

Article

The Relationship Between Air Pollution and All-Cause Mortality in Singapore

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Abstract: Ambient air pollution is a risk factor for both acute and chronic diseases and poses serious health threats to the world population. We aim to study the relationship between air pollution and all-cause mortality in the context of a city-state exposed to the Southeast Asian haze problem. The primary exposure was ambient air pollution, as measured by the Pollutants Standards Index (PSI). The outcome of interest was all-cause mortality from 2010–2015. A time-stratified case-crossover design was performed. A conditional Poisson regression model, including environmental variables such as PSI, temperature, wind speed, and rainfall, was fitted to the daily count of deaths to estimate the incidence rate ratio (IRR) of mortality per unit increase in PSI, accounting for overdispersion and autocorrelation. To account for intermediate exposure effects (maximum lag of 10 days), a distributed lag non-linear model was used. There were 105,504 deaths during the study period. Increment in PSI was significantly associated with an increased risk of mortality. The adjusted IRR of mortality per the 10-unit increase in PSI was 1.01 (95%CI = 1.00–1.01). The lag effect was stronger when PSI was in the unhealthy range compared to the good and moderate ranges. At lag = 7 days,

PSI appeared to have an adverse effect on mortality, although the effect was not significant. These findings provide evidence on the general health hazard of exposure to air pollution and can potentially guide public health policies in the region.

Keywords: transboundary; haze; air pollution; healthcare; environmental epidemiology; public health; mortality; Southeast Asia; particulate matter

1. Introduction

Ambient air pollution, as a risk factor for both acute and chronic diseases such as lung cancer, heart diseases, and acute respiratory infections, poses serious health threats to the world population [1]. It is well established that both long-term [2] and short-term [3–5] exposure to ambient air pollution impact mortality, in particular cardiovascular and respiratory mortality. Although the deleterious effects of air pollution have been demonstrated in many Western countries [6–8], there are fewer comparable studies conducted in Asia [9–14]. Meanwhile, air quality remains a major problem in Asian cities, with effects on cardiovascular and respiratory mortality noted in time-series data [9,15,16], along with significant public health implications [17].

Seasonal exposure to transboundary haze is a major environmental health problem in Singapore, a heavily urbanized South-east Asian city-state [18,19]. The Meteorological Service Singapore (MSS), which operates under the National Environment Agency (NEA), has established a robust system of monitoring stations across the city-state to provide round-the-clock surveillance of air quality. This surveillance capability creates opportunities for researchers to investigate the health effects associated with air pollution. The haze problem in Singapore generally coincides with the dry season from July to September, when the southwest monsoon shifts the haze resulting from forest fires caused by fire-fallow cultivation in neighboring countries toward Singapore [20]. During periods of haze exposure, there is increased atmospheric loading of particulate matter and other aerosolized pollutants [21]. Previous studies in Singapore suggest that during periods of haze, outpatient attendances for haze-related conditions such as respiratory tract illness rise [22,23] and inpatient admissions increase [24]. Time-series studies have demonstrated an association between haze exposure and acute ischemic stroke [25], acute myocardial infarction [19] as well as cardiac arrest [11]. Studies in similar urbanized Asian settings have demonstrated associations between particulate matter air pollution and short-term mortality [15,26]. We were, thus interested in investigating the association between short-term mortality (within 10 days of exposure) and ambient air pollution in our local context.

2. Materials and Methods

2.1. Setting

Singapore is a Southeast Asian city-state with a tropical climate and a multi-ethnic population of 5.6 million people over 722 square kilometers [27]. It has a tropical rainforest climate [28] with stable temperature and pressure, high humidity and rainfall, and an absence of seasonality [28,29]. In this study, we examined the association of air pollution and all-cause mortality during the six-year period of 2010 to 2015 (inclusive).

2.2. Southeast Asian (SEA) Transboundary Haze Situation

Haze pollution has been a recurrent issue in the Southeast Asian region. One of the earliest records of transboundary haze occurred in 1982, and this phenomenon has since been an annual occurrence in the region [30]. The intensity of the haze varies from year to year, and at its worst, it can affect the populations of six neighboring Southeast Asian countries [31]. The haze has been attributed to forest fires due to fire-fallow cultivation practices in the region [31,32].

