2.44
South Korea	Seoul	2000–2009	10.35	93.02	25.02	5.42	12.89 (–3.98, 26.53)	61.64 (37.76, 85.92)	63.67 (20.06, 129.79)	9.2
	Incheon	2000–2009	2.63	26.22	7.61	1.74	12.72 (–3.19, 25.86)	67.19 (43.04, 89.64)	59.82 (23.86, 116.54)	6.7
	Daejeon	2000–2009	1.48	13.86	3.73	1.04	13.08 (–2.60, 26.69)	65.63 (41.03, 87.72)	47.96 (18.15, 94.20)	5.6
	Daegu	2000–2009	2.57	27.5	7.39	1.81	14.55 (–0.50, 28.08)	57.64 (30.12, 84.71)	57.63 (24.96, 104.41)	7
	Gwangju	2000–2009	1.42	14.11	3.36	0.93	14.11 (–0.74, 27.40)	66.36 (43.90, 87.83)	50.20 (19.87, 100.70)	6.9
	Ulsan	2000–2009	0.96	9.56	2.65	0.69	14.55 (0.93, 27.35)	61.08 (29.58, 86.72)	51.00 (24.07, 91.72)	6.2
	Busan	2000–2009	3.68	45.38	14.08	2.76	14.84 (1.42, 26.69)	62.79 (31.08, 90.72)	57.88 (28.21, 105.67)	7.1
China	Shenyang	2005–2008	6.26	66.65	31.69	6.4	8.17 (–14.00, 25.00)	65.44 (40.00, 87.00)	114.22 (52.62, 214.75)	58
	Anshan	2004–2006	1.2	27.62	14.14	1.91	11.36 (–10.22, 27.50)	55.18 (29.00, 80.25)	110.88 (42.75, 221.50)	28
	Beijing	2007.1–2008.9	11.72	117.74	54.16	14.06	14.76 (–2.31, 28.50)	54.22 (20.00, 86.00)	138.90 (34.00, 298.80)	41.5

Tangshan	2006–2008	3.37	18.94	8.33	2.93	12.57 (–4.93, 27.30)	60.54 (29.00, 88.00)	97.53 (48.00, 189.05)	50.33
Tianjin	2005–2008	11.09	10.92	6.4	0.66	13.29 (–4.30, 28.30)	58.78 (26.00, 86.00)	100.84 (36.00, 212.60)	30.25
Taiyuan	2004–2008	3.43	24.15	8.93	1.9	11.23 (–6.00, 26.07)	55.06 (25.00, 83.00)	132.13 (46.06, 251.16)	59.6
Lanzhou	2004–2008	2.63	18.66	–	–	7.43 (–9.00, 21.00)	56.32 (27.00, 84.00)	156.41 (52.50, 368.37)	73.2
Xian	2004–2008	6.5	26.18	12.07	7.24	13.42 (–2.00, 28.00)	66.52 (36.00, 92.00)	132.09 (64.00, 244.00)	79
Suzhu	2005–2008	5.35	34.21	12.68	4.63	17.18 (2.00, 30.20)	77.01 (54.00, 96.00)	89.82 (32.00, 184.00)	28.75
Shanghai	2001–2004	22.32	119.04	44.21	14.29	17.72 (4.03, 30.68)	72.88 (53.50, 90.75)	102.01 (36.60, 225.67)	35.75
Wuhan	2003–2005	9.79	57.51	32.69	6.95	17.90 (2.77, 31.90)	71.14 (51.00, 91.00)	129.77 (54.00, 234.00)	69.67
Hangzhou	2002–2004	6.24	20.11	6.84	3.82	17.94 (4.20, 30.70)	72.21 (46.00, 95.00)	120.46 (47.85, 232.00)	30
Fuzhou	2004–2006	1.18	15.86	6.73	1.5	20.66 (8.47, 30.60)	69.16 (51.00, 88.25)	72.33 (26.00, 144.50)	11.33
Guangzhou	2007–2008	11.07	79.45	29.35	14.99	22.84 (11.75, 31.20)	71.00 (46.00, 90.00)	73.79 (24.77, 160.73)	29.5
Hong Kong	1996–2002	7.24	84.18	23.77	16.17	23.65 (15.00, 29.90)	77.92 (58.00, 92.00)	51.62 (21.46, 98.37)	9

[a] Source: World Population Prospects (2015)

[b] Annual average maximum duration of consecutive days with PM_{10} concentrations of ≥ 75 μg/m³

[c] Causes of death were based on the International Classification of Disease codes

Table 6. Pooled country-specific increases in mortality risk for each additional consecutive day of high PM_{10} concentrations according to cause of death and age.

	Japan	South Korea	China
All causes [a]	0.68 (0.35, 1.01)	0.48 (0.30, 0.66)	0.24 (0.14, 0.33)
Causes of death			
Cardiovascular [b]	0.96 (0.40, 1.53)	0.48 (0.14, 0.82)	0.27 (0.11, 0.44)
Respiratory [c]	0.43 (–0.45, 1.31)	1.13 (0.37, 1.89)	0.68 (0.44, 0.93)
Age			
0–64 years [d]	0.28 (–0.40, 0.96)	0.49 (0.19, 0.80)	–
≥65 years [e]	0.77 (0.41, 1.14)	0.48 (0.26, 0.70)	–

[a] Percent increase (95% confidence interval) in total daily non-accidental mortality.

[b] Percent increase (95% confidence interval) in cardiovascular disease mortality.

[c] Percent increase (95% confidence interval) in respiratory disease mortality.

[d] Percent increase (95% confidence interval) in total daily non-accidental mortality at <65 years of age.

[e] Percent increase (95% confidence interval) in total daily non-accidental mortality at ≥65 years of age.

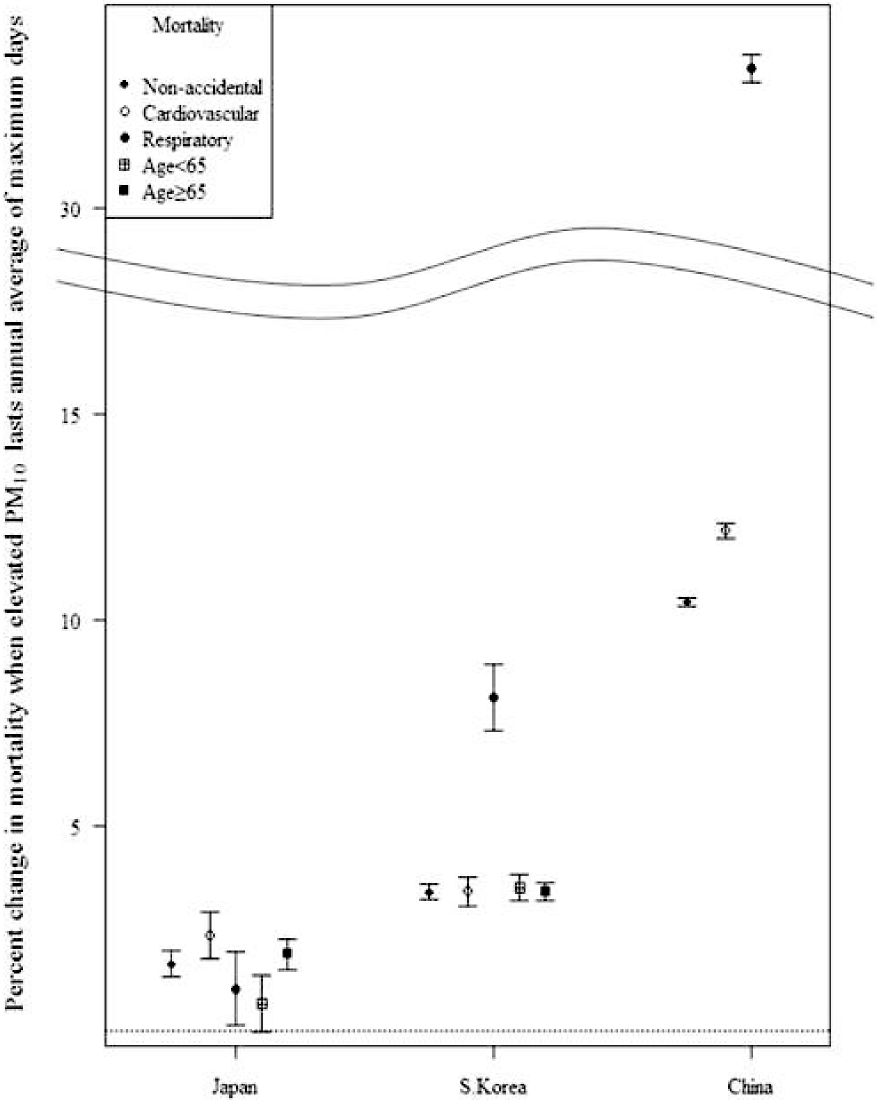


Figure 9. Mortality risk for high PM_{10} concentrations lasting the annual average maximum duration.

4.4 Discussion

We observed significant durational effects on mortality for consecutive days with elevated PM_{10} concentrations while accounting for the effects of absolute PM_{10} concentrations. Although many relevant studies have evaluated the association between PM concentrations and health, the focus has been on absolute air pollution concentrations as the variable of interest, and not on the health effects of prolonged periods with elevated PM_{10} concentrations. To the best of our knowledge, this is the first study to examine the association between mortality and duration of elevated air pollution, and to quantify the durational effects while accounting for absolute air pollution concentrations. Moreover, the present study evaluated data from multiple sites with large differences in their air pollution conditions. Our results indicate that there are additional mortality risks due to the duration of multi-day periods with elevated air pollution in all three East Asian countries that we evaluated.

Among all continents, Asia has the highest greenhouse gas emissions and plays an instrumental role in the global environment (Wang et al. 2014). Furthermore, China is now the world's largest consumer of coal and the leading producer of greenhouse gases (Siddiqi 1995; Streets et al. 2003). China has exhibited 10% annual increases in emissions, and its major cities (e.g., Beijing) have air pollution concentrations that are 100 times higher than the World Health Organization's recommended limits. In addition, 40% of Chinese cities fail to meet the World Health Organization's residential air quality standards. In this context, China remains heavily dependent on coal for energy, which generates significant particulate air pollution. Thus, it is valuable to compare the health effects of air pollution in China and adjacent countries, and our findings are enhanced by the use of multiple nearby locations. Although China exhibited the weakest durational effect, it had extremely long periods with high PM_{10} concentrations, compared to South Korea and Japan, which resulted in the greatest overall mortality risk for prolonged periods of elevated PM_{10} concentrations.

Although Japan had the lowest PM_{10} concentrations and the shortest periods with elevated PM_{10} concentrations, it exhibited the greatest durational effect among the 3 countries. In addition, epidemiological studies have reported associations of air pollution with health effects in the general population, even at concentrations below the current air quality standards (Brunekreef et al. 1995; Desqueyroux et al. 2002; Hoek and Brunekreef 1994). Therefore, high PM_{10} events are problematic in both developing and developed countries.

We also observed that the durational effects varied according to age and the cause of death. Respiratory mortality in South Korea and China was associated with higher incremental risks, compared to cardiovascular mortality, although cardiovascular mortality in Japan was associated with a higher incremental risk, compared to respiratory mortality. The durational effect of PM_{10} exposure was also greatest among $\geq$65-year-old individuals in Japan (vs. <65-year-old individuals), although no significant difference was observed in South Korea. This result might be related to differences in population demographics, as Japan remains the world leader in population aging, despite the increased aging population in South Korea (Suzuki 2013).

Policy-based interventions may help reduce the morbidity and mortality that are associated with elevated air pollution periods. For example, accurate warning systems can alert the public to take the necessary actions and precautions. In this context, research indicates that single days with elevated air pollution are dangerous, and prolonged periods with elevated air pollution have an additive effect on human health. Thus, individuals could take measures to avoid prolonged exposure to high PM_{10} concentrations. These measures might involve using an air cleaner, staying inside, and/or taking a leave or vacation from work during periods with high PM_{10} concentrations. Governments could also facilitate adequate risk communication measures, and could consider re-scheduling large outdoor events or activities during periods with high PM_{10} concentrations.

A central limitation of the present study is the data quality, as it is assumed that there is underreporting of mortality in China (Banister and Hill 2004; Merli 1998; Zimmer et al. 2007). Nevertheless, the present study aimed to estimate the association between air pollution and mortality, and not to estimate the specific mortality rates. Therefore, any issues with the data quality are likely not associated with variations in the air pollution concentrations. Another limitation is that intra-community variations were not considered in the present study, and occupation and lifestyle factors may affect exposure to air pollution (e.g., outdoor workers have greater exposure and different exposure patterns, compared to office workers). This discrepancy may have placed greater emphasis on populations with urban characteristics in our analyses.

4.5 Conclusions

Our findings suggest that the duration of periods with elevated PM_{10} concentrations is associated with increased risk of mortality in East Asia. This effect was in addition to the mortality effects of absolute daily PM_{10} concentrations, and was consistently observed in our country-specific, age-specific, and mortality type-specific subanalyses. A better understanding of differential risks will help guide public policy decisions regarding risk assessments and air pollution standards.

Chapter 5

General Discussion

5.1 Summary of the topics

The adverse health effects of episodes of air pollution were established over 60 years ago by investigations in Europe and North America , and the adverse health effects of air pollution have been the subject to intense study ever since, not only in developed countries, but also in developing and undeveloped countries.

We demonstrated that seasonal and geographical variation in the short-term association of PM_{10} with daily mortality (Chapter 2), the modifying effect of temperature on the relationship between PM_{10} and mortality due to non-accidental, cardiovascular, and respiratory death (Chapter 3), and the durational effects with the number of elevated PM_{10} days while considering the adverse health effects from the PM_{10} level itself as well (Chapter 4).

