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Influences of socioeconomic vulnerability and intra-urban air pollution exposure on short-term mortality during extreme dust events

Hung Chak Ho[1,2], Man Sing Wong[1,2*], Lin Yang[3], Ta-Chien Chan[4], Muhammad Bilal[1,2]

1. Department of Land Surveying and Geo-Informatics, The Hong Kong Polytechnic University, Hong Kong
2. Research Institute for Sustainable Urban Development, The Hong Kong Polytechnic University, Hong Kong
3. School of Nursing, The Hong Kong Polytechnic University, Hong Kong
4. Research Center for Humanities and Social Sciences, Academia Sinica, Taiwan

Corresponding Author: Man Sing Wong, Department of Land Surveying and Geo-Informatics, Hong Kong Polytechnic University, Hong Kong

Email: lswong@polyu.edu.hk

Abstract

Air pollution has been shown to be significantly associated with morbidity and mortality in urban areas, but there is a lack of studies focused on studying extreme pollution events such as extreme dust episodes in high-density Asian cities, even though such cities have had extreme climate episodes that could have adverse health implications for downwind areas. More importantly, only a few studies have comprehensively investigated the mortality risks of extreme dust events for socioeconomically vulnerable populations.

This paper examined the association between air pollutants and mortality risk in Hong Kong from 2006 to 2010, with a case-crossover analysis, to determine the elevated risk after an extreme dust event in a high-density city. The results indicate that $PM_{10-2.5}$ dominated the all-cause mortality effect at the lag 0 day (OR: 1.074 [1.051, 1.098]). This study also found that people who were aged >= 65, unemployed, or non-married had higher risks of all-cause mortality and cardiorespiratory mortality during days with extreme dust events. In addition, people who were in areas with higher air pollution had significantly higher risk of all-cause mortality.

In conclusion, the results of this study can be used to target the vulnerable among a population or an area and the day(s) at risk to assist in health protocol development and emergency planning, as well as to develop early warnings for the general public in

order to mitigate potential mortality risk for vulnerable population groups caused by extreme dust events.

Capsule: Data-driven methods are established 1) to identify socioeconomically vulnerable populations and high-risk areas across a city, and 2) to evaluate the utility of more general health protocols prior to their adoption.

Keywords: extreme dust events; short-term mortality risk; social vulnerability; socioeconomic vulnerability; spatial analytics

Introduction

Air pollution has been associated with all-cause, respiratory and cardiovascular morbidity and mortality in urban areas (Garcia et al., 2016; Jerrett et al., 2005; Lu et al., 2015; Pope III & Dockery, 2006), especially in a common urban form in Asian countries, namely a “high-density city” or a “compact city” with high-density living (Ko et al., 2007; Meng et al., 2013; Wong et al., 1999; Wong et al., 2002; Wong et al., 2015). Some studies have also found that extreme pollution events, especially an extreme dust event, can severely increase the health risk within a short period. For example, a 39% increase in emergency admissions in Brisbane and a 20% increase in respiratory emergency department visits in Sydney were found during an extreme dust event across Australia in 2009 (Barnett et al., 2012; Merrifield et al., 2013). While the number of extreme dust events across a city may be rare, it is important to analyze their impacts on morbidity or mortality prior to the occurrence of the next extreme event, in order to improve health warnings and emergency plans for disaster risk management. Similar health studies have commonly been conducted for the other types of extreme weather (e.g. heat waves) with an event-based model or a case-crossover model (Ho et al., 2017; Kosatsky et al., 2012). However, there are only a few studies analyzing the adverse effect of extreme dust events on the elevated mortality risk within a very short period (“short-term mortality”). In addition, most pollution studies have not focused on extreme dust events in a high-density Asian city, despite the fact that dust storms across Asia have been recognized as extreme climate episodes with adverse health implications (Zhang et al., 2005; Wong et al., 2010; Wong et al. 2015; Xiao et al., 2015). For example, deserts in Mongolia and northwestern China on average have released 800 tera-grams of dust each year and induced serious air pollution in the northern China and South Korea (Chung and Yoon, 1996; Zhang et al., 1997). Strong easterly and south-easterly winds from the desert and arid surfaces can also bring desert dust to other areas. As a result, Japan (Var et al., 2000), Taiwan (Lin, 2001) and Hong Kong (Wai & Tanner, 2005; Wong et al., 2010) have also observed extreme dust events in the past. In an extreme case, Wong et al. (2010) found a significant increase of PM_{10} concentration on days with extreme dust events that could be 2 to 6 times higher than the days without dust storms. It is important to evaluate the mortality risk during such storms in order to develop an appropriate mitigation protocol for public health surveillance.

