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Title: Spatiotemporal Influence of Temperature, Air Quality, and Urban Environment on Cause-Specific Mortality during Hazy Days

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Abstract

Haze is an extreme weather event that can severely increase air pollution exposure, resulting in higher burdens on human health. A few studies have explored the health effects of haze, and none have investigated the spatiotemporal interaction between temperature, air quality and urban environment that may exacerbate the adverse health effects of haze.

We investigated the spatiotemporal pattern of haze effects and explored the additional effects of temperature, air pollution and urban environment on the short-term mortality risk during hazy days. We applied a Poisson regression model to daily mortality data of 2007 through 2014, to analyze the short-term mortality risk during haze events in Hong Kong. We evaluated the adverse effect on five types of cause-specific mortality after four types of haze events. We also analyzed the additional effect contributed by the spatial variability of urban environment on each type of cause-specific mortality during a specific haze event. A regular hazy day (lag 0) has higher all-cause mortality risk than a day without haze (odds ratio: 1.029 [1.009, 1.049]). We have also observed high mortality risks associated with mental disorders and nervous system during hazy days. In addition, extreme weather and air quality contributed to haze-related mortality, while cold weather and higher ground-level ozone had stronger influences on mortality risk. Areas with a high-density environment, lower vegetation, higher anthropogenic heat, and higher $PM_{2.5}$ featured stronger effects of haze on mortality than the others. A combined influence of haze, extreme weather/air quality, and urban environment can result in extremely high mortality due to mental/behavioral disorders or diseases of the nervous system.

In conclusion, we developed a data-driven technique to analyze the effects of haze on mortality. Our results target the specific dates and areas with higher mortality during haze events, which can be used for development of health warning protocols/systems.

Keywords: haze; short-term mortality risk; cause-specific mortality; spatial analytics; community vulnerability

Introduction

Air pollution has been associated with a heavy burden of mortality and morbidity (Qiu et al., 2014; Shang et al., 2013). During an extreme pollution event, negative changes in air quality can severely increase human health risks (Brook et al., 2016). Previous studies have focused on studying the short-term mortality effects of isolated extreme events, for example, dust storms and wildfire smoke (Crooks et al., 2016; Johnston et al., 2011; Othman et al., 2014; Tobías et al., 2011; Wong et al., 2017). These studies have observed significantly more deaths during extreme events compared to days with baseline air pollution (e.g. traffic-related pollution). However, there have been no studies attempting to investigate the influence of haze on daily mortality, and only a few studies have explored the relationship between haze and morbidity risk (Kunii et al., 2002; Zhang et al., 2014; Zhang et al., 2015b), despite the fact that haze is a common meteorological phenomenon that can cause heavy air pollution (Tao et al., 2014). Alternatively, some environmental health studies have used high daily particulate matter concentrations (PM) as a measure of hazy dust (Liu et al., 2014), but such studies cannot separate the health impacts of haze from the other types of air pollution such as wildfire dust events and dust storms. Therefore, those results cannot directly represent the morbidity and mortality risks during a hazy day. In summary, it is necessary to conduct a comprehensive study to estimate the relationship between haze and mortality, in order to target vulnerable populations and high-risk areas for health interventions.

Haze is commonly observed in Asia due to rapid industrialization and urbanization (Huang et al., 2014), and is usually associated with low visibility (Zhang et al., 2015). While the major component of haze can be particulate matters (PM) (Tao et al., 2014), temperature and humidity can also influence a haze event, resulting in lower visibility and higher air pollution on a hazy day (Deng et al. 2016). This complex system of haze formation has been studied from a climatological perspective (Tan et al., 2009; Tao et al., 2014). However, no studies have included this atmospheric interaction in an environmental health study. Previous studies on haze and health have applied simple bio-statistical analyses to describe the general health risk of haze (Kunii et al., 2002; Zhang et al., 2014; Zhang et al., 2015b). These studies were unable to provide evidence of how interactions between the different components of the geophysical environment, such as temperature, ground-level ozone, and the built environment, can enhance the effect of hazy days on health risk. In addition, these studies have explored the relationship between haze events and only cardiovascular and respiratory diseases attributable to air pollution. None of them have investigated the relationship between haze and mental disorders, although adverse mental health conditions have recently found to be associated with extreme weather (Ding et al., 2015; Rataj et al., 2016; Wang et al., 2014).

Therefore, it is essential to develop an innovative study investigating the spatiotemporal influence of temperature, air pollution, and urban environment on haze mortality. The aim of this study is to apply a data-driven technique to comprehensively analyze the short-term mortality risk after a haze event, for the purpose of better developing public health protocols. The specific objectives of this study include: 1) to estimate the short-term cause-specific mortality risk during days with haze; 2) to compare the short-term mortality risk during hazy days with different temperature and air quality, and; 3) to evaluate haze mortality in areas with different urban environments based on delineations of spatial data.