Although outside of the scope of this study, it is interesting to mention that the biological plausibility of the association between particulate air pollution and health has been assessed for respiratory and cardiovascular diseases, with an increasing amount of evidence pointing toward a causal link. Further epidemiological identification of individual traits associated with increased risk of mortality and morbidity from increased concentrations of PM air pollution will continue to direct ongoing research into the pathological mechanism from exposure, provide critical data for risk assessment, and inform policymakers.

5.2 Public health insights

Most cities where outdoor air pollution is monitored do not meet the WHO guidelines for acceptable pollutant levels. Excessive air pollution is often a by-product of unsustainable policies in sectors such as transport, energy, waste management, and industry, and reducing air pollution is an incredibly efficient way to improve the health of a population. In most cases, healthier strategies will also be more economical in the long term due to healthcare cost savings as well as climate improvement.

Avoiding or reducing exposure could be an alternative way to reduce air pollution's adverse health effects, and policy-based interventions may help reduce the morbidity and mortality that are associated with air pollution. For example, accurate warning systems can alert the public to take necessary actions and precautions. Governments must also facilitate adequate risk communication measures, and should consider re-scheduling large outdoor events or activities during periods with high PM_{10} concentrations.

Reference

Analitis, A., Katsouyanni, K., Dimakopoulou, K., Samoli, E., Nikoloulopoulos, A.K., Petasakis, Y., Touloumi, G., Schwartz, J., Anderson, H.R. and Cambra, K., 2006. Short-term effects of ambient particles on cardiovascular and respiratory mortality. Epidemiology, 17(2): 230-233.

Anderson, H., Atkinson, R., Bremner, S. and Marston, L., 2003. Particulate air pollution and hospital admissions for cardiorespiratory diseases: are the elderly at greater risk? The European Respiratory Journal, Supplement, 40: 39s-46s.

Anderson, J.O., Thundiyil, J.G. and Stolbach, A., 2012. Clearing the air: a review of the effects of particulate matter air pollution on human health. Journal of Medical Toxicology, 8(2): 166-175.

Atkinson, R.W., Anderson, H.R., Sunyer, J., Ayres, J., Baccini, M., Vonk, J.M., Boumghar, A., Forastiere, F., Forsberg, B., Touloumi, G., Schwartz, J. and Katsouyanni, K., 2001. Acute effects of particulate air pollution on respiratory admissions: results from APHEA 2 project. Air Pollution and Health: a European Approach. American Journal of Respiratory Critical Care Medicine, 164(10 Pt 1): 1860-6.

Auchincloss, A.H., Roux, A.V.D., Dvonch, J.T., Brown, P.L., Barr, R.G., Daviglus, M.L., Goff Jr, D.C., Kaufman, J.D. and O'Neill, M.S., 2008. Associations between recent exposure to ambient fine particulate matter and blood pressure in the Multi-Ethnic Study of Atherosclerosis (MESA). Environental Health Perspectives, 116(4): 486.

Baccini, M., Biggeri, A., Accetta, G., Kosatsky, T., Katsouyanni, K., Analitis, A., Anderson, H.R., Bisanti, L., D'Ippoliti, D. and Danova, J., 2008. Heat effects on mortality in 15 European cities. Epidemiology, 19(5): 711-719.

Basu, R., 2009. High ambient temperature and mortality: a review of epidemiologic studies from 2001 to 2008. Environmental Health, 8(1): 40.

Basu, R. and Samet, J.M., 2002. Relation between elevated ambient temperature and mortality: a review of the epidemiologic evidence. Epidemiologic Reviews, 24(2): 190-202.

Bateson, T.F. and Schwartz, J., 2004. Who is sensitive to the effects of particulate air pollution on mortality?: a case-crossover analysis of effect modifiers. Epidemiology, 15(2): 143-149.

Bell, M.L., Ebisu, K., Peng, R.D., Walker, J., Samet, J.M., Zeger, S.L. and Dominici, F., 2008. Seasonal and regional short-term effects of fine particles on hospital admissions in 202 US counties, 1999–2005. American Journal of Epidemiology, 168(11): 1301-1310.

Bell, M.L., Samet, J.M. and Dominici, F., 2004. Time-series studies of particulate matter. Annual Review of Public Health, 25: 247-280.

Braga, A.L., Zanobetti, A. and Schwartz, J., 2001a. The time course of weather-related deaths. Epidemiology, 12(6): 662-7.

Braga, A.L.F., Zanobetti, A. and Schwartz, J., 2001b. The lag structure between particulate air pollution and respiratory and cardiovascular deaths in 10 US cities. Journal of Occupational and Environmental Medicine, 43(11): 927-933.

Brunekreef, B. and Holgate, S.T., 2002. Air pollution and health. The Lancet, 360(9341): 1233-1242.

Cakmak, S., Dales, R.E. and Judek, S., 2006. Do gender, education, and income modify the effect of air pollution gases on cardiac disease? Journal of Occupational and Environmental Medicine, 48(1): 89-94.

Chen, B., Hong, C. and Kan, H., 2004. Exposures and health outcomes from outdoor air pollutants in China. Toxicology, 198(1): 291-300.

Chen, R., Peng, R.D., Meng, X., Zhou, Z., Chen, B. and Kan, H., 2013. Seasonal variation in the acute effect of particulate air pollution on mortality in the China Air Pollution and Health Effects Study (CAPES). Science of the Total Environment, 450: 259-265.

Clougherty, J.E., 2010. A growing role for gender analysis in air pollution epidemiology. Environental Health Perspectives, 118(2): 167-76.

Crouse, D.L., Peters, P.A., van Donkelaar, A., Goldberg, M.S., Villeneuve, P.J., Brion, O., Khan, S., Atari, D.O., Jerrett, M. and Pope III, C.A., 2015. Risk of nonaccidental and cardiovascular mortality in relation to long-term exposure to low concentrations of fine particulate matter: a Canadian national-level cohort study, University of British Columbia.

Curriero, F.C., Heiner, K.S., Samet, J.M., Zeger, S.L., Strug, L. and Patz, J.A., 2002. Temperature and mortality in 11 cities of the eastern United States. American Journal of Epidemiology, 155(1): 80-87.

Daniels, M.J., Dominici, F., Samet, J.M. and Zeger, S.L., 2000. Estimating particulate matter-mortality dose-response curves and threshold levels: An analysis of daily time-series for the 20 largest US cities. American Journal of Epidemiology, 152(5): 397-406.

Davis, B.B. and Zenser, T.V., 1985. Biological changes in thermoregulation in the elderly. Homeostatic Function and Aging: 157-166.

Dockery, D.W., Pope, C.A., Xu, X., Spengler, J.D., Ware, J.H., Fay, M.E., Ferris Jr, B.G. and Speizer, F.E., 1993. An association between air pollution and mortality in six US cities. New England Journal of Medicine, 329(24): 1753-1759.

Dominici, F., McDermott, A. and Hastie, T.J., 2004. Improved semiparametric time series models of air pollution and mortality. Journal of the American Statistical Association, 99(468): 938-948.

Dominici, F., Peng, R.D., Bell, M.L., Pham, L., McDermott, A., Zeger, S.L. and Samet, J.M., 2006. Fine particulate air pollution and hospital admission for cardiovascular and respiratory diseases. Journal of the American Medical Association, 295(10): 1127-1134.

Dominici, F., Peng, R.D., Zeger, S.L., White, R.H. and Samet, J.M., 2007. Particulate air pollution and mortality in the United States: did the risks change from 1987 to 2000? American Journal of Epidemiology, 166(8): 880-888.

Dominici, F., Samet, J.M. and Zeger, S.L., 2000. Combining evidence on air pollution and daily mortality from the 20 largest US cities: a hierarchical modelling strategy. Journal of the Royal Statistical Society: Series A (Statistics in Society), 163(3): 263-302.

Eržen, I., Medved, S. and Kastelec, D., 2014. Experimental research on physiological response of elderly with cardiovascular disease during heat wave period. Indoor and Built Environment. 24(4): 534-543.

Everson, P.J. and Morris, C.N., 2000. Inference for multivariate normal hierarchical models. Journal of the Royal Statistical Society: Series B (Statistical Methodology), 62(2): 399-412.

Filleul, L., Rondeau, V., Cantagrel, A., Dartigues, J.-F. and Tessier, J.-F., 2004. Do subject characteristics modify the effects of particulate air pollution on daily mortality among the elderly? Journal of Occupational and Environmental Medicine, 46(11): 1115-1122.

Gasparrini, A. and Armstrong, B., 2011. The impact of heat waves on mortality. Epidemiology, 22(1): 68.

Gasparrini, A., Armstrong, B., Kovats, S. and Wilkinson, P., 2012. The effect of high temperatures on cause-specific mortality in England and Wales. Occupational and Environmental Medicine, 69(1): 56-61.

Goldberg, M.S., Burnett, R.T., Bailar 3rd, J., Tamblyn, R., Ernst, P., Flegel, K., Brook, J., Bonvalot, Y., Singh, R. and Valois, M.-F., 2001. Identification of persons with cardiorespiratory conditions who are at risk of dying from the acute effects of ambient air particles. Environmental Health Perspectives, 109(Suppl 4): 487.

Gordon, C.J., 2003. Role of environmental stress in the physiological response to chemical toxicants. Environmental Research, 92(1): 1-7.

Gordon, C.J. and Leon, L.R., 2005. Thermal stress and the physiological response to environmental toxicants. Reviews on Environmental Health, 20(4): 235-264.

Gouveia, N. and Fletcher, T., 2000. Time series analysis of air pollution and mortality: effects by cause, age and socioeconomic status. Journal of Epidemiology and Community Health, 54(10): 750-755.

Guo, Y., Barnett, A.G., Pan, X., Yu, W. and Tong, S., 2011. The impact of temperature on mortality in Tianjin, China: a case− crossover design with a distributed lag non-linear model. Environmental Health Perspectives, 119: 1719-1725.

Hales, S., Salmond, C., Town, G.I., Kjellstrom, T. and Woodward, A., 2000. Daily mortality in relation to weather and air pollution in Christchurch, New Zealand. Australian and New Zealand Journal of Public Health, 24(1): 89-91.

Hastie, T.J. and Tibshirani, R.J., 1990. Generalized additive models, 43. CRC Press.

Huang, W., Cao, J., Tao, Y., Dai, L., Lu, S.-E., Hou, B., Wang, Z. and Zhu, T., 2012. Seasonal variation of chemical species associated with short-term mortality effects of PM2. 5 in Xi'an, a central city in China. American Journal of Epidemiology, 175(6): 556–566.

International Agency for Research on Cancer, 2013. Outdoor air pollution a leading environmental cause of cancer deaths. Lyon, Geneva.

Kalkstein, A. and Sheridan, S., 2007. The social impacts of the heat–health watch/warning system in Phoenix, Arizona: assessing the perceived risk and response of the public. International Journal of Biometeorology, 52(1): 43-55.

Kampa, M. and Castanas, E., 2008. Human health effects of air pollution. Environmental Pollution, 151(2): 362-367.

Kan, H., London, S.J., Chen, G., Zhang, Y., Song, G., Zhao, N., Jiang, L. and Chen, B., 2008a. Season, sex, age, and education as modifiers of the effects of outdoor air pollution on daily mortality in Shanghai, China: The Public Health and Air Pollution in Asia (PAPA) Study. Environmental Health Perspectives, 116(9): 1183-1188.

Katsouyanni, K., Pantazopoulou, A., Touloumi, G., Tselepidaki, I., Moustris, K., Asimakopoulos, D., Poulopoulou, G. and Trichopoulos, D., 1993. Evidence for interaction between air pollution and high temperature in the causation of excess mortality. Archives of Environmental Health: An International Journal, 48(4): 235-242.

Katsouyanni, K., Schwartz, J., Spix, C., Touloumi, G., Zmirou, D., Zanobetti, A., Wojtyniak, B., Vonk, J., Tobias, A. and Pönkä, A., 1996. Short term effects of air pollution on health: a European approach using epidemiologic time series data: the APHEA protocol. Journal of Epidemiology and Community Health, 50 (Suppl 1): S12-S18.

Katsouyanni, K., Touloumi, G., Samoli, E., Gryparis, A., Le Tertre, A., Monopolis, Y., Rossi, G., Zmirou, D., Ballester, F. and Boumghar, A., 2001. Confounding and effect modification in the short-term effects of ambient particles on total mortality: results from 29 European cities within the APHEA2 project. Epidemiology, 12(5): 521-531.

Katsouyanni, K., Touloumi, G., Spix, C., Schwartz, J., Balducci, F., Medina, S., Rossi, G., Wojtyniak, B., Sunyer, J. and Bacharova, L., 1997. Short term effects of ambient sulphur dioxide and particulate matter on mortality in 12 European cities: results from time series data from the APHEA project. British Medical Journal, 314(7095): 1658.

Kenney, W.L. and Hodgson, J.L., 1987. Heat tolerance, thermoregulation and ageing. Sports Medicine, 4(6): 446-456.

Kim, M., Kim, H. and You, M., 2014. The role of public awareness in health-protective behaviours to reduce heat wave risk. Meteorological Applications, 21(4): 867-872.

Kim, S.E., Lim, Y.-H. and Kim, H., 2015. Temperature modifies the association between particulate air pollution and mortality: A multi-city study in South Korea. Science of the Total Environment, 524: 376-383.

Krewski, D., Burnett, R.T., Goldberg, M.S., Hoover, K., Siemiatycki, J., Jerrett, M., Abrahamowicz, M., White, W.H., 2000. Re-analysis of the Harvard six-cities and American Cancer Society Cohort Studies of particulate air pollution and mortality, Health Effects Institute, Cambridge, MA.