In regard to previous health studies, some have reported a significant association between mortality and dust events (Chan & Ng, 2011; Lee et al., 2013; Johnston et al., 2011; Perez et al., 2008; Perez et al., 2012), while some others found an insignificant increase in mortality after dust events (Al-Taiar & Thalib, 2014; Chen et al., 2004; Hashizume et al., 2010; Kwon et al., 2002). It is, therefore, believed that the adverse health effects of dust are varied because of the geographical location and environmental setting of cities.

Compared to traditional cities in developed countries, a high-density city has a completely different urban climatic system due to its urban morphology that can highly influence wind ventilation and can affect air pollution risk (Steward & Oke, 2012). For example, Hong Kong is a typical high-density city, with urban areas occupied by high-rise buildings and narrow streets (Chen et al., 2012). This urban morphology forms “urban canyons” that can control wind speed and wind direction (Wong et al., 2011). On a day with an extreme dust event, urban canyons can trap the dust pollutants, and as a result increase urban mortality. Thus, it is necessary to develop a comprehensive assessment mechanism to evaluate the implications of extreme dust events for daily mortality across a high-density city.

More importantly, previous studies mainly focused on adverse effects of dust events based on the mortality of the general population (Chen et al., 2004; Johnston et al., 2011). Only a few studies have sketchily described the difference in mortality risk between sub-groups of the population at the individual level after dust events (Lee et al., 2013; Al-Taiar & Thalib, 2014), but this missing part is essential for understanding the influence of socioeconomic vulnerability on mortality. Referring to the guideline of the United Nations Office for Disaster Risk Reduction (https://www.unisdr.org/we/inform/terminology), the relationship between subgroups of a population and mortality is related to the "socioeconomic vulnerability" for disaster risk management, that can determine the socioeconomic conditions or processes increasing the susceptibility of an individual to the impacts of a natural hazard. Among these dust mortality studies, age and gender are the only socioeconomic vulnerability factors that have been examined, while others that should have adverse effects on mortality (e.g. social isolation and socioeconomic deprivation) have not been discussed (Clougherty & Kubzansky, 2009; Makri & Stilianakis, 2008; Martins et al., 2004; Medina-Ramón & Schwartz, 2008). There has also been no study identifying the difference in mortality risk between areas with higher and lower air pollution exposure during an extreme dust event. Failure to consider the influences of spatial pollution exposure and individual-level socioeconomic vulnerability may reduce the ability to identify populations at risk during extreme dust events appropriately.

In order to investigate the influences of spatial pollution exposure and socioeconomic vulnerability on mortality during a dust storm comprehensively, we applied a time-stratified case-crossover study to estimate the mortality risk of air pollution during extreme dust events between 2006 and 2010 in Hong Kong. Our objectives are 1) to evaluate the contribution of air pollution to dust mortality, 2) to identify the vulnerable population(s) during an extreme dust event, and 3) to evaluate whether areas with higher air pollution are the locations with higher mortality risk ("high-risk areas") for the general population and vulnerable sub-population(s) during an extreme dust event. The results of our study can further be used to develop environmental health protocols and emergency response systems for extreme dust events across a high-density Asian city in the future.

Methods

Data Collection

We retrieved mortality data of 2006 through 2010 from the Hong Kong Census and Statistics Department. This mortality dataset includes the following variables for each decedent: 1) cause of death according to the 10^{th} revision of the International Classification of Diseases (ICD-10), 2) date of death, 3) age, 4) gender, 5) marital status, 6) occupation and 7) location of residence. Location of residence is based on the finest district level for regional planning in Hong Kong, namely the "Tertiary Planning Unit" (TPU).

Hourly air pollution data ($PM_{2.5}$, NO_2, O_3, PM_{10}, and SO_2) were retrieved from all monitoring stations of the Hong Kong Environmental Protection Department, and were recalculated to a daily average. In this study, data from three roadside stations

(Mong Kok, Causeway Bay, and Central) were excluded from calculation, in order to minimize the bias from traffic-related pollution. This pollution dataset was co-matched with the mortality dataset based on the date of death of each decedent.