2.3. Exposure Variables

The primary exposure variable was the daily average Pollutant Standard Index (PSI), which reflects the concentration of pollutants in the air. Pollutant levels are continuously monitored at 22 telemetric air quality monitoring stations across the island. PSI is computed based on six air pollutants: fine particulate matter with a width smaller than $2.5\ \mu\text{m}$ ($\text{PM}_{2.5}$), particulate matter with a width smaller than $10\ \mu\text{m}$ (PM_{10}), sulfur dioxide (SO_2), carbon monoxide (CO), ozone (O_3) and nitrogen dioxide (NO_2). A sub-index is computed for each pollutant based on a piecewise linear function mapping ambient concentrations onto a 0–500 scale; the largest sub-index value is then used to compute the PSI [33]. PSI was based on a scale devised by the United States Environmental Protection Agency to provide a way for news agencies to report daily air quality. PSI has been used in several countries including the United States, Brunei Darussalam, and Singapore. In Singapore, the NEA categorizes 24-h PSI into good (0–50), moderate (51–100), unhealthy (101–200), very unhealthy (201–300), and hazardous (>300) ranges. The confounding variables in this study were daily average temperature, daily average wind speed, and daily total rainfall. Historical 24-h PSI data and other environmental data were extracted (in November 2017) from governmental websites—www.haze.gov.sg and www.weather.gov.sg, respectively, using an application programming interface (API) script and formatted specifically for this study.

2.4. Outcome Variable

As air pollution is linked to a range of acute and chronic diseases [9,15,16], all-cause rather than cause-specific mortality was selected to be the outcome of interest in this study. Mortality data were obtained from the Ministry of Home Affairs' Registry of Birth and Death through the National Registry of Diseases Office (NRDO). The Registration of Births and Deaths Act mandates that all deaths are to be registered within 24 h of occurrence [34]. Certification of cause of death follows the International Classification of Diseases 9th and 10th Revision codes and is performed by medical practitioners [35].

2.5. Ethics Approval

The SingHealth Centralised Institutional Review Board and the Domain Specific Review Board granted approval for this study with a waiver of patient consent (CIRB reference number: 2017/2380).

2.6. Statistical Analysis

A time-stratified case-crossover approach was used to examine the association between all-cause mortality and PSI. For every death occurring on a day with at least one death, the day of death was considered as a "case" and its "controls" were derived using the same day-of-week in the same month and year [36]. Conditional Poisson regression was used to compare the incidence rate ratio (IRR) of mortality across NEA's recommended range of PSI (good, moderate, and unhealthy, with cut-offs previously stated), accounting for over-dispersion and autocorrelation. Daily average temperature, daily average wind speed, and daily total rainfall were included in the multivariable Poisson models. Conditional Poisson regression was also used to estimate the IRR of mortality per 10 unit increase in PSI across the PSI ranges.

To account for intermediate exposure effects, a distributed lag non-linear model (generalized linear model with quasi-Poisson family) was used [37]. The model comprises the following components: natural cubic splines with 5 degrees of freedom (df) at equal intervals for daily average PSI; natural cubic splines with 7 df per year to describe the long-term time trends, and indicator variables to represent the day of the week. The effect of PSI was assessed through the choice of two bases to describe the relationship in the space of PSI and lags. The knots were placed at equal intervals in the range of PSI and at equal intervals in the logarithmic scale of lags to allow more flexibility in the first part of the distributed lag curve where more variability is expected [38,39]. The maximum lag was set to 10 days. The number of knots, which defines the df in each dimension, was fixed at five on the grounds of parsimony; studies have shown that the bias in estimates for natural splines does

not drop dramatically with each increment of df from five onwards [40]. Data analyses were done using the Stata SE Version 13 and R Version 3.0.2. Statistical significance was set at <0.05 .

3. Results

3.1. Study Population

A total of 105,504 deaths was observed during the study period. Over the study period, 16,437 deaths were reported in 2010, 16,850 deaths in 2011, 17,231 deaths in 2012, 17,783 deaths in 2013, 18,243 deaths in 2014 and 18,960 deaths in 2015. Figure 1 shows the time trend of PSI over the years [41–43]. The median daily average PSI in each quarter of each year of the study period, as well as the proportions of days with daily average PSI in the good/moderate/unhealthy range, are shown in Figure 1. The PSI level was higher in 2014 and 2015 than earlier years.