Laden, F., Neas, L.M., Dockery, D.W. and Schwartz, J., 2000. Association of fine particulate matter from different sources with daily mortality in six US cities. Environental Health Perspectives, 108(10): 941-947.

Lee, J.-T., Son, J.-Y. and Cho, Y.-S., 2007. A comparison of mortality related to urban air particles between periods with Asian dust days and without Asian dust days in Seoul, Korea, 2000–2004. Environmental Research, 105(3): 409-413.

Levy, D., Sheppard, L., Checkoway, H., Kaufman, J., Lumley, T., Koenig, J. and Siscovick, D., 2001. A case-crossover analysis of particulate matter air pollution and out-of-hospital primary cardiac arrest. Epidemiology, 12(2): 193-199.

Lien, C.A., 2003. Thermoregulation in the elderly. Syllabus on Geriatric Anesthesiology: 20.

Ma, Y., Chen, R., Pan, G., Xu, X., Song, W., Chen, B. and Kan, H., 2011. Fine particulate air pollution and daily mortality in Shenyang, China. Science of the Total Environment, 409(13): 2473-2477.

Makri, A. and Stilianakis, N.I., 2008. Vulnerability to air pollution health effects. International Journal of Hygiene and Environmental Health, 211(3–4): 326-336.

Mar, T.F., Norris, G.A., Koenig, J.Q. and Larson, T.V., 2000. Associations between air pollution and mortality in Phoenix, 1995-1997. Environental Health Perspectives, 108(4): 347.

McMichael, A.J., Wilkinson, P., Kovats, R.S., Pattenden, S., Hajat, S., Armstrong, B., Vajanapoom, N., Niciu, E.M., Mahomed, H. and Kingkeow, C., 2008. International study of temperature, heat and urban mortality: the 'ISOTHURM'project. International Journal of Epidemiology, 37(5): 1121-1131.

Moolgavkar, S.H. and Luebeck, E.G., 1996. A critical review of the evidence on particulate air pollution and mortality. Epidemiology: 420-428.

Morris, R.D. and Naumova, E.N., 1998. Carbon monoxide and hospital admissions for congestive heart failure: evidence of an increased effect at low temperatures. Environental Health Perspectives, 106(10): 649.

Nawrot, T.S., Torfs, R., Fierens, F., De Henauw, S., Hoet, P.H., Van Kersschaever, G., De Backer, G. and Nemery, B., 2007. Stronger associations between daily mortality and fine particulate air pollution in summer than in winter: evidence from a heavily polluted region in western Europe. Journal of Epidemiology and Community Health, 61(2): 146-9.

Nel, A., 2005. Air pollution-related illness: effects of particles. Science, 308(5723): 804-806.

O'Neill, M.S., Jerrett, M., Kawachi, I., Levy, J.I., Cohen, A.J., Gouveia, N., Wilkinson, P., Fletcher, T., Cifuentes, L. and Schwartz, J., 2003. Health, wealth, and air pollution: advancing theory and methods. Environental Health Perspectives, 111(16): 1861.

Oliveira, M.S.d., Leon, A.P.d., Mattos, I.E. and Koifman, S., 2011. Differential susceptibility according to gender in the association between air pollution and mortality from respiratory diseases. Cadernos de Saúde Pública, 27(9): 1827-1836.

Park, A.K., Hong, Y.C. and Kim, H., 2011. Effect of changes in season and temperature on mortality associated with air pollution in Seoul, Korea. Journal of Epidemiology and Community Health, 65: 368-375.

Peng, R.D., Dominici, F., Pastor-Barriuso, R., Zeger, S.L. and Samet, J.M., 2005. Seasonal analyses of air pollution and mortality in 100 US cities. American journal of epidemiology, 161(6): 585-594.

Peters, A., 2005. Particulate matter and heart disease: evidence from epidemiological studies. Toxicology and applied pharmacology, 207(2): 477-482.

Peters, A., Döring, A., Wichmann, H.E. and Koenig, W., 1997. Increased plasma viscosity during an air pollution episode: a link to mortality? The lancet, 349(9065): 1582-1587.

Peters, A., Perz, S., Döring, A., Stieber, J., Koenig, W. and Wichmann, H.E., 1999. Increases in Heart Rate during an Air Pollution Episode. American Journal of Epidemiology, 150(10): 1094-1098.

Plunkett, L., Turnbull, D. and Rodricks, J., 1992. Differences between adults and children affecting exposure assessment. Similarities and

Differences Between Children and Adults: Implications for Risk Assessment: 79-94.

Pope 3rd, C., 2000. Epidemiology of fine particulate air pollution and human health: biologic mechanisms and who's at risk? Environental Health Perspectives, 108(Suppl 4): 713.

Pope, C.A., 2000. Invited Commentary: Particulate Matter-Mortality Exposure-Response Relations and Threshold. American Journal of Epidemiology, 152(5): 407-412.

Pope III, C.A. and Dockery, D.W., 2006. Health effects of fine particulate air pollution: lines that connect. Journal of the Air & Waste Management Association, 56(6): 709-742.

Qian, Z., He, Q., Lin, H.-M., Kong, L., Bentley, C.M., Liu, W. and Zhou, D., 2008. High temperatures enhanced acute mortality effects of ambient particle pollution in the “oven” city of Wuhan, China. Environental Health Perspectives, 116(9): 1172-1178.

Qian, Z., Lin, H.-M., Stewart, W.F., Kong, L., Xu, F., Zhou, D., Zhu, Z., Liang, S., Chen, W. and Shah, N., 2010. Seasonal pattern of the acute mortality effects of air pollution. Journal of the Air & Waste Management Association, 60(4): 481-488.

Ren, C. and Tong, S., 2006. Temperature modifies the health effects of particulate matter in Brisbane, Australia. International Journal of Biometeorology, 51(2): 87-96.

Roberts, S., 2004. Interactions between particulate air pollution and temperature in air pollution mortality time series studies. Environmental Research, 96(3): 328-337.

Sacks, J.D., Stanek, L.W., Luben, T.J., Johns, D.O., Buckley, B.J., Brown, J.S. and Ross, M., 2011. Particulate matter-induced health effects: who is susceptible? Environental Health Perspectives, 119(4): 446.

Samet, J., Zeger, S., Kelsall, J., Xu, J. and Kalkstein, L., 1998. Does weather confound or modify the association of particulate air pollution with mortality?: an analysis of the Philadelphia data, 1973–1980. Environmental Research, 77(1): 9-19.

Samet, J.M., Zeger, S.L., Dominici, F., Curriero, F., Coursac, I., Dockery, D.W., Schwartz, J. and Zanobetti, A., 2000. The national morbidity, mortality, and air pollution study. Part II: Morbidity and mortality from air pollution in the United States. Research Report (Health Effects Institute), 94(Pt 2): 5.

Sandström, T., Frew, A., Svartengren, M. and Viegi, G., 2003. The need for a focus on air pollution research in the elderly. European Respiratory Journal, 21(40 suppl): 92s-95s.

Schwartz, J., 1994a. Nonparametric smoothing in the analysis of air pollution and respiratory illness. Canadian Journal of Statistics, 22(4): 471-487.

Schwartz, J., 1994b. Total suspended particulate matter and daily mortality in Cincinnati, Ohio. Environental Health Perspectives, 102(2): 186-189.

Schwartz, J., 2000. The distributed lag between air pollution and daily deaths. Epidemiology, 11(3): 320-326.

Schwartz, J. and Marcus, A., 1990. Mortality and air pollution J London: A time series analysis. American Journal of Epidemiology, 131(1): 185-194.

Schwartz, J., Spix, C., Touloumi, G., Bacharova, L., Barumamdzadeh, T., Le Tertre, A., Piekarksi, T., De Leon, A.P., Pönkä, A. and Rossi, G., 1996. Methodological issues in studies of air pollution and daily counts of deaths or hospital admissions. Journal of Epidemiology and Community Health, 50(Suppl 1): S3-11.

Schwartz, J. and Zanobetti, A., 2000. Using meta-smoothing to estimate dose-response trends across multiple studies, with application to air pollution and daily death. Epidemiology, 11(6): 666-672.

Seaton, A., Godden, D., MacNee, W. and Donaldson, K., 1995. Particulate air pollution and acute health effects. The lancet, 345(8943): 176-178.

Stafoggia, M., Schwartz, J., Forastiere, F. and Perucci, C., 2008. Does temperature modify the association between air pollution and mortality? A multicity case-crossover analysis in Italy. American Journal of Epidemiology, 167(12): 1476-1485.

Steenland, K. and Savitz, D.A., 1997. Topics in environmental epidemiology. Oxford University Press, USA.

Straif, K., Cohen, A. and Samet, J., 2013. Air Pollution and Cancer: IARC Scientific Publication No. 161. International Agency for Research on Cancer, Lyon, France.

Sutton, A.J., Abrams, K.R., Jones, D.R., Jones, D.R., Sheldon, T.A. and Song, F., 2000. Methods for meta-analysis in medical research. J. Wiley.

Tanaka, T.Y. and Chiba, M., 2006. A numerical study of the contributions of dust source regions to the global dust budget. Global and Planetary Change, 52(1): 88-104.

Theophanides, M., Anastassopoulou, J. and Theophanides, T., 2011. Air Polluted Environment and Health Effects. INTECH Open Access Publisher.

Touloumi, G., Atkinson, R., Tertre, A.L., Samoli, E., Schwartz, J., Schindler, C., Vonk, J.M., Rossi, G., Saez, M. and Rabszenko, D., 2004. Analysis of health outcome time series data in epidemiological studies. Environmetrics, 15(2): 101-117.

UNEP Year Book, 2014. Emerging issues update. Air Pollution: World's Worst Environmental Health Risk. United Nations Environment Programme, Nairobi, Kenya.

Van Houwelingen, H.C., Arends, L.R. and Stijnen, T., 2002. Advanced methods in meta-analysis: multivariate approach and meta-regression. Statistics in Medicine, 21(4): 589-624.

Wang, X., Dockery, D.W., Wypij, D., Gold, D.R., Speizer, F.E., Ware, J.H. and Ferris, B.G., 1993. Pulmonary Function Growth Velocity in Children 6 to 18 Years of Age. American Journal of Respiratory and Critical Care Medicine, 148(6): 1502-1508.

Wong, C.-M., Vichit-Vadakan, N., Kan, H. and Qian, Z., 2008. Public Health and Air Pollution in Asia (PAPA): a multicity study of short-term effects of air pollution on mortality. Environental Health Perspectives, 116(9): 1195.

World Health Organization, 1996. International statistical classification of diseases and related health problems 10th Revision (ICD-10). World Health Organization, Geneva, Switzerland.

World Health Organization, 2003. Health aspects of air pollution with particulate matter, ozone and nitrogen dioxide: report on a WHO working group, Bonn, Germany.

World Health Organization, 2004. Health Aspects of Air Pollution: Results from the WHO Project "Systematic Review of Aspects of air Pollution in Europe", World Health Organization, Copenhagen, Denmark.

World Health Organization, 2006. Air quality guidelines for particulate matter, ozone, nitrogen dioxide, and sulfur dioxide. Global update 2005, Summary of risk assessment, World Health Organization, Geneva, Switzerland.

Yauk, C., Polyzos, A., Rowan-Carroll, A., Somers, C.M., Godschalk, R.W., Van Schooten, F.J., Berndt, M.L., Pogribny, I.P., Koturbash, I. and Williams, A., 2008. Germ-line mutations, DNA damage, and global hypermethylation in mice exposed to particulate air pollution in an urban/industrial location. Proceedings of the National Academy of Sciences, 105(2): 605-610.

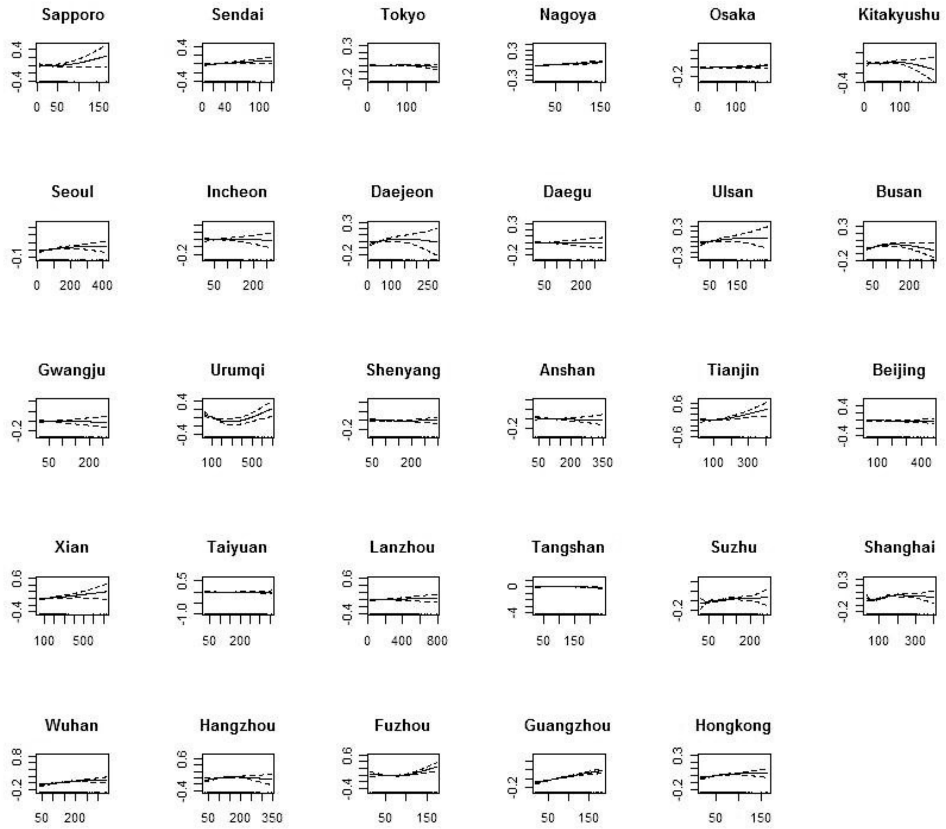
Yi, O., Hong, Y.-C. and Kim, H., 2010. Seasonal effect of PM10 concentrations on mortality and morbidity in Seoul, Korea: A temperature-matched case-crossover analysis. Environmental Research, 110(1): 89-95.