We also retrieved the spatial pollution exposure data from the Aerosol Optical Thickness (AOT) based on satellite images. The AOT can indicate particulate matters at ground level in a spatial context, with the appropriate combination of land use information and other meteorological factors, such as wind speed (Bilal et al., 2016; Wong et al., 2015). The spatial distribution of AOT can influence the health risk during typical air pollution events (Lai et al., 2014). In our study, AOT data were derived from the average of four cloud-free MODIS images retrieved on Apr 17, 2006, Apr 28, 2009 and Mar 26, 2010 to represent a specific scenario during extreme dust events in Hong Kong. Average AOT values of each TPU were calculated based on the AOT images derived from the simplified high resolution Moderate Resolution Imaging Spectroradiometer (MODIS) Aerosol Retrieval Algorithm (Bilal et al., 2013; Bilal & Nichol, 2015) using MODIS images at 500m resolution. The average AOT of each TPU was co-matched with the mortality dataset based on locations of residence.

Case-crossover design

We applied a time-stratified case-crossover design to estimate the excess mortality during an extreme dust event. The time-stratified case-crossover approach is a common epidemiological design that can directly estimate the exposure-mortality relationship based on a small sample size of cases, and with less bias due to the number of control samples. Unlike time-series analysis, which needs to be controlled or adjusted by the weekday/weekend effect, seasonality and long-term trends, a case-crossover approach is independent of such effects based on its “cases as their own self-matched controls” structure (Maclure, 1991). The ability of this design to estimate adverse health effects of an extreme weather event has also been amply demonstrated (Bell et al., 2008; Ho et al., 2017; Johnston et al., 2011; Perez et al., 2012; Tobías et al., 2011). In this case-crossover study, days with extreme dust events were identified based on a previous study (Wong et al., 2010) using the NASA Aerosol Robotic Network’s (AERONET) sunphotometer size distribution inversion data, the backward trajectories model of Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT), and meteorological reports. For each death on a day with extreme dust events (case days), exposure on the case days was compared with the exposure on the same weekday each week within the same calendar month (control days), in order to prevent bias introduced by alternative control selection methods (Chan & Ng, 2011; Bell et al., 2008; Ho et al., 2017; Janes et al., 2005; Johnson et al., 2011; Perez et al., 2008; Perez et al., 2012). This set of cases and controls was used to estimate the potential increase in health risk immediately after an extreme dust event. A conditional logistics regression model from the *survival* package of R statistical software was used to estimate the odds ratios (OR) for mortality associated with extreme dust events (Therneau, 2015). Following previous studies using a case-crossover approach for dust mortality estimation (Chan & Ng, 2011; Johnson et al., 2011; Tobías et al., 2011), the daily average of air pollutants ($PM_{10\text{-}2.5}$, $PM_{2.5}$, NO_2, O_3, and SO_2), average temperature and relative humidity for case days and control days were included in the model, while concentrations of $PM_{10\text{-}2.5}$ were retrieved by subtracting $PM_{2.5}$ from PM_{10}. In addition, a non-linearity test of additional squared terms for both $PM_{10\text{-}2.5}$ and $PM_{2.5}$ were added to the regression models (Basu et al., 2015). This case-crossover analysis was repeated for deaths on the three days after extreme dust events (lag 1 to lag 3), in order to evaluate whether there was a prolonged effect on mortality due to trapping of massive amounts of dust in urban canyons. All-cause mortality and cardiorespiratory mortality (ICD-10 codes I00-I99 and ICD-10 codes J00-J99) were examined in this study.

Effect modification of mortality risk

We examined the effect modification of individual-level socioeconomic vulnerability by creating a dummy interactive variable for vulnerable and high-exposure groups. Four vulnerable groups were selected: 1) age >= 65, 2) female, 3) economically inactive, 4) non-married. In detail, the categories are: 1) represents seniors who have been recognized as a vulnerable group in past research (Cutter et al., 2003; Medina-Ramón & Schwartz, 2008); 2) indicates the difference in vulnerability by gender (Cutter et al., 2003); 3) represents socioeconomic vulnerability due to unemployment or retirement (Bell et al., 2012; Cutter et al., 2003; Ho et al., 2015; Ho et al., 2017; Makri & Stilianakis, 2008); and 4) represents a group with potential social isolation (Wong et al., 2016). These vulnerability and exposure factors were compared with the control groups (age < 65, male, employed, and married) in order to evaluate the statistical significance of each variable.