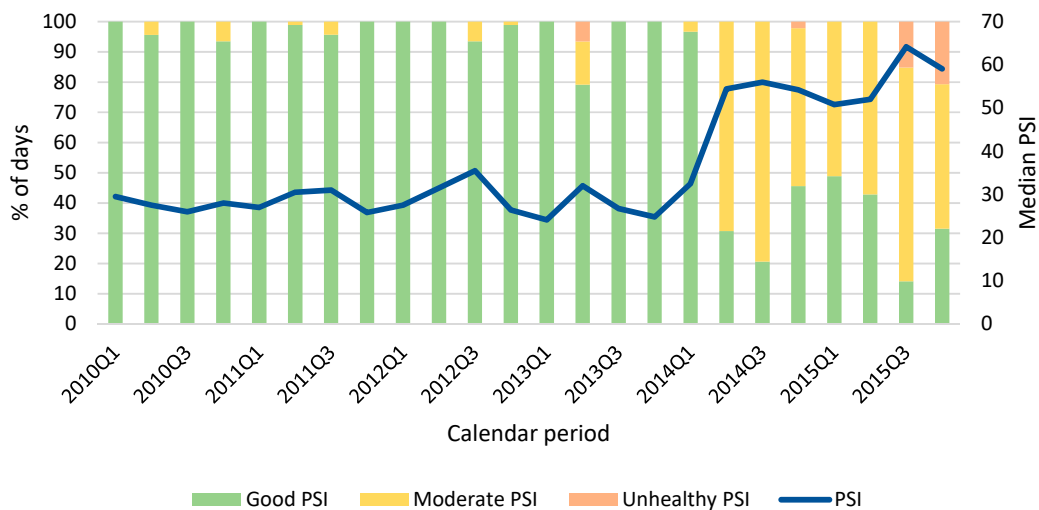


Figure 1. Time trend of Pollutant Standards Index (PSI).

3.2. Description of Environmental Variables

During the study period, the median of daily average PSI was 32.8 with interquartile range (IQR) 25.7–47.0 (Table 1). Comparing the days with PSI in the good, moderate and unhealthy ranges, temperature ($p < 0.001$) and wind speed ($p = 0.020$) tended to be higher in the moderate and unhealthy PSI ranges, while rainfall ($p < 0.001$) tended to be higher in the good PSI range.

Table 1. Characteristics of Pollutant Standards Index (PSI), temperature, wind speed, and rainfall in the study period by PSI ranges specified by the National Environment Agency.

	Overall (n = 2191)	Good PSI (n = 1721)	Moderate PSI (n = 429)	Unhealthy PSI (n = 41)	p- Value
Daily average PSI, median (IQR)	32.8 (25.7–47.0)	29.5 (24.5–36.0)	58.4 (54.5–65.6)	130.3 (109.2–150.4)	-
Daily average temperature in °C, median (IQR)	27.9 (27.0–28.7)	27.7 (26.9–28.5)	28.5 (27.8–29.0)	28.9 (28.4–29.2)	<0.001
Daily average wind speed in km/h, median (IQR)	7.8 (6.4–10.5)	7.7 (6.3–10.3)	8.5 (6.4–11.1)	8.1 (6.7–11.0)	0.020
Daily total rainfall in mm, median (IQR)	0.0 (0.0–4.0)	0.2 (0.0–4.8)	0.0 (0.0–2.2)	0.0 (0.0–0.2)	<0.001
Number of days with rain, n (%)	1051 (48.0)	874 (50.8)	166 (38.7)	11 (26.8)	<0.001

3.3. Short-Term Effects of PSI on Mortality

Compared to good PSI range, moderate (IRR 1.05, 95% CI 1.03–1.07) and unhealthy ranges (IRR 1.08, 95% CI 1.03–1.14) of PSI were associated with a higher risk of mortality (Table 2). Increment in PSI was significantly associated with an increased risk of mortality. The adjusted IRR of mortality per 10-unit increase in PSI was 1.01, with a 95% confidence interval (CI) 1.00–1.01. After stratifying by PSI ranges, the increased risk of mortality for each 10-unit increment of PSI (IRR 1.01, 95% CI 1.00–1.02) remained in the good PSI range but did not have any association in the moderate and unhealthy PSI ranges.

Table 2. Incidence rate ratio (IRR) of mortality associated with each Pollutant Standards Index (PSI) range specified by the National Environment Agency and each 10-unit increment in the daily average PSI within each PSI range.

	Risk Associated with Each PSI Range Compared to Good PSI		Risk Associated with Each 10-Unit Increase in PSI	
	Unadjusted IRR (95% CI)	Adjusted IRR (95% CI) ^	Unadjusted IRR (95% CI)	Adjusted IRR (95% CI) ^
Overall	Not applicable	Not applicable	1.01 (1.01–1.02) *	1.01 (1.00–1.01) *
Good PSI	1.00 (reference)	1.00 (reference)	1.02 (1.01–1.03) *	1.01 (1.00–1.02) *
Moderate PSI	1.06 (1.04–1.08) *	1.05 (1.03–1.07) *	0.98 (0.95–1.02)	0.98 (0.94–1.02)
Unhealthy PSI	1.10 (1.05–1.16) *	1.08 (1.03–1.14) *	0.99 (0.87–1.14)	0.99 (0.85–1.16)

* statistical significance with $p < 0.05$. ^ adjusted for daily average temperature, daily average wind speed, and daily total rainfall.