Zanobetti, A. and Schwartz, J., 2009. The effect of fine and coarse particulate air pollution on mortality: a national analysis. Environental Health Perspectives, 117(6): 898-903.

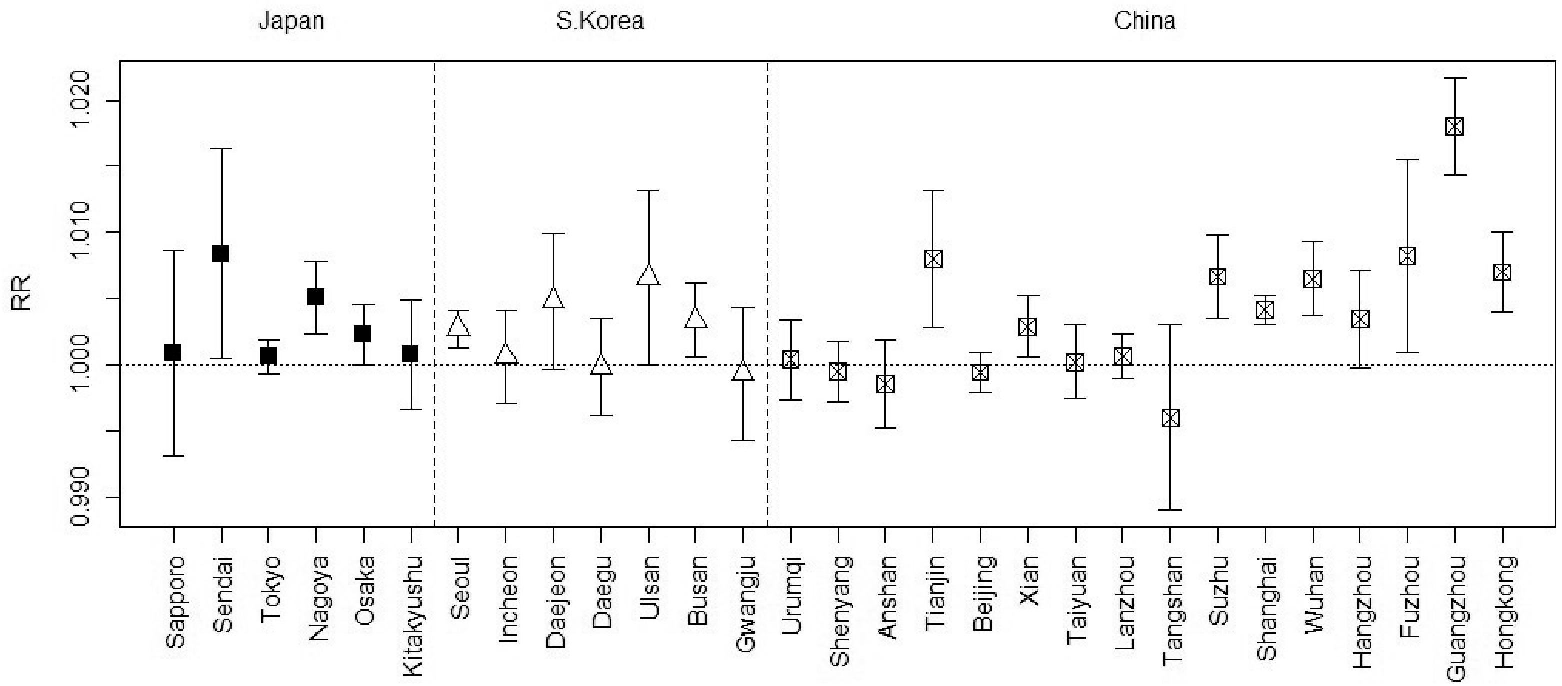
Zeka, A., Zanobetti, A. and Schwartz, J., 2006. Individual-level modifiers of the effects of particulate matter on daily mortality. American Journal of Epidemiology, 163(9): 849-859.

Zereini, F. and Wiseman, C.L., 2010. Urban airborne particulate matter. Environmental Science and Engineering. Springer.

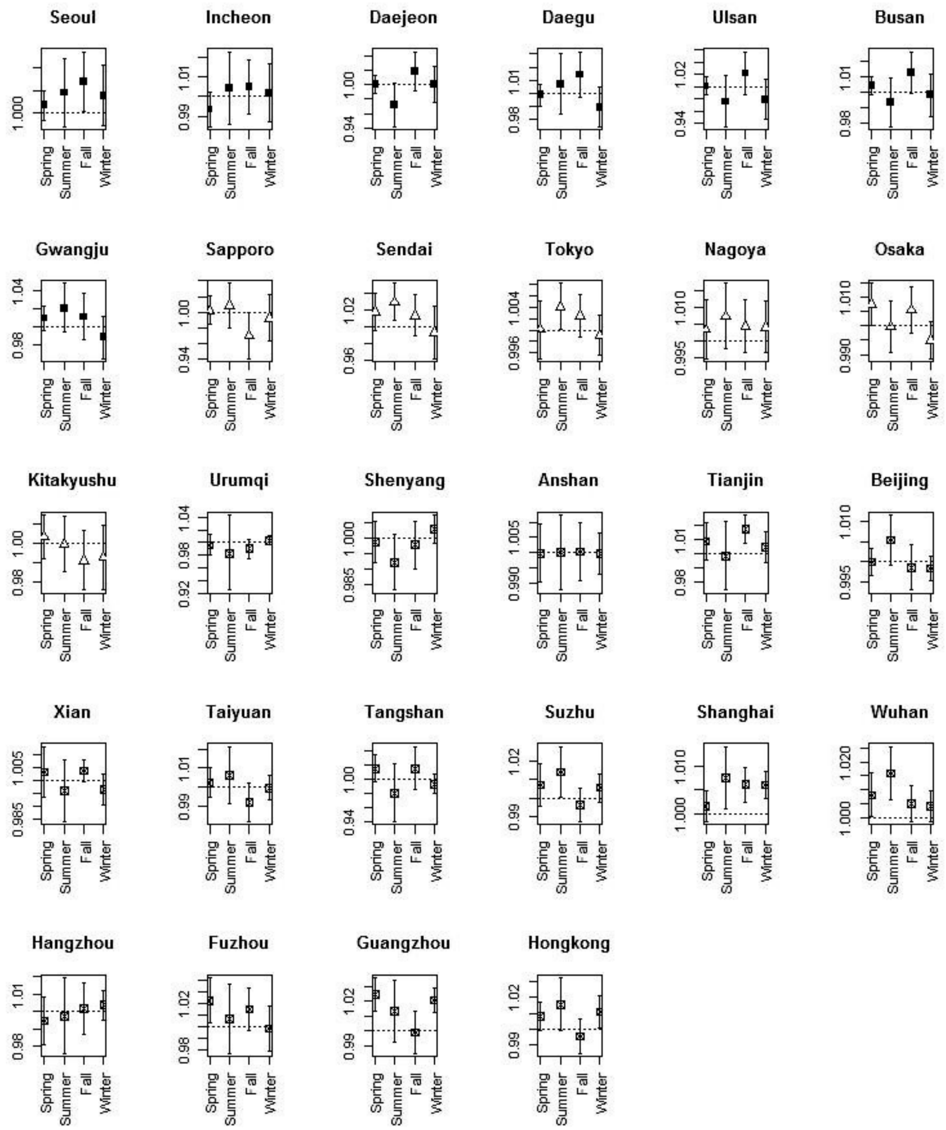
Appendix 1. City-specific smoothing spline plots of the association between particulate matter and mortality.



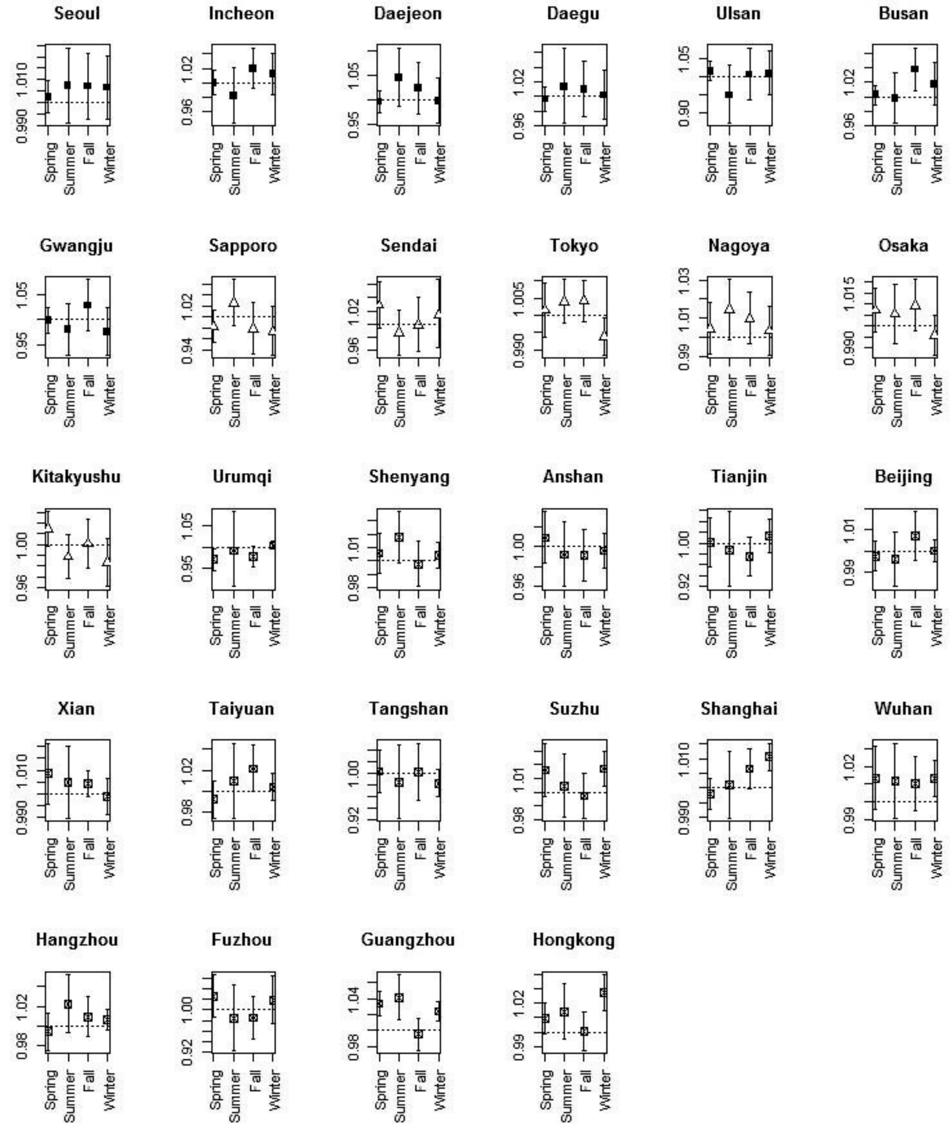
Appendix 2. Relative risks in mortality associated with a 10 μg/m^3 increase in particulate matter (PM) smaller than 10 μm (PM_{10}) for 29 cities. Bars represent the 95% confidence intervals.



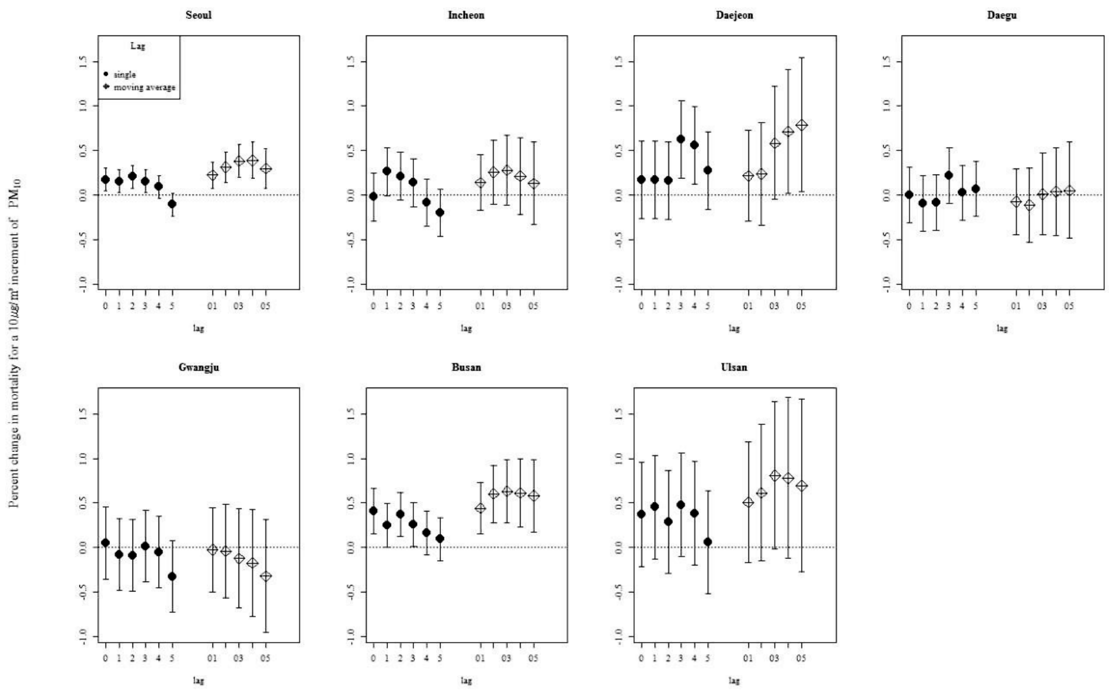
Appendix 3. City-specific seasonal effects of particulate matter (PM) smaller than 10 μm (PM_{10}) on cardiovascular mortality.