For the vulnerable populations identified above, we have further evaluated the effect modification of spatial pollution exposure on all vulnerable groups, in order to investigate whether areas with higher air pollution can further contribute to higher mortality risk. Similar to the analyses above, each vulnerable population group was evaluated by creating a dummy interactive variable for high-exposure groups. In this study, the high-exposure groups are the decedents in areas with higher AOT (>= 33^{th} percentile), in which these areas represent regions with higher air pollution potentially contributed by particulate matters. We repeated the analyses for decedents in the general population and decedents in each vulnerable population group, by comparing these case groups with the control groups (decedents in AOT <33th percentile), in order to evaluate whether there is a difference in risk with statistically significant between areas with higher and lower air pollution.

Results

Data summary

There were ten identified days with extreme dust events between 2006 and 2010 (Apr. 16-17, 2006; Apr. 27-30, 2009; and Mar. 23-26, 2010). Average $PM_{10\text{-}2.5}$ concentration of these 10 days was 44.47 μg/m^3, and 964 decedents were reported within these days in Hong Kong. Comparing all decedents on case days and control days, $PM_{10\text{-}2.5}$ concentrations on case days were on average 147.6% higher than on the control days, while other air pollutants were generally lower except O_3. These findings were consistent with other Asian dust studies indicating exponential increases of PM_{10} and O_3 during extreme dust events (Chen et al., 2004).

Mortality risk of air pollution during an extreme dust event

We estimated the ORs of $PM_{10\text{-}2.5}$, and $PM_{2.5}$ on the days with extreme dust events (Table 2). $PM_{10\text{-}2.5}$ significantly increased both all-cause and cardiorespiratory mortality. On a day with an extreme dust event (lag 0), a 7.4% increase in all-cause mortality and

7.0% increase in cardiorespiratory mortality are expected with a 10 μg/m^3 increase of $PM_{10-2.5.}$ It can be concluded that $PM_{10-2.5}$, the major component of a dust storm, was the key factor contributing to adverse health effect across this high-density city. In contrast, although some studies have found that $PM_{2.5}$ may increase mortality during an extreme dust event, this was not the case for Hong Kong.

In addition, there were no prolonged influences of extreme dust events in Hong Kong. The day after an extreme dust event (lag 1) had 3.1% lower all-cause mortality and 1.9% lower cardiorespiratory mortality than the lag 0 day. Results for two and three days after a storm (lag 2 and lag 3) were very insignificant, with extreme values of the 95^{th} confidence intervals. This implies that extreme dust events do not result in a prolonged pollution event in the post-storm period in a high-density city, and the increase in pollutants on the day of extreme dust events is the only factor contributing to fatal effects in Hong Kong.

Effects of socioeconomic vulnerability on mortality risk

Among all socioeconomic vulnerability variables based on individual-level data, economic inactivity had the highest influence on mortality risk (Table 3). People who were economically inactive had approximately 5.5% higher all-cause mortality risk and 5.6% higher cardiorespiratory mortality risk from a 10 μg/m^3 increase in $PM_{10-2.5}$ than those who were employed during a day with an extreme dust event. Seniors and non-married persons also had higher mortality risk. A person aged >=65 had 4.4% higher risk of all-cause mortality and 5.3% higher cardiorespiratory mortality than who were under the age of 65. A person who was not married had 4.1% higher risk of all-cause mortality and 4.7% higher cardiorespiratory mortality. Table 3 also showed that females had insignificantly higher risk of all-cause mortality and cardiorespiratory mortality on a day with an extreme dust event.