3.4. Intermediate-Term Effects of PSI on Mortality

Figure 2 shows the IRR of mortality by PSI at specific lag 0, 3, 7 and 10 and by lag at specific PSI corresponding to approximately (rounded up to the nearest integer) the 5th (PSI = 12) and 95th (PSI = 198) percentile of the PSI distribution, cut-off between the good and moderate PSI ranges (PSI = 50), and cut-off between the moderate and unhealthy PSI ranges (PSI = 100). The plots of IRR by PSI at specific lag indicated that at lag 7, the IRR of mortality spiked in the very unhealthy range compared to good, moderate, and unhealthy ranges; the association was, however, not significant.

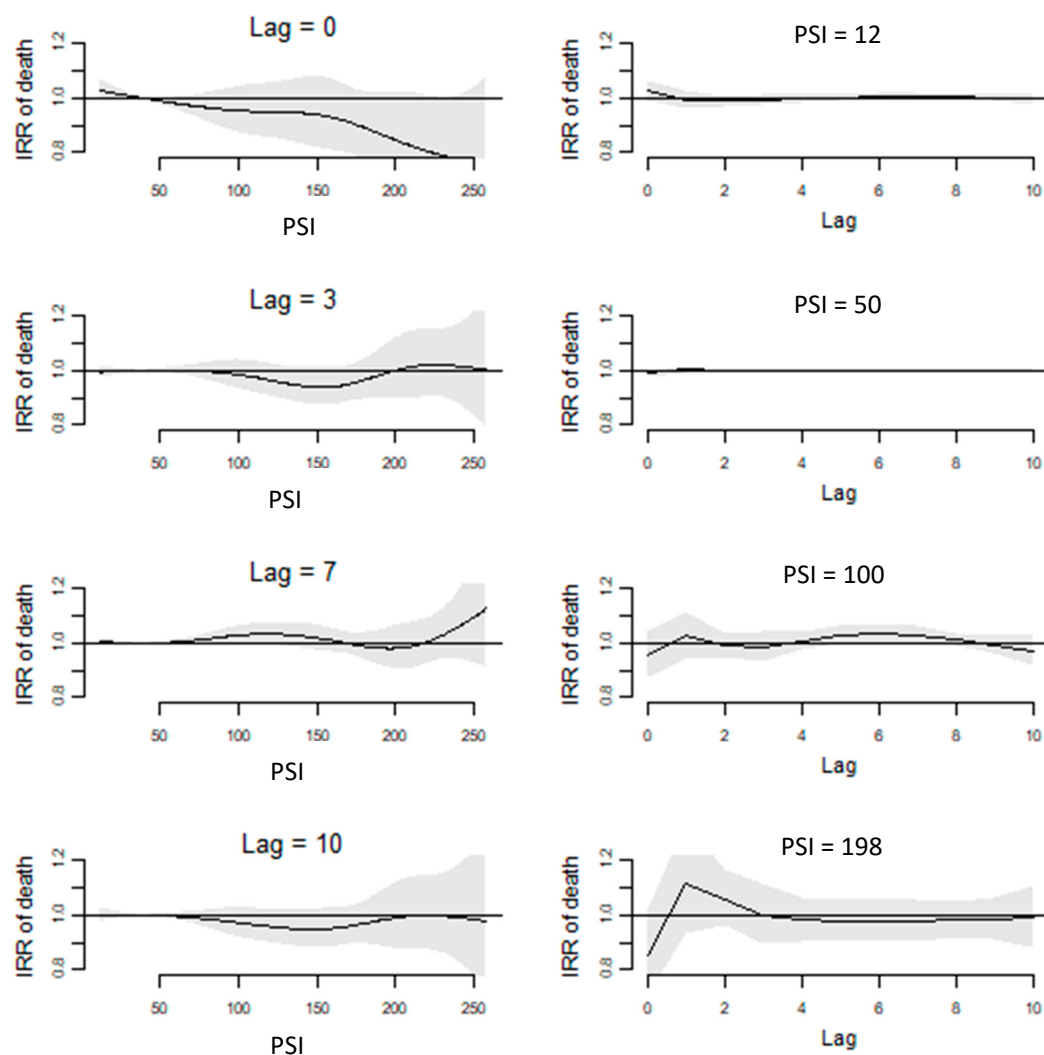


Figure 2. Incidence rate ratio (IRR) of mortality by the Pollutant Standard Index (PSI) at specific lags (left) and IRR of the mortality by a lag at specific PSI (right).