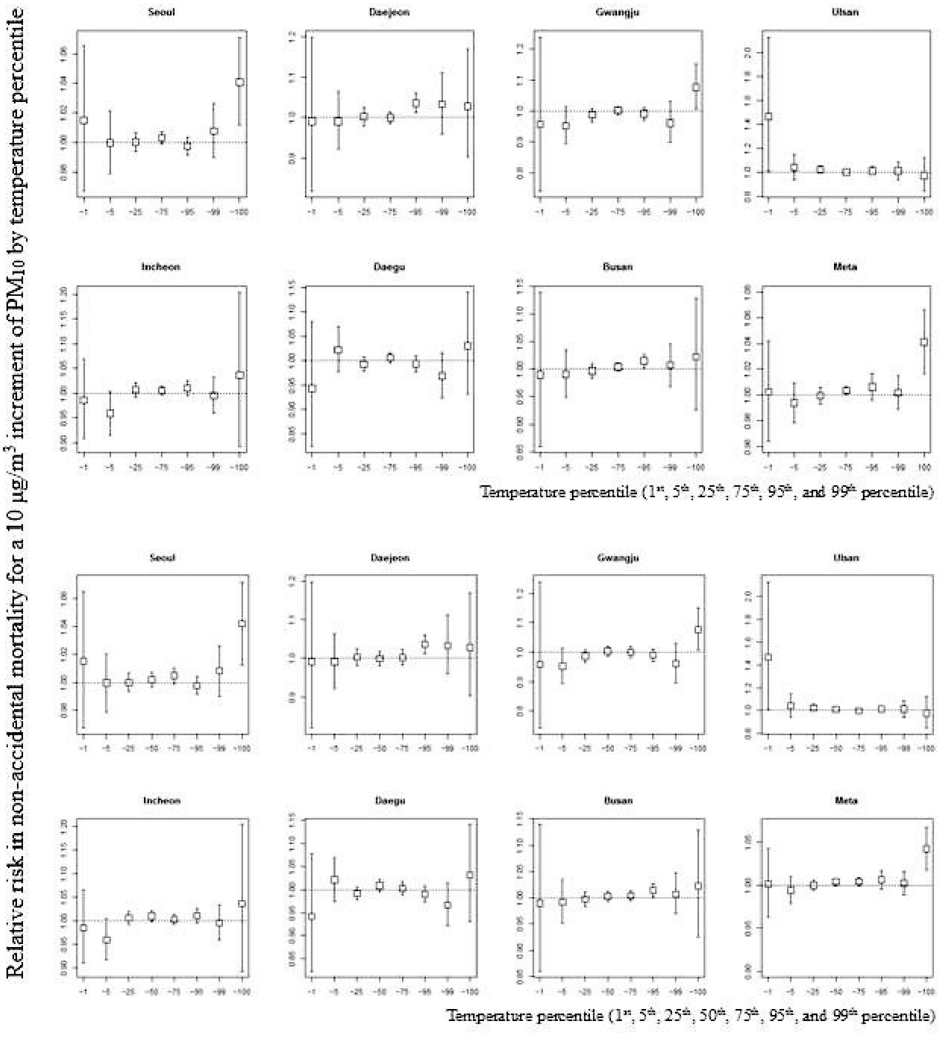
Appendix 4. City-specific seasonal effects of particulate matter (PM) smaller than 10 µm (PM_{10}) on respiratory mortality.



Appendix 5. City-specific results of the lag structures on the effect of particulate matter <10 μm (PM_{10}) in aerodynamic diameter on non-accidental mortality.



Appendix 6. City-specific results of the relative risk in daily mortality and the 95% confidence interval for a 10 μg/m³ increment in particulate matter <10 μm in aerodynamic diameter by different temperature ranges.



Appendix 7. City-specific results of the percent change in daily mortality and the 95% confidence interval for a 10 μg/m³ increment in particulate matter <10 μm in aerodynamic diameter by age groups and the temperature level on the day of death.

City	Cause of death	Age	Temperature strata						
			>1%	1−5%	5−25%	25−75%	75−95%	95−99%	99−100%
Seoul	Non-accidental	<65	1.49 (-3.32, 6.55)	-0.03 (-2.11, 2.09)	0.01 (-0.64, 0.66)	0.31 (-0.1, 0.72)	-0.26 (-0.87, 0.36)	0.77 (-1.03, 2.6)	4.11 (1.16, 7.14)
		≥65	1.28 (-2.03, 4.69)	-0.77 (-2.25, 0.75)	0.2 (-0.27, 0.67)	0.66 (0.36, 0.96)	0.63 (0.18, 1.09)	1.28 (-0.02, 2.6)	0.41 (-1.74, 2.61)
	CVD	<65	3.82 (-6.8, 15.65)	0.73 (-3.7, 5.37)	1.41 (0, 2.84)	0.74 (-0.17, 1.65)	-0.06 (-1.41, 1.31)	0.1 (-3.95, 4.31)	6.47 (0.33, 12.98)
		≥65	4.93 (-1.31, 11.56)	2.19 (-0.52, 4.99)	0.15 (-0.7, 1)	0.91 (0.38, 1.45)	0.86 (0.04, 1.7)	1.42 (-0.97, 3.87)	-0.76 (-4.55, 3.19)
	RD	<65	16.42 (-8.22, 47.67)	1.88 (-9.7, 14.94)	-0.6 (-4.39, 3.34)	2.34 (-0.16, 4.91)	-0.86 (-4.53, 2.96)	1.97 (-8.37, 13.49)	-0.31 (-19.06, 22.8)
		≥65	4.2 (-6.81, 16.52)	0.93 (-4.07, 6.18)	0.74 (-0.92, 2.43)	-0.25 (-1.33, 0.85)	1.36 (-0.3, 3.05)	1.43 (-3.3, 6.39)	-1.76 (-9.75, 6.93)
Incheon	Non-accidental	<65	-1.38 (-9.05, 6.94)	-4.13 (-8.49, 0.42)	0.71 (-0.73, 2.17)	0.56 (-0.28, 1.41)	1.05 (-0.42, 2.54)	-0.45 (-4.06, 3.29)	3.66 (-10.78, 20.44)
		≥65	0.92 (-4.82, 7.02)	2.35 (-0.84, 5.65)	0.26 (-0.76, 1.29)	-0.12 (-0.72, 0.47)	0.16 (-0.92, 1.26)	3.52 (1, 6.11)	-2.42 (-12.67, 9.03)
	CVD	<65	-15.1 (-31, 4.46)	-5.89 (-15.24, 4.48)	0.97 (-2.06, 4.11)	0.17 (-1.66, 2.04)	3.09 (-0.18, 6.47)	-2.22 (-9.96, 6.2)	-5.91 (-33.41, 32.95)
		≥65	10.83 (0.68, 21.99)	6.57 (1.04, 12.4)	-0.3 (-2.05, 1.48)	-0.45 (-1.47, 0.58)	0.82 (-1.1, 2.77)	2 (-2.52, 6.73)	1.81 (-15.39, 22.5)
	RD	<65	11.95 (-21.2, 59.03)	5.61 (-15.48, 31.98)	-3.88 (-10.9, 3.68)	6.03 (1.26, 11.03)	2 (-6.18, 10.9)	3.69 (-17.73, 30.67)	-2.72 (-54.99, 110.25)
		≥65	-2.34 (-20.29, 19.65)	4.07 (-6.31, 15.59)	-0.81 (-4.22, 2.71)	-0.4 (-2.4, 1.64)	-1.51 (-5.35, 2.49)	-3.13 (-11.78, 6.37)	-31.15 (-54.09, 3.25)
Daejeon	Non-accidental	<65	-0.96 (-18.21, 19.93)	-0.95 (-7.8, 6.41)	0.24 (-1.93, 2.46)	-0.01 (-1.46, 1.46)	3.6 (1.19, 6.07)	3.31 (-4.03, 11.22)	2.82 (-9.65, 17.01)
		≥65	-3.66 (-15.04, 9.26)	-4.04 (-8.26, 0.37)	1.3 (-0.18, 2.8)	0.27 (-0.69, 1.25)	0.83 (-0.84, 2.52)	2.85 (-2.12, 8.07)	-4.29 (-13.43, 5.81)
	CVD	<65	2.12 (-36.9, 65.28)	-4.59 (-18.42, 11.59)	-2.23 (-6.83, 2.61)	-0.59 (-3.65, 2.57)	1.62 (-3.59, 7.11)	-9.33 (-25.14, 9.81)	4.57 (-22.77, 41.59)

		≥65	-8.86 (-27.55, 14.65)	-2.05 (-9.54, 6.07)	2.37 (-0.3, 5.1)	-0.13 (-1.91, 1.69)	0.58 (-2.53, 3.78)	-0.95 (-9.79, 8.75)	-0.63 (-17.07, 19.08)
	RD	<65	-19.42 (-63.79, 79.33)	-36.72 (-63.76, 10.49)	-5.95 (-16.66, 6.15)	-2.92 (-10.56, 5.38)	12.67 (0.37, 26.48)	-0.64 (-38.03, 59.31)	23.77 (-20.33, 92.27)
		≥65	-21.18 (-49.05, 21.93)	-4.34 (-17.73, 11.23)	1.88 (-2.86, 6.86)	0.82 (-2.26, 4)	2.64 (-2.84, 8.43)	4.34 (-11.24, 22.66)	-19.43 (-43.95, 15.83)
Daegu	Non-accidental	<65	-5.75 (-17.66, 7.88)	2.15 (-2.44, 6.96)	-0.78 (-2.24, 0.69)	0.57 (-0.46, 1.61)	-0.7 (-2.36, 0.98)	-3.13 (-7.65, 1.6)	3.04 (-6.9, 14.04)
		≥65	-5.6 (-13.74, 3.31)	-0.51 (-3.61, 2.7)	-0.2 (-1.21, 0.83)	-0.36 (-1.06, 0.35)	0.99 (-0.22, 2.2)	2.17 (-0.99, 5.43)	1.73 (-4.9, 8.82)
	CVD	<65	-5.43 (-28.54, 25.15)	-1.49 (-10.8, 8.78)	-1.48 (-4.61, 1.75)	1.69 (-0.57, 4.01)	2.07 (-1.65, 5.92)	-13 (-22.31, -2.58)	-17.46 (-38.14, 10.13)
		≥65	-13.59 (-26.81, 2.01)	0.55 (-5.01, 6.44)	0.47 (-1.37, 2.34)	0.4 (-0.89, 1.7)	1.72 (-0.5, 3.99)	3.7 (-2.22, 9.98)	6.76 (-5.38, 20.47)
	RD	<65	30.61 (-26.53, 132.18)	-22.8 (-40.86, 0.77)	-7.9 (-15.46, 0.33)	-2.02 (-7.7, 4)	-7.47 (-16.57, 2.62)	13.23 (-13.57, 48.35)	-53.59 (-83.8, 32.94)
		≥65	-10.63 (-34.17, 21.32)	-0.2 (-10.54, 11.34)	0.3 (-3.2, 3.92)	0.53 (-1.87, 2.98)	0.65 (-3.49, 4.96)	-8.83 (-19.96, 3.86)	-3.11 (-27.02, 28.62)
Gwangju	Non-accidental	<65	-4.25 (-26, 23.89)	-4.78 (-10.61, 1.43)	-1.36 (-3.43, 0.75)	0.09 (-1.24, 1.43)	-0.93 (-3, 1.18)	-3.86 (-10.3, 3.04)	7.62 (0.66, 15.08)
		≥65	-1.86 (-17.66, 16.97)	0.81 (-2.91, 4.68)	-0.95 (-2.3, 0.42)	0.07 (-0.8, 0.95)	0.5 (-0.91, 1.94)	0.31 (-3.97, 4.78)	1.13 (-3.25, 5.71)
	CVD	<65	-52.76 (-74.98, -10.8)	-6.56 (-18, 6.47)	-2.6 (-7.13, 2.15)	1.99 (-0.99, 5.05)	-0.13 (-4.84, 4.82)	13.76 (-2.88, 33.24)	15.03 (1.38, 30.53)
		≥65	22.76 (-15.15, 77.6)	6.47 (-0.7, 14.16)	0.88 (-1.78, 3.61)	0.77 (-0.95, 2.51)	0.24 (-2.55, 3.12)	0.43 (-7.62, 9.18)	-0.65 (-9.31, 8.84)
	RD	<65	-79.3 (-98.45, 176.46)	-6.5 (-37.2, 39.2)	-9.65 (-20.97, 3.29)	-2.67 (-9.77, 4.98)	-4.32 (-15.61, 8.48)	-1.63 (-32.53, 43.43)	-49.68 (-90.23, 159.2)
		≥65	-6.19 (-53.69, 90.04)	-5.04 (-17.01, 8.66)	-1.86 (-6.5, 3)	2.2 (-0.76, 5.26)	-0.36 (-5.63, 5.2)	3.77 (-10.99, 20.99)	3.81 (-10.22, 20.04)
Busan	Non-accidental	<65	-1.02 (-14, 13.92)	-0.95 (-5.13, 3.41)	-0.34 (-1.67, 1.01)	0.37 (-0.39, 1.13)	1.44 (0.22, 2.67)	0.69 (-3.1, 4.63)	2.2 (-7.41, 12.81)
		≥65	-0.96 (-10.16, 9.18)	-2.68 (-5.56, 0.28)	0.1 (-0.85, 1.05)	0.87 (0.32, 1.43)	0.48 (-0.41, 1.37)	2.95 (0.17, 5.81)	4.71 (-2.97, 12.99)
	CVD	<65	-21.22 (-41.5, 6.08)	-3.76 (-11.69, 4.89)	0.73 (-2, 3.53)	-1.07 (-2.6, 0.49)	0.04 (-2.49, 2.64)	1.11 (-6.72, 9.6)	-3.65 (-20.99, 17.5)
		≥65	-18.1 (-30.41, -3.63)	-3.03 (-7.92, 2.12)	0.02 (-1.59, 1.65)	1.05 (0.11, 1.99)	0.76 (-0.78, 2.33)	-1.94 (-6.72, 3.08)	3.59 (-9.03, 17.97)
	RD	<65	-12.27 (-63.27, 109.59)	5.62 (-16.59, 33.73)	-2.62 (-9.91, 5.26)	-2.38 (-6.76, 2.21)	6.12 (-1.98, 14.89)	1.68 (-17.78, 25.75)	7.4 (-42.14, 99.39)