Effects of intra-urban air pollution on mortality risk

Based on the results above, we further evaluate the influence of intra-urban air pollution on mortality risk of the general population and specific vulnerable populations (seniors, the economically inactive, and non-married). The results indicated that the spatial distribution of pollution exposure influenced dust-related mortality. Grouped by all decedents, there were higher all-cause and cardiorespiratory mortality risks in areas with AOT >= 33^{th} percentile (ORs: 1.045 [1.020, 1.070] and 1.044 [1.004, 1.086]). There were also higher all-cause and cardiorespiratory mortality risks in areas with higher intra-urban air pollution for the senior population (OR: 1.043 [1.019, 1.067] and 1.047 [1.002, 1.095]). In addition, for people who were economically inactive, all-cause mortality risk was found to be higher in areas with higher pollution (OR: 1.049 [1.018, 1.080]); and people who were not married were expected to have higher cardiorespiratory mortality risk during an extreme dust event (OR: 1.038 [1.004, 1.073]).

Discussion

Comparison with other studies

In this study, a time-stratified case-crossover approach was applied to estimate the mortality risk of air pollution after an extreme dust event. Our results indicate that $PM_{10-2.5}$ is the dominant factor in the air pollution risk of an extreme dust event, contributing to a 7.4% increase in all-cause mortality and 7% increase in cardiorespiratory mortality on the day of an extreme dust event. There was a weak prolonged effect of extreme dust events in Hong Kong, such that the significant influence on mortality from $PM_{10-2.5}$ continued on the day after an extreme dust event, after which there was no further effect on mortality. At lag 0, the mortality risks are 1.9-3.1% higher than at lag 1. We also evaluated four socioeconomic vulnerability factors and found that persons who were economically inactive or non-married or seniors had higher mortality risk after an extreme dust event. In addition, both the general population and vulnerable populations had higher mortality risk in areas with higher pollution exposure (AOT >=33th percentile) than the other regions in Hong Kong.

These results are consistent with previous findings; e.g. Johnston et al. (2011)

found a 16% increase [3%, 30%] in all-cause mortality at a lag of 3 days after a dust event in Sydney, Australia; Chen et al. (2004) indicated there was a 7.66% and 4.92% increase in respiratory deaths on the first and second day after a dust storm in Taipei, Taiwan; Lee et al. (2013) observed a weaker but significant association between dust and mortality in seven cities in South Korea, with a 2.91% increase in cardiovascular mortality found on the day of a dust storm. These results and our study all indicated an increased risk immediately after a dust event, even though all these study areas were relatively far from the deserts. In contrast, one study of areas nearby the Arabian Desert, such as Kuwait, found no significant association between dust events and mortality (Al-Taiar & Thalib, 2014), which implies that extreme dust episodes induce significant health effects in downwind cities, while cities near the desert may have insignificant links between dust and mortality. This is an important finding, since all these studies demonstrate excessive amounts of particulate matters during an extreme dust event, while not all these studies found significant association between dust and mortality. This further implies that differences in amounts of particulate matters between dusty days and regular days may be the key to inducing severe mortality, in which locations closer to a desert are expected to have higher baseline particulate matters that have already contributed to a long-term adverse health impact to the general population, with less discernable short-term impact from dust storms. This phenomenon is also observed with other extreme climatic events; for example, the difference in temperature between days was found in one study to be the major factor behind increasing mortality risk due to an extreme weather event (Zeng et al., 2014).

Protocols for Disaster Risk Reduction

In this study, we also evaluated the relationship of mortality and socioeconomic vulnerability. Based on our finding, a person who is economically inactive or not married or older has the highest risk immediately after an extreme dust event. This is important to public community health planning, since socioeconomic deprivation is well documented as a key variable involved in vulnerability in terms of general health (Bell et al., 2012), climatic risk (Aminipouri et al., 2016; Chan et al., 2012; Ho et al., 2017), and air pollution (Clougherty & Kubzansky. 2009; Makri & Stilianakis, 2008; Martins et al., 2004). This vulnerability factor may be associated with poor housing quality, social isolation, and lack of health care, and all these sub-factors may directly or indirectly raise the community health risk on days immediately after an extreme dust event. Failure to consider such socioeconomic vulnerability factors may reduce the possibility of identifying and protecting at-risk population groups during extreme dust events in the future. Previous dust mortality studies have only focused on vulnerability due to advanced age (Lee et al., 2013; Al-Taiar & Thalib, 2014). Our study shows that factors other than age are important for identifying at-risk groups, while potential social isolation (operationalized here as the non-married population) and unemployment in particular were associated with an increase in risk similar to that for advanced age. This supports our conclusion that more socioeconomic vulnerability factors need to be addressed in research and public policy on dust episodes.