4. Discussion

In this study, we examined the effect of air pollution on mortality in Singapore and demonstrated a significant association between an increase in PSI and mortality. In the short-term (lag = 7 days), PSI in the very unhealthy range appeared to have an adverse effect on mortality, although the effect was not statistically significant. In the longer term (lag >7 days), PSI in the unhealthy range similarly did not appear to have an effect on mortality. This could be attributed to the harvesting effect whereby PSI affected mainly a pool of frail individuals, and the depletion of this pool led to the reduction of potential deaths a few days later, thereby reducing the impact from PSI temporarily [44,45]. On the other hand, the trend towards a reduced IRR at lag = 10 days, rather than a clear protective effect, is only suggestive but not conclusive of harvesting as an explanation. Reactive organizational-level protection measures, such as increased utilization of air filtration devices and more stringent limits on outdoor exposure for employed personnel, may also require time to take effect.

This is, to our knowledge, the first study linking the Southeast Asian haze to mortality in Singapore. While other studies in the region have documented increased morbidity associated with transboundary haze episodes, particularly for cardiovascular and respiratory morbidity, studies

focusing on mortality are lacking [46]. One study in neighboring Malaysia [47] also demonstrated adverse associations between all-cause mortality and respiratory-specific mortality, and air pollution encountered during transboundary haze episodes. However, their study did not demonstrate a harvesting effect, perhaps because of the shorter lag times (up to seven days) studied [47].

Our findings of a significant association between air pollution and mortality mostly corroborated the findings of other studies which used different measures of air quality and research designs, conducted in Australia [48,49], Europe [50], and Asia [14]. Interestingly, Yin and colleagues [14] found the highest risk of mortality when the lag was 0 compared to longer lags (up to six days), with no association between air pollution and mortality when lags were > 2 days. This is in contrast to our finding of the higher risk of mortality at lag 7 when PSI was in the very unhealthy range, although the association was similarly not significant.

The association between air pollution and mortality found in our study could possibly be attributed to an intermix of upper and lower respiratory tract infection and inflammation, allergic and hyperimmune reactions, oncologic implications, cardiovascular diseases, and distributed complications throughout the body, as mechanisms contributing to the degradation of health. In our previous studies, we similarly found an elevated risk of stroke [25], acute myocardial infarction [19], and out-of-hospital cardiac arrest [11] after exposure to unhealthy PSI ranges. Notably, airborne particulates are classified as Group 1 carcinogens by the WHO (World Health Organization) and IARC (International Agency for Research on Cancer), due to their ability to penetrate deep into the lungs and bloodstreams unfiltered; while the PM_{10} and $PM_{2.5}$ particulates encompassed within the PSI metric are medically dangerous as thoracic and respirable particles, their presence might reasonably be correlated with submicron particles of even greater penetration. While the current study aims to investigate all-cause mortality as a way of providing highly general statistics between airborne pollution and population health, greater specific insights into the roles of these individual potential causes may be gained via a future cause-specific study.

4.1. Study Strengths

The strengths of the present study include high-quality death count data obtained from a national registry, which lends confidence in the complete data capture. Also, exposure data was directly measured by meteorological stations spread across the studied city-state of Singapore (and not obtained via modeling). Additionally, the conditional Poisson regression model used in this study accounted for overdispersion and autocorrelation in the time-dependent count's data [36], hence suppressing regression inaccuracies [51] and the distributed lag non-linear model accounted for longer-term lag of up to 10 days.

4.2. Future Work

In this ecological study, we have demonstrated an association between PSI and mortality; however, it does not prove a causative relationship. Furthermore, as characteristic of data from death registries, there was no patient-level data available for subgroup analyses to identify susceptible subpopulations. A future cause-specific study with patient-level data can provide greater insights into susceptible subpopulations and the roles of individual potential causes of mortality.

As data of individual pollutant concentrations were not available, this limits the ability to relate the risk of mortality with each pollutant. However, the use of PSI is more pragmatic for the purpose of interpretation, informing policies and formulating public health messages as our results have shown.

5. Conclusions

In this study, we have demonstrated an association between exposure to elevated PSI levels and an increased short-term risk of mortality in Singapore. Air pollution is a tremendous public health issue, and our study has incorporated the Singapore context into the existing and growing body of evidence on the effect of air pollution on health [12,22,52–56].

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