		≥65	14.93 (-20.78, 66.72)	-2.26 (-11.73, 8.23)	1.45 (-1.85, 4.86)	2.19 (0.25, 4.18)	-1.16 (-4.42, 2.21)	6.09 (-4.46, 17.81)	0.34 (-23.54, 31.67)
Ulsan	Non-accidental	<65	46.65 (1.01, 112.9)	3.97 (-6.16, 15.19)	2.18 (-0.65, 5.09)	0.41 (-1.42, 2.27)	1.31 (-1.78, 4.5)	1.2 (-5.88, 8.81)	-2.66 (-15.76, 12.48)
		≥65	-0.27 (-22.71, 28.68)	5.16 (-2.16, 13.02)	0.54 (-1.46, 2.57)	0.56 (-0.76, 1.9)	1.95 (-0.49, 4.46)	-0.81 (-6.02, 4.68)	-2.2 (-11.8, 8.45)
	CVD	<65	41.8 (-32.26, 196.83)	-12.8 (-30.86, 9.97)	-0.81 (-6.55, 5.28)	0.54 (-3.3, 4.53)	-5.62 (-12.21, 1.46)	4.66 (-10.48, 22.35)	-16.33 (-43.23, 23.32)
		≥65	-19.21 (-49.39, 28.97)	-3.61 (-15.6, 10.08)	-0.65 (-4.1, 2.92)	0.4 (-1.96, 2.82)	3.02 (-1.36, 7.6)	-0.09 (-9.58, 10.4)	-11.93 (-27.49, 6.96)
	RD	<65	227.69 (-70.73, 3568.74)	41.37 (-12.53, 128.5)	-0.67 (-13.88, 14.58)	1.5 (-8.95, 13.15)	-4.9 (-22.45, 16.63)	2.73 (-37.9, 69.96)	10.67 (-69.25, 298.27)
		≥65	53.96 (-25.78, 219.41)	27.91 (3.22, 58.49)	0.87 (-5.19, 7.32)	-1.14 (-5.31, 3.22)	0.19 (-7.6, 8.63)	-0.91 (-16.97, 18.26)	-23.63 (-46.47, 8.95)

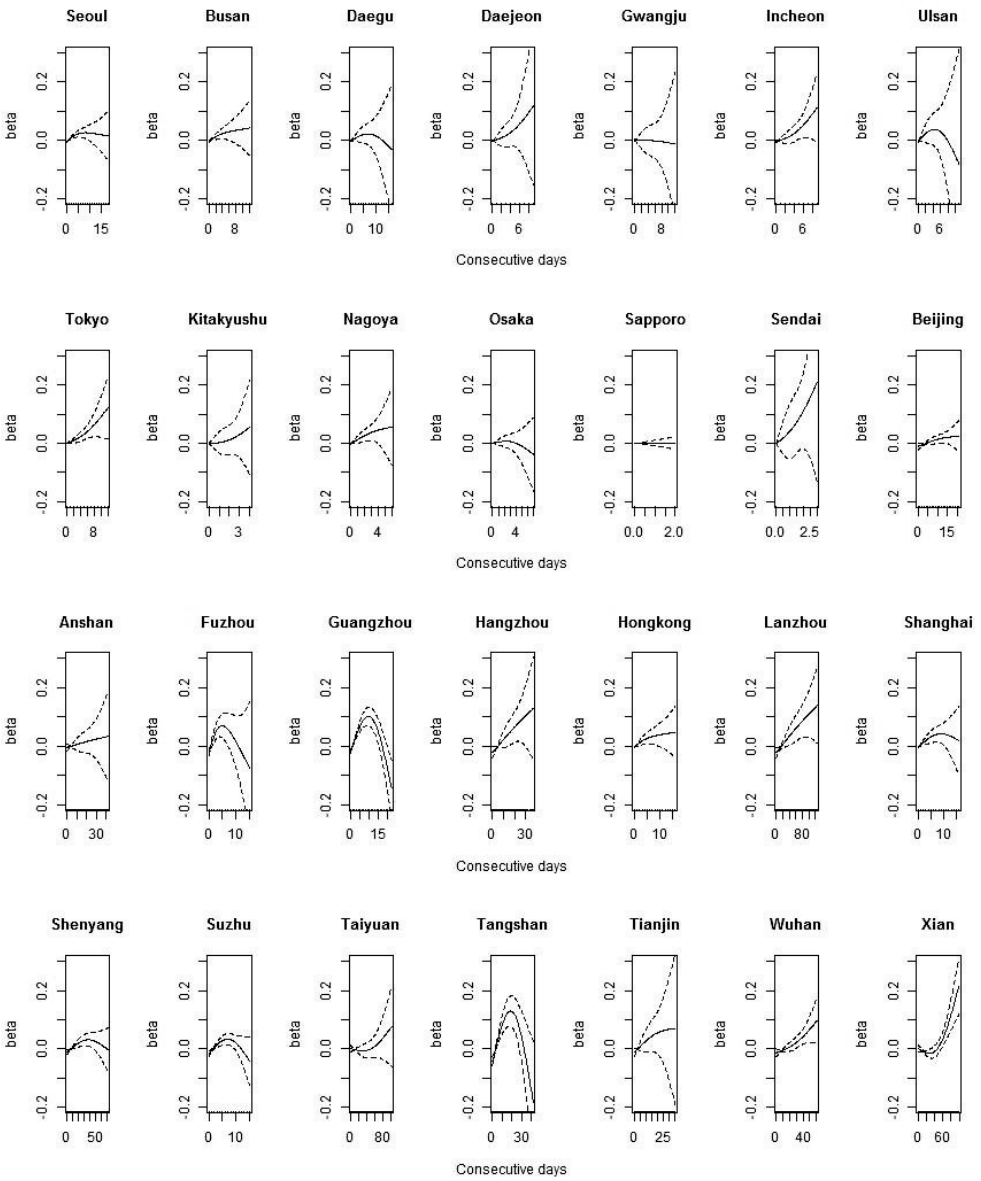
Appendix 8. City-specific results of the percent change in daily mortality and the 95% confidence interval for a 10 μg/m^3 increment in particulate matter < 10μm in aerodynamic diameter by sex and the temperature level on the day of death.

City	Cause of death	Sex	Temperature strata						
			>1%	1−5%	5−25%	25−75%	75−95%	95−99%	99−100%
Seoul	Non-accidental	Men	1.73 (5.62, -2.02)	0.28 (1.98, -1.38)	0.25 (0.77, -0.27)	0.6 (0.93, 0.27)	-0.01 (0.48, -0.51)	1.86 (3.31, 0.43)	1.95 (4.32, -0.37)
		Women	1.11 (5.25, -2.86)	-1.29 (0.5, -3.06)	0.01 (0.56, -0.55)	0.46 (0.81, 0.1)	0.7 (1.24, 0.16)	0.13 (1.71, -1.43)	1.28 (3.97, -1.35)
	CVD	Men	0.14 (8.54, -7.62)	3.04 (6.5, -0.31)	0.46 (1.5, -0.56)	1.19 (1.84, 0.54)	0.13 (1.13, -0.87)	1.81 (4.85, -1.14)	3.07 (7.81, -1.47)
		Women	8.38 (16.39, 0.91)	0.58 (3.89, -2.63)	0.48 (1.52, -0.55)	0.55 (1.21, -0.1)	1.08 (2.09, 0.08)	0.26 (3.21, -2.62)	-0.85 (3.93, -5.42)
	RD	Men	3.48 (18.23, -9.44)	0.76 (7.22, -5.31)	1.18 (3.27, -0.87)	0.91 (2.24, -0.4)	1.16 (3.18, -0.82)	1.43 (7.44, -4.23)	0.85 (10.55, -8)
		Women	10.97 (29.29, -4.74)	1.59 (8.97, -5.29)	-0.16 (2.13, -2.41)	-0.84 (0.69, -2.35)	0.57 (2.96, -1.77)	1.51 (8.5, -5.02)	-6.73 (8.63, -19.92)
Incheon	Non-accidental	Men	0.39 (7.07, -5.87)	-0.57 (3.03, -4.03)	0.42 (1.56, -0.71)	0.48 (1.14, -0.18)	1.19 (2.39, 0.01)	1.8 (4.71, -1.03)	4.65 (18.18, -7.34)
		Women	-0.96 (6.38, -7.79)	1.12 (5.11, -2.72)	0.47 (1.72, -0.76)	-0.35 (0.37, -1.06)	-0.37 (0.94, -1.66)	2.79 (5.91, -0.23)	-5.65 (7.58, -17.25)
	CVD	Men	3.08 (17.25, -9.37)	2.75 (10.11, -4.12)	0.47 (2.66, -1.66)	0.09 (1.39, -1.19)	2.89 (5.3, 0.54)	2.16 (8.12, -3.47)	5.18 (33.4, -17.08)
		Women	6.58 (19.77, -5.16)	4.66 (11.68, -1.93)	-0.48 (1.7, -2.62)	-0.61 (0.65, -1.85)	-0.02 (2.34, -2.33)	-0.13 (5.58, -5.53)	-3.79 (20.34, -23.08)
	RD	Men	-9.59 (21.59, -32.77)	4.87 (18.59, -7.26)	-3.12 (1.03, -7.1)	2.5 (4.96, 0.09)	1.21 (5.9, -3.28)	-4.49 (8.01, -15.54)	-17.21 (27.99, -46.45)
		Women	7.94 (33.13, -12.48)	3.89 (20.6, -10.51)	0.8 (5.72, -3.88)	-2.37 (0.57, -5.21)	-4.87 (0.87, -10.29)	0.99 (14.12, -10.63)	-40.26 (11.69, -68.05)
Daejeon	Non-accidental	Men	-1.03 (14.08, -14.13)	-0.58 (4.59, -5.5)	0.44 (2.16, -1.24)	-0.05 (1.07, -1.15)	2.33 (4.25, 0.45)	2.47 (8.49, -3.22)	1.24 (12.02, -8.51)
		Women	-5.16 (10.84, -18.86)	-6.52 (-0.97, -11.76)	1.5 (3.3, -0.28)	0.48 (1.68, -0.71)	0.44 (2.51, -1.6)	3.45 (9.78, -2.52)	-6.2 (6.57, -17.45)
	CVD	Men	-9.73 (20.8, -32.55)	0.88 (10.93, -8.27)	0.71 (4.13, -2.6)	0.36 (2.62, -1.85)	0.27 (4.26, -3.57)	-10.39 (2.6, -21.73)	6.99 (31.04, -12.64)