These results imply that a protocol for disaster risk reduction should develop as follows: a) a target on sustainable planning in areas with higher intra-urban air pollution (e.g. increases in city ventilation paths and vegetation cover for improving air quality), in order to reduce the modifying effect of mortality risk during an extreme dust event from regional pollution; b) arouse the public especially to seniors and people with lower socioeconomic status to increase their awareness for disaster preparation, as they may have less resources and prior education to cope with an outbreak of disaster; and c) developing community network and social awareness systems for disaster risk management, as results have shown that vulnerable population with higher social isolation can have higher risk from natural disasters; and d) implementing a warning system for reporting days with potential higher risk to the public. In conclusions, items a) and d) involve top-down design involving governance and policy-making for disaster management, while b) and c) can be bottom-up strategies involving local non-governmental organizations (NGOs) and charitable organizations.

Limitations and future directions

One limitation of this study is that the model has not comprehensively accounted for the spatial effect, as similar to other time-stratified studies. This is partially due to the limitation of weather station data, as stated in other studies (Ho et al., 2017; Thach et al., 2015), in which these stations are sparsely and unevenly distributed. In order to develop a spatiotemporal approach or an ecological study to predict dust mortality, higher quality spatial data are required. Remote sensing satellite imagery may thus be an alternative for developing a spatiotemporal study, but this may be constrained by satellite overpass times and cloud-contamination. Therefore, a combination of both in-situ air quality monitoring data and satellite images may prove most useful for future studies.

Another limitation in the present research is the vulnerability variables. Although this study investigated the modifying effect of gender, unemployment, older age and marital status on mortality risk, other factors such as household income, education level, and underlying diseases should also be included in a more comprehensive assessment. However, due to the limitation of the mortality data used in this study, there was no such individual-level information for each decedent in Hong Kong. An alternative method, using census data to represent socieconomic vulnerability, has been suggested by others (Chan et al., 2012; Ho et al., 2017). However, this method is more appropriate for determining the social environment influencing an individual, but not for defining the personal characteristics of an individual (Kosatsky et al., 2012) who may be more vulnerable and therefore at risk during an extreme event. For the purpose of this study, it is more appropriate to use personal characteristics of each decedent for modelling, while for further study, using census data for estimating community vulnerability may be appropriate for determining intra-city risk (Chan et al., 2012).

Results from this study suggest that a combination of pollution data from an air quality monitoring network and a health dataset can be used to develop protocols for future health warning systems. Similar approaches have been applied to determine days with potential disaster risk based on other extreme climatic events, such as heat waves (Chau et al., 2009), with promising results, as significant risk reduction was found after a warning system had been set up (Chau et al., 2009; Tan et al., 2007). Incorporating these ideas, the results from this study can be further used to help set guidelines for public health surveillance, by determining days at risk based on weather forecasting and the hourly reports of $PM_{10-2.5}$ from governmental monitoring stations.

Conclusions

In this study, a time-stratified case-crossover approach was developed to evaluate both the risk of $PM_{10-2.5}$ immediately after an extreme dust event, and the difference in risk of vulnerable population groups in a high-density city (Hong Kong). We observed a significant increase in mortality risk on the day of an extreme dust event. The results also show that persons who were economically inactive or elderly or non-married had a higher $PM_{10-2.5}$ risk during a day with an extreme dust event, and areas with higher AOT also had higher mortality risk. Based on these observations, the areas and population groups vulnerable to dust-induced mortality can be pinpointed, while pollution data from an air quality monitoring network can be used to develop a protocol for a health warning system. Combining satellite images and air quality monitoring network data is recommended, in order to provide holistic and synoptic observations over an area, and this can be further developed to estimate community health risks in different neighborhoods and for the purpose of public health surveillance.

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Captions of Figures

Figure 1 – Total number of deaths in all TPU during extreme dust events between 2006 and 2010.

Figure 2 – Areas with higher and lower intra-urban air pollution (determined by AOT) in Hong Kong.