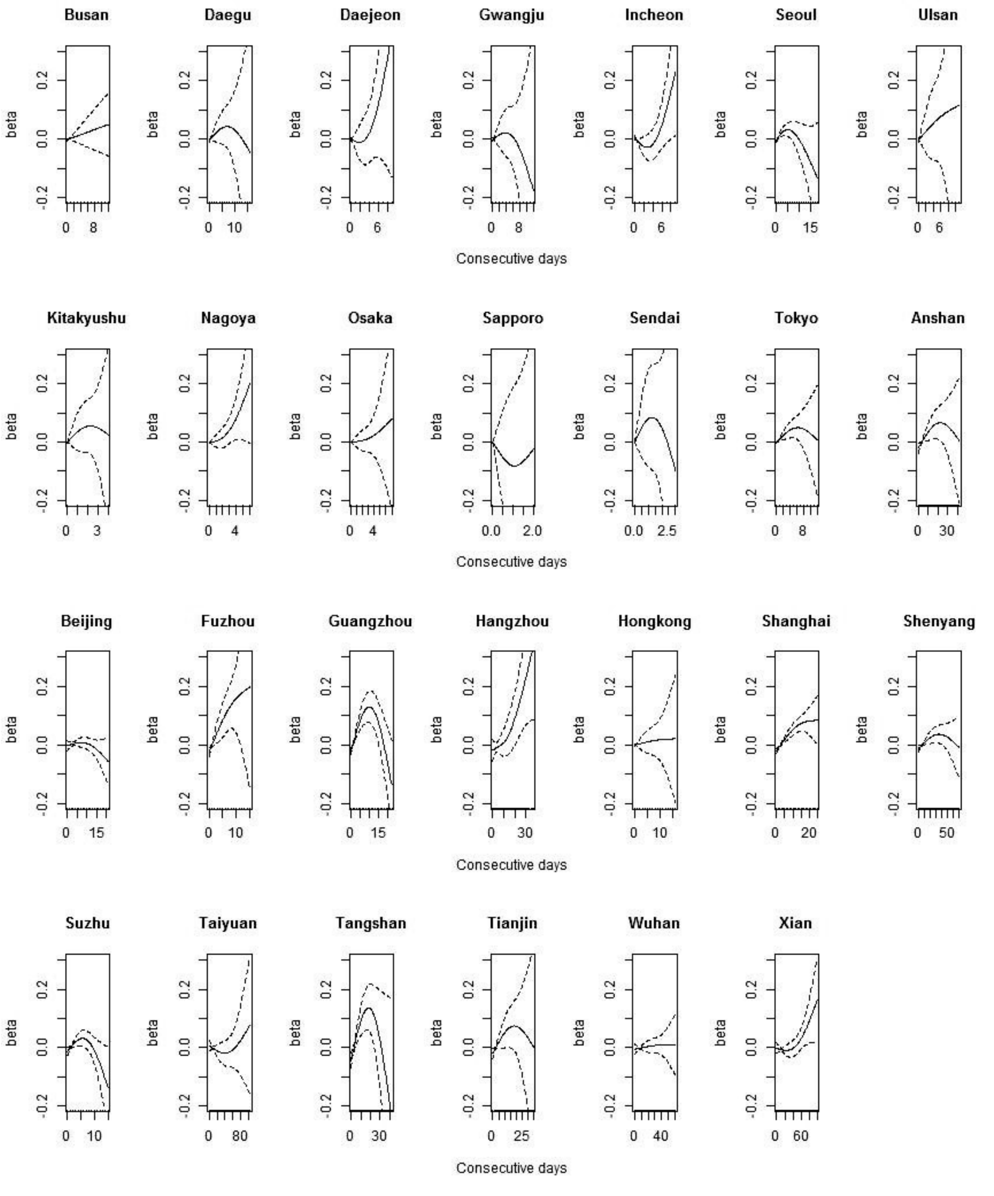
		Women	-4.35 (28.19, -28.63)	-6.43 (4.05, -15.86)	1.78 (5.09, -1.43)	-0.77 (1.43, -2.93)	1.29 (5.12, -2.41)	2.96 (14.55, -7.46)	-5.98 (19.76, -26.19)
	RD	Men	-10.98 (44.97, -45.34)	-8.54 (9.84, -23.85)	0.04 (6.08, -5.64)	0.69 (4.64, -3.12)	7.09 (14.32, 0.32)	12.84 (36.65, -6.82)	-3.96 (38.58, -33.43)
		Women	-29.63 (30.2, -61.96)	-8.78 (16, -28.27)	1.69 (8.73, -4.9)	-0.08 (4.43, -4.4)	0.86 (8.9, -6.59)	-7.81 (18.97, -28.56)	-15.45 (28.06, -44.18)
Daegu	Non-accidental	Men	-3.24 (7.24, -12.71)	0.4 (4.09, -3.16)	-0.41 (0.73, -1.54)	-0.25 (0.55, -1.04)	0.33 (1.66, -0.98)	-2.44 (1.25, -5.99)	-1.85 (6.26, -9.34)
		Women	-9.13 (1.5, -18.65)	0.04 (3.9, -3.68)	-0.3 (0.95, -1.52)	0.21 (1.07, -0.65)	0.54 (2, -0.91)	3.33 (7.24, -0.45)	6.46 (15.29, -1.7)
	CVD	Men	-3.95 (16.46, -20.79)	1.67 (9.33, -5.46)	-0.28 (2.05, -2.55)	1.84 (3.47, 0.23)	4.36 (7.23, 1.57)	-1.4 (6.31, -8.56)	0 (17.45, -14.86)
		Women	-20.07 (-1.14, -35.38)	-1.46 (5.4, -7.87)	0.17 (2.43, -2.05)	-0.34 (1.24, -1.89)	-0.37 (2.33, -3)	0.69 (8.22, -6.32)	3.95 (21.26, -10.89)
	RD	Men	-21.3 (19.7, -48.26)	-3.94 (10.44, -16.45)	-0.72 (3.85, -5.09)	-2.39 (0.66, -5.35)	-1.73 (3.55, -6.75)	-4.71 (11.88, -18.84)	-14.97 (23.12, -41.28)
		Women	16.37 (65.36, -18.11)	-3.37 (11.91, -16.57)	-1.96 (2.82, -6.52)	2.91 (6.31, -0.38)	0.34 (6.41, -5.39)	-6.41 (11.09, -21.15)	-4.31 (44.43, -36.6)
Gwangju	Non-accidental	Men	3.37 (26.4, -15.46)	-5.3 (-0.62, -9.75)	-0.8 (0.84, -2.4)	-0.22 (0.8, -1.23)	0.19 (1.83, -1.42)	-1.64 (3.54, -6.56)	0.83 (6.21, -4.29)
		Women	-9.26 (12.3, -26.67)	3.77 (8.42, -0.68)	-1.27 (0.36, -2.87)	0.3 (1.36, -0.74)	-0.12 (1.6, -1.82)	-0.07 (5.39, -5.25)	5.64 (11.34, 0.23)
	CVD	Men	-6.38 (49.39, -41.32)	-3.35 (6.6, -12.36)	1.06 (4.56, -2.33)	0.74 (2.96, -1.42)	0.26 (3.79, -3.14)	1.61 (13.9, -9.35)	-1.78 (10.67, -12.82)
		Women	-6.02 (44.76, -38.99)	8.06 (16.93, -0.13)	-1.1 (2.1, -4.19)	1.3 (3.38, -0.74)	0 (3.5, -3.38)	3.96 (14.53, -5.63)	7.92 (18.51, -1.73)
	RD	Men	-28.9 (99.76, -74.69)	-15.28 (3.97, -30.97)	-4.41 (1.89, -10.31)	1.22 (5.01, -2.44)	-0.54 (6.3, -6.95)	5.51 (26.4, -11.94)	2.01 (22.65, -15.17)
		Women	-5.61 (143.75, -63.45)	3.88 (22.16, -11.67)	-1.56 (5.07, -7.78)	1.64 (5.93, -2.48)	-1.64 (6.02, -8.75)	0.22 (26.13, -20.37)	3.33 (30.72, -18.32)
Busan	Non-accidental	Men	-0.9 (10.56, -11.17)	-1.37 (2.03, -4.65)	-0.21 (0.86, -1.25)	0.57 (1.18, -0.04)	0.24 (1.22, -0.73)	1.81 (4.94, -1.22)	5.15 (14.09, -3.08)
		Women	-1.06 (11.31, -12.05)	-2.99 (0.57, -6.43)	0.12 (1.27, -1.01)	0.88 (1.55, 0.22)	1.6 (2.68, 0.53)	2.52 (5.97, -0.82)	2.28 (11.84, -6.47)
	CVD	Men	-15.89 (2.3, -30.85)	-2.25 (4.05, -8.17)	-0.41 (1.59, -2.36)	0.28 (1.43, -0.86)	0.15 (2.05, -1.71)	-2.22 (3.94, -8.02)	2.23 (18.98, -12.16)
		Women	-23.19 (-5.26, -37.73)	-3.46 (2.72, -9.27)	0.46 (2.44, -1.48)	0.63 (1.76, -0.49)	0.99 (2.89, -0.87)	0.11 (6.18, -5.61)	1.59 (18.57, -12.96)
	RD	Men	28.46 (100.79, -17.81)	-4.65 (8.32, -16.06)	0.88 (5.12, -3.2)	1.53 (3.96, -0.84)	-0.2 (3.93, -4.16)	7.42 (21.59, -5.1)	14.18 (58.89, -17.95)

		Women	-13.12 (47.81, -48.93)	2.21 (17.1, -10.78)	1.26 (5.95, -3.23)	1.53 (4.25, -1.13)	-0.57 (4.21, -5.12)	0.69 (16.29, -12.82)	-15.48 (24.01, -42.4)
Ulsan	Non-accidental	Men	14.28 (54.51, -15.47)	6.96 (16.11, -1.46)	0.88 (3.22, -1.41)	0.46 (1.96, -1.02)	2.12 (4.84, -0.53)	-5.62 (0.33, -11.22)	0.73 (12.33, -9.66)
		Women	10.09 (47.35, -17.75)	2.82 (11.94, -5.56)	1.44 (3.83, -0.9)	0.56 (2.14, -0.99)	1.33 (4.18, -1.44)	6.25 (12.96, -0.07)	-6.36 (6.88, -17.96)
	CVD	Men	10.37 (107.29, -41.23)	-13.19 (3.56, -27.24)	-2.83 (1.72, -7.18)	0.99 (4.01, -1.94)	-1.64 (3.81, -6.8)	-1.91 (11.08, -13.39)	2.22 (28.39, -18.62)
		Women	-12.78 (43.58, -47.01)	0.37 (16.83, -13.78)	1.21 (5.39, -2.8)	0.11 (2.94, -2.64)	2.25 (7.53, -2.77)	4.13 (16.7, -7.08)	-28.48 (-6.2, -45.47)
	RD	Men	64.42 (299.84, -32.39)	64.67 (110.08, 29.08)	-0.33 (7.76, -7.81)	-3.49 (1.93, -8.62)	4.82 (15.53, -4.89)	10.07 (37.75, -12.05)	-32.03 (6.21, -56.51)
		Women	59.42 (366.03, -45.47)	-9.58 (27.18, -35.71)	3.29 (12.2, -4.91)	2.65 (8.84, -3.19)	-6.98 (4.32, -17.05)	-10.51 (15.01, -30.37)	1.94 (70.76, -39.15)

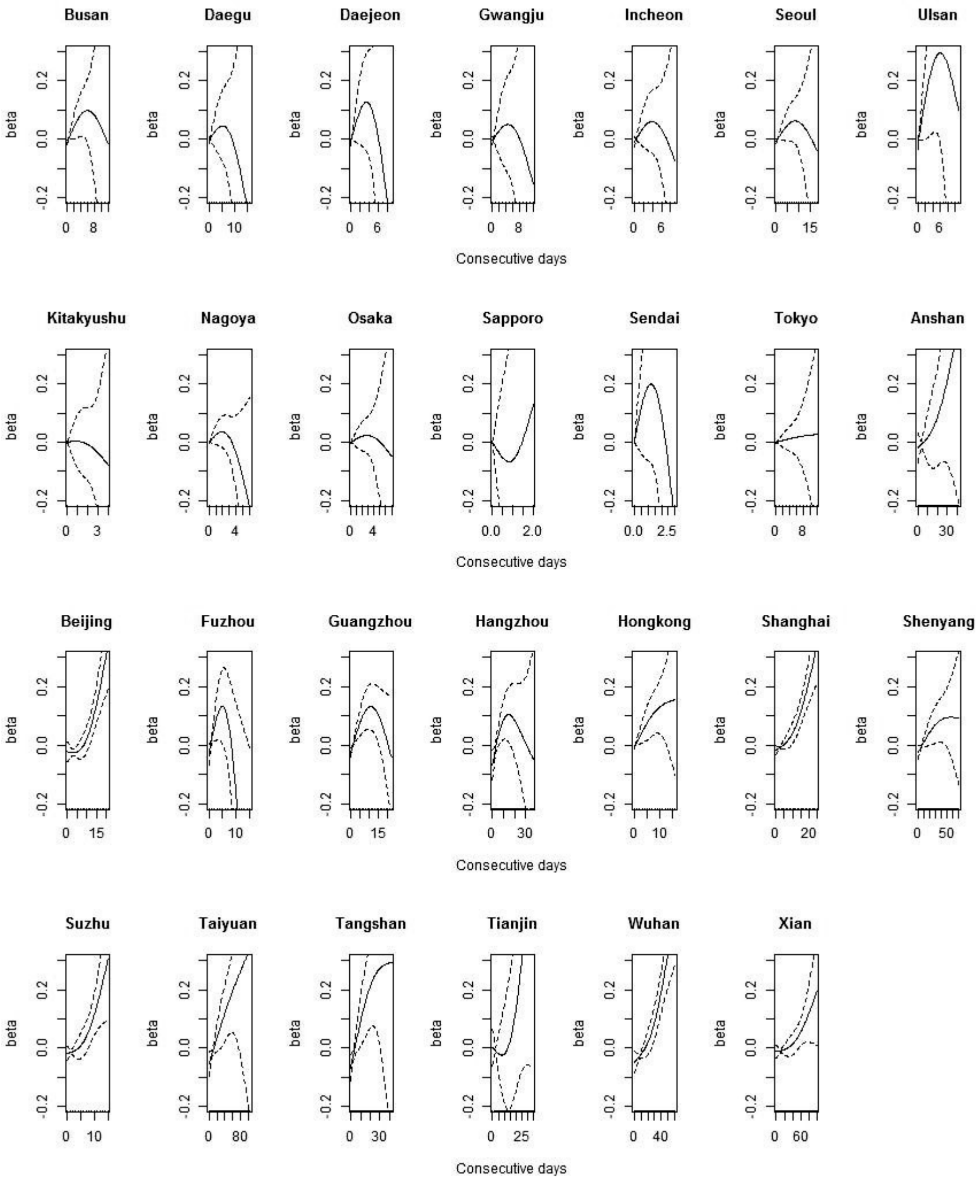
Appendix 9. City specific results: Risk of total mortality patterns as the elevated air pollution level last days in 28 locations, with 95% confidence intervals.



Appendix 10. City specific results: Risk of cardiovascular mortality patterns as the elevated air pollution level last days in 28 locations, with 95% confidence intervals.



Appendix 11. City specific results: Risk of respiratory mortality patterns as the elevated air pollution level last days in 28 locations, with 95% confidence intervals.



Appendix 12. City-specific increases in mortality risk for each additional consecutive day of high PM_{10} concentrations (≥75 μg/m³) according to cause of death and age.

Country	City	Annual average maximum duration of exposure (days)	Duration effects				
			Percent increase in mortality for each additional consecutive day with PM_{10} of ≥75 μg/m³ (95% confidence interval)				
			Non-accidental	Cardiovascular	Respiratory	0–64 years	≥65 years
Japan	Sapporo	0.31	0.46 (–10.06, 12.21)	–3.19 (–21.58, 19.51)	3.17 (–25.13, 42.18)	3.48 (–18.37, 31.16)	0.53 (–0.47, 1.53)
	Sendai	1.38	5.58 (–0.88, 12.46)	3.63 (–7.50, 16.11)	8.83 (–8.68, 29.70)	1.16 (–11.77, 15.98)	6.33 (–0.93, 14.11)
	Tokyo	3.56	0.65 (0.26, 1.04)	0.93 (0.27, 1.60)	0.30 (–0.75, 1.37)	0.39 (–0.42, 1.20)	0.73 (0.29, 1.18)
	Nagoya	3.56	1.29 (0.37, 2.21)	1.42 (–0.14, 3.00)	0.68 (–1.75, 3.18)	1.10 (–0.84, 3.08)	1.34 (0.30, 2.39)
	Osaka	3.19	0.18 (–0.69, 1.05)	0.44 (–1.12, 2.02)	0.79 (–1.42, 3.04)	–0.92 (–2.68, 0.87)	0.53 (–0.47, 1.53)
	Kitakyushu	2.44	0.78 (–1.54, 3.15)	2.29 (–1.86, 6.61)	–0.71 (–6.22, 5.14)	–0.33 (–5.46, 5.09)	1.02 (–1.56, 3.67)
South Korea	Seoul	9.2	0.44 (0.22, 0.67)	0.48 (0.05, 0.91)	0.80 (–0.20, 1.81)	0.44 (0.06, 0.81)	0.46 (0.18, 0.74)
	Incheon	6.7	0.84 (0.13, 1.56)	0.25 (–1.08, 1.60)	1.08 (–1.58, 3.81)	1.25 (0.02, 2.50)	0.64 (–0.23, 1.52)
	Daejeon	5.6	0.76 (–0.45, 1.99)	0.88 (–1.66, 3.49)	2.44 (–2.11, 7.19)	0.42 (–1.75, 2.64)	0.93 (–0.53, 2.40)

	Daegu	7	0.33 (–0.24, 0.91)	0.65 (–0.44, 1.76)	0.51 (–1.77, 2.85)	1.01 (0.03, 2.00)	–0.02 (–0.73, 0.69)
	Gwangju	6.9	–0.03 (–1.05, 1.00)	0.12 (–1.71, 1.99)	0.76 (–2.77, 4.42)	–0.55 (–2.39, 1.33)	0.19 (–1.03, 1.42)
	Ulsan	6.2	0.78 (–0.55, 2.12)	1.37 (–1.47, 4.29)	5.44 (0.24, 10.91)	0.86 (–1.33, 3.10)	0.72 (–0.94, 2.41)
	Busan	7.1	0.61 (0.12, 1.10)	0.43 (–0.47, 1.34)	2.00 (0.12, 3.92)	0.22 (–0.59, 1.04)	0.83 (0.22, 1.44)
China	Shenyang	58	0.09 (0.02, 0.16)	0.11 (0.01, 0.21)	0.25 (0.02, 0.48)	–	–
	Anshan	28	0.10 (–0.14, 0.33)	0.33 (0.01, 0.65)	0.65 (–0.33, 1.64)	–	–
	Beijing	41.5	0.21 (0.02, 0.40)	–0.06 (–0.33, 0.22)	1.15 (0.55, 1.74)	–	–
	Tangshan	50.33	0.46 (0.17, 0.76)	0.65 (0.13, 1.16)	1.28 (0.43, 2.15)	–	–
	Tianjin	30.25	0.34 (–0.07, 0.75)	0.47 (–0.06, 1.01)	0.86 (–0.77, 2.52)	–	–
	Taiyuan	59.6	0.01 (–0.06, 0.09)	–0.02 (–0.15, 0.10)	0.42 (0.13, 0.71)	–	–
	Lanzhou	73.2	0.13 (0.05, 0.22)	–	–	–	–
	Xian	79	0.07 (0.02, 0.13)	0.07 (–0.01, 0.15)	0.12 (0.02, 0.23)	–	–
	Suzhou	28.75	0.40 (0.07, 0.72)	0.11 (–0.42, 0.64)	1.32 (0.44, 2.21)	–	–

Shanghai	35.75	0.45 (0.32, 0.58)	0.60 (0.39, 0.81)	1.00 (0.64, 1.36)	–	–
Wuhan	69.67	0.14 (0.06, 0.23)	0.04 (–0.08, 0.15)	0.65 (0.41, 0.89)	–	–
Hangzhou	30	0.42 (0.10, 0.75)	0.66 (0.12, 1.21)	0.54 (–0.18, 1.26)	–	–
Fuzhou	11.33	1.03 (0.26, 1.81)	2.00 (0.85, 3.16)	0.54 (–1.94, 3.08)	–	–
Guangzhou	29.5	0.42 (0.11, 0.73)	0.59 (0.08, 1.10)	0.79 (0.08, 1.49)	–	–
Hong Kong	9	0.50 (0.13, 0.87)	0.20 (–0.49, 0.89)	1.42 (0.48, 2.37)	–	–

Appendix 13. City-specific increases in total daily non-accidental mortality risk for each additional consecutive day of high PM_{10} concentrations (≥50 μg/m^3 and ≥75 μg/m^3).

Country	City	Consecutive day with PM_{10} of ≥50 μg/m^3		Consecutive day with PM_{10} of ≥75 μg/m^3	
		Maximum duration days	Percent increase in total daily non-accidental mortality	Maximum duration days	Percent increase in total daily non-accidental mortality
Japan	Sapporo	4	2.91 (-1.43, 7.44)	2	0.46 (-10.06, 12.21)
	Sendai	8	1.24 (-0.28, 2.77)	3	5.58 (-0.88, 12.46)
	Tokyo	24	0.32 (0.18, 0.47)	12	0.65 (0.26, 1.04)
	Nagoya	22	0.38 (0.03, 0.72)	6	1.29 (0.37, 2.21)
	Osaka	18	0.29 (-0.02, 0.6)	7	0.18 (-0.69, 1.05)
	Kitakyushu	18	0.33 (-0.38, 1.05)	4	0.78 (-1.54, 3.15)
South Korea	Seoul	48	0.07 (-0.01, 0.15)	18	0.44 (0.22, 0.67)
	Incheon	26	0.03 (-0.17, 0.24)	9	0.84 (0.13, 1.56)
	Daejeon	19	0.16 (-0.31, 0.62)	9	0.76 (-0.45, 1.99)
	Daegu	52	0.13 (-0.02, 0.27)	16	0.33 (-0.24, 0.91)
	Gwangju	36	-0.15 (-0.46, 0.15)	12	-0.03 (-1.05, 1.00)
	Ulsan	20	0.49 (0, 0.98)	11	0.78 (-0.55, 2.12)

	Busan	27	0.34 (0.17, 0.51)	12	0.61 (0.12, 1.10)
China	Shenyang	232	-0.01 (-0.04, 0.01)	71	0.09 (0.02, 0.16)
	Anshan	73	0.01 (-0.09, 0.1)	42	0.10 (-0.14, 0.33)
	Beijing	83	0 (-0.06, 0.07)	21	0.21 (0.02, 0.40)
	Tangshan	82	0.02 (-0.08, 0.12)	42	0.46 (0.17, 0.76)
	Tianjin	80	0.07 (-0.11, 0.25)	35	0.34 (-0.07, 0.75)
	Taiyuan	185	0.04 (-0.01, 0.09)	103	0.01 (-0.06, 0.09)
	Lanzhou	273	0.03 (-0.01, 0.06)	125	0.13 (0.05, 0.22)
	Xian	264	0 (-0.03, 0.03)	99	0.07 (0.02, 0.13)
	Suzhu	53	0.06 (-0.06, 0.17)	15	0.40 (0.07, 0.72)
	Shanghai	57	-0.01 (-0.06, 0.05)	25	0.45 (0.32, 0.58)
	Wuhan	111	-0.04 (-0.1, 0.02)	61	0.14 (0.06, 0.23)
	Hangzhou	40	0.3 (0.11, 0.49)	40	0.42 (0.10, 0.75)
	Fuzhou	23	0.25 (-0.1, 0.6)	15	1.03 (0.26, 1.81)
	Guangzhou	40	0.38 (0.17, 0.59)	22	0.42 (0.11, 0.73)
	HongKong	43	0.23 (0.13, 0.34)	16	0.50 (0.13, 0.87)

Abstract in Korean

동아시아 지역의 미세먼지 사망 관련성에 대한 환경 요인 영향

서울대학교 보건대학원

보건학과 보건통계 전공

김샛별

대기오염에 대한 환경보건학적 중요성이 대두되기 시작하면서 대기오염으로 인한 사망률 또는 유병률에 대한 역학연구가 현재까지 활발하게 진행되어 오고 있으나, 계절별 영향, 대기오염과 기온과의 상호작용으로 인한 영향, 그리고 고농도 대기오염의 지속일수 영향의 구체적 인과관계는 명확히 규명되지 않았다. 따라서 본 학위논문에서는 대기오염물질 중에서 위해성이 큰 것으로 알려지고 있는 미세먼지를 중심으로 동아시아 지역의 미세먼지와 사망간의 관련성을 다각적으로 살펴보고 이를 정량적으로 비교·평가하고자 하였다.

먼저 동아시아 3개국(일본, 한국, 그리고 중국)의 29개 도시에서 미세먼지로 인한 단기 사망영향의 계절성을 살펴보았다. 시계열 모형을 사용하여 계절에 따라 미세먼지가 일별 사망자 수에 미치는 영향을 도시별로 산출 한 후, 베이지안 모형을 사용하여 나라별로 풀링하였다. 두 번째로 기온 수정효과를 보기 위하여 한국 7개 도시에서 계층화된 시계열 모형을 사용하여 서로 다른 기온 구간에서의 미세먼지 사망영향을 질병별, 연령별로 추정한 후, 최대우도추정법을 통해 각 도시의 추정치를 종합한 메타 분석을 실시하였다. 마지막으로 고농도 미세먼지의 일수가 지속될 때 추가적으로 사망영향이 있는지 보기 위하여 총 3국의 28개 도시에 대하여 일일 평균 미세먼지 농도가 75 μg/m³ 이상인 날이 연속적으로 지속될 때의 사망영향을 추정하였다. 일일 평균 미세먼지농도, 기상변수, 계절적 추세 및 요일을 통제하여 각 도시별 추정치를 산출 한 후, 국가 별 추정을 메타분석을 통해 수행하였다.

계절별 미세먼지의 사망영향은 나라별로 상이하게 나타났다. 일본에서는 미세먼지가 10μg/m³ 증가 시, 비사고사망이 봄에 0.44% (95% CI: 0.03%, 0.8%), 그리고 가을에 0.42% (95% CI: 0.02%, 0.82%) 유의하게 증가하였다. 한국에서는 미세먼지가10μg/m³ 증가 시, 비사고사망이 여름에 0.51% (95% CI: 0.01%, 1.01%), 그리고 가을에 0.45% (95% CI: 0.03%, 0.87%) 유의하게 증가하였다. 중국에서는 미세먼지가 10μg/m³

증가 시, 비사고사망이 여름에 0.33% (95% CI: 0.01%, 0.66%), 겨울에 0.41% (95% CI: 0.09%, 0.73%) 유의하게 증가하였다.

기온에 따른 층화분석 결과, 기온이 높은 구간에서 미세먼지에 대한 사망영향이 다른 구간에 비하여 큰 것으로 나타났다. 메타 분석 결과, 65세 이상의 노인 및 여성그룹에서는 기온이 상위 1%일 때 미세먼지의 영향이 가장 크게 나타났고, 65세 미만 및 남성그룹에서는 기온이 상위 5%일 때 미세먼지의 영향이 가장 크게 나타났다.

고농도 미세먼지 지속일수는 국가별 도시별로 편차가 크게 나타났다. 연구 기간 동안 중국 란저우 시는 최장 125일동안 미세먼지 농도가 75 μg/m³ 이상인 날이 지속되었고, 일본 삿포로는 최장 이틀 지속되었다. 국가별 연평균최장지속기간은 일본 2.4일, 한국 6.96일, 중국 42.26일이었다. 분석 결과, 미세먼지가 고농도(일별 평균 미세먼지 농도≥75 μg/m³)인 날이 지속될 경우, 미세먼지 농도 자체의 위험을 배제하고서도 지속기간에 대한 추가 사망위험이 있는 것으로 나타났다. 고농도 일수가 하루 더 지속 될 때, 사망영향이 일본은 0.68% (95% CI: 0.35%, 1.01%), 한국은 0.48% (0.95% CI: 0.30%, 0.66%), 중국은 0.24 % (95 % CI: 0.14%, 0.33%) 증가하는 것으로 나타났다.

본 연구결과를 통하여 동아시아 지역의 3개국에서 계절 및 기온에 따라 미세먼지의 사망영향이 다르게 나타나는 것을 확인하였고, 고농도

미세먼지에 단기적이더라도 지속 노출 되었을 경우 추가 사망위험이 있는 것 역시 확인하였다. 일반적인 미세먼지-사망 연구에서 추가 변수 및 모형 확장을 통해 유의미한 결과를 도출함으로써 기존 연구들이 주었던 결과보다 더 정확하게 미세먼지-사망 관계를 추정할 수 있는 모형을 제시할 수 있었고 이는 정책결정자들이 미세먼지 건강영향을 더욱 잘 이해하는데 기여할 것으로 본다.

주요어: 대기오염, 미세먼지, 사망률, 시계열 분석, 계절성, 수정효과, 기온, 동아시아

학번: 2011-30692