Pollutants	Case (n = 964)	Control (n = 3367)	T-Test (p-value)	% Difference
$PM_{10-2.5}$	**44.47 μg/m^3**	**17.96 μg/m^3**	**<0.05**	**147.6%**
O_3	**65.37 μg/m^3**	**44.02 μg/m^3**	**<0.05**	**48.5%**
NO_2	45.1 μg/m^3	55.87 μg/m^3	<0.05	-19.3%
SO_2	11 μg/m^3	16.95 μg/m^3	<0.05	-35.1%
$PM_{2.5}$	33.31 μg/m^3	33.64 μg/m^3	0.54	-0.98%

Table 1: Data Summary. This table reports the average values of all pollutants, separated by all cases and all controls. **Bold text** indicates the pollutants with significantly higher values (μg/m^3) on the days with dust storms (case days) compared to days without a dust storm. % Difference is the percentage difference between average values of all cases and all controls.

Pollutant		OR (all-cause mortality)	OR (cardiorespiratory mortality)
$PM_{10\text{-}2.5}$	Lag 0	**1.074 [1.051, 1.098]**	**1.070 [1.036, 1.105]**
	Lag 1	**1.043 [1.023, 1.064]**	**1.051 [1.021, 1.083]**
$PM_{2.5}$	Lag 0	0.899 [0.876, 0.922]	0.919 [0.885, 0.954]
	Lag 1	0.908 [0.888, 0.928]	0.921 [0.891, 0.952]

Table 2. Table of odds ratios (OR) at lag 0 to 1 of all-cause and cardiorespiratory mortality, for 10 μg/m^3 increase of $PM_{10\text{-}2.5}$ and $PM_{2.5}$, with the 95th confidence interval. **Bold text** indicates the most significant results

Socioeconomic Vulnerability (Individual Level)		OR at lag 0 (all-cause mortality)	OR at lag 0 (cardiorespiratory mortality)
Age	>=65	**1.044 [1.029, 1.059]**	**1.053 [1.029, 1.078]**
	<65	1.047 [0.994, 1.103]	1.045 [0.920, 1.186]
Gender	Female	1.057 [1.014, 1.102]	1.062 [0.998, 1.131]
	Male	1.033 [1.018, 1.049]	1.030 [1.009, 1.052]
Socioeconomic Status	Economically Inactive	**1.055 [1.039, 1.070]**	**1.056 [1.030, 1.081]**
	Economically Active	1.024 [0.992, 1.057]	1.019 [0.974, 1.066]
Marital Status	Non-married	**1.041 [1.018, 1.065]**	**1.047 [1.004, 1.093]**
	Married	1.034 [1.013, 1.056]	1.030 [1.003, 1.056]

Table 3. Tables of the effect modification of socioeconomic vulnerability for 10 μg/m^3 increase of $PM_{10-2.5}$, with 95^{th} confidence interval. **Bold text** indicates results with significant difference between vulnerable and non-vulnerable groups.

Influence of Intra-urban air pollution		OR at lag 0 (all-cause mortality)	OR at lag 0 (cardiorespiratory mortality)
General Population	Areas with higher AOT (>=33^{th} percentile)	**1.045 [1.020, 1.070]**	**1.044 [1.004, 1.086]**
	Areas with lower AOT (<33^{th} percentile)	1.031 [1.012, 1.050]	1.029 [1.002, 1.057]
Aged >=65	Areas with higher AOT (>=33^{th} percentile)	**1.043 [1.019, 1.067]**	**1.047 [1.002, 1.095]**
	Areas with lower AOT (<33^{th} percentile)	1.030 [1.008, 1.053]	1.029 [1.001, 1.057]
Economically inactive	Areas with higher AOT (>=33^{th} percentile)	**1.049 [1.018, 1.080]**	1.048 [0.999, 1.099]
	Areas with lower AOT (<33^{th} percentile)	1.029 [1.011, 1.049]	1.029 [1.001, 1.059]
Non-married	Areas with higher AOT (>=33^{th} percentile)	1.041 [1.014, 1.069]	**1.038 [1.004, 1.073]**
	Areas with lower AOT (<33^{th} percentile)	1.037 [1.000, 1.075]	1.038 [0.982, 1.099]

Table 4. Tables of the effect modification of intra-urban air pollution on general population and vulnerable populations, for $10\ \mu g/m^3$ increase of $PM_{10-2.5}$, with 95^{th} confidence interval. **Bold text** indicates results with significant difference between areas with higher air pollution and lower pollution.