Hong Kong was selected as the setting for this study, due to multiple hazy days having been observed between 2007 and 2014. In addition, the high-density built environment of this city can reduce air ventilation, thereby increasing air pollution across urban areas (Wong et al., 2011).

Data and Methods

Temporal Data

We obtained mortality data for 2007 to 2014 (inclusive) from the Hong Kong Census and Statistics Department. This mortality dataset includes decedents with the following information: 1) date of death; 2) cause of death classified by the 10^{th} revision of the International Statistical Classification of Diseases and Related Health Problems (ICD-10), and; 3) the location of residence registered by the 2006 Tertiary Planning Unit (TPU) of Hong Kong. An hourly report of haze was obtained from the Hong Kong Observatory, used for classifying days with and without haze in Hong Kong. Based on the definition provided by the Hong Kong Observatory, a "hazy day" is a calendar day with at least one hour of "visibility < 5 km, relative humidity < 95 %, no fog, no mist, and no precipitation". Daily averages of hourly temperature and hourly relative humidity data were retrieved from the weather station located at the Hong Kong Observatory, and were used as control variables for statistical modelling. We also used air quality data (NO_2, O_3, and SO_2) as potential confounders or control variables. These air quality data were the daily averages of seven monitoring stations at both urban and rural areas of Hong Kong (Central Western, Sham Shui Po, Sha Tin, Tai Po, Tsuen Wan, Kwai Chung, and Tap Mun), under the operation of the Hong Kong Environmental Protection Department.

Spatial data

We have used four spatial maps that can represent the following environmental factors: 1) sky view factor (SVF); 2) vegetation coverage; 3) anthropogenic heat; and 4) air pollution exposure. These maps were used to estimate the spatiotemporal influence of the urban environment on mortality risk during a hazy day.

SVF is a ratio with a range of dimensionless values from 0 to 1 for demonstrating the portion of unobscured sky in an area. It is commonly used to represent building morphology, especially to determine air ventilation for urban climatic research and air pollution studies (Hodul et al., 2016). In this study, we followed the high-accuracy method of Zakšek et al. (2011) to map the SVF across Hong Kong. This SVF map was derived from both airborne LiDAR data and a building map of Hong Kong to precisely represent the built environment of both urban and rural areas (Yang et al., 2015). High density, high-rise environments have lower SVF and poor ventilation that may induce poor air quality, while higher SVF can indicate an area with more open spaces and better air ventilation.

Vegetation coverage is known to be a factor that can improve air quality through its influence on pollutant deposition and dispersion (Janhäll, 2015). To accurately locate vegetation for mortality estimation, we have used a vegetation map derived from the land use and land cover information from the Planning Department of Hong Kong.

Anthropogenic heat is a common factor that can increase the occurrence and intensity of haze (Srivastava et al., 2012). In this study, we used a high-spatial-quality map from Wong et al. (2015b) to describe the intra-urban variability of annually averaged daytime anthropogenic heat flux across Hong Kong.

Fine particulate matter ($PM_{2.5}$) is the air pollutant that has the strongest association with haze (Tao et al., 2014). Therefore, we mapped the $PM_{2.5}$ with 142 cloud-free Moderate Resolution Imaging Spectroradiometer (MODIS) Aerosol Optical Depth (AOD) datasets across Hong Kong based on the method of Bilal et al. (2017), to describe the spatial variability of daytime air pollution exposure. This method of Bilal et al. (2017) is accurate for local application in Hong Kong ($R = 0.78$).

We aggregated these four maps to the TPU-level by averaging all values within a TPU, and we added the aggregated information of these four maps into models as covariates (Wong et al., 2017). There were 287 TPUs in Hong Kong based on the 2006 version, which can maintain high spatial variability of all spatial maps after aggregation.

Estimation of Cause-Specific Mortality Risk

There are two common epidemiological designs to analyze effects or air pollution or extreme weather on health risk: 1) “time-series analysis” and 2) “case-only analysis". Time-series analysis compiles all data of a study period for modelling (Atkinson et al., 2014; Breitner et al., 2014), resulting in a more comprehensive estimation that is also more suitable for separating effect modification from the "main effect" of air pollution (Qiu et al., 2015). However, time-series analysis cannot directly differentiate excess mortality of cases from control groups, while case-only analysis can estimate it, with the additional benefits of simplifying data analysis and reducing model complexity (Kosatsky et al., 2012). Therefore, case-only analysis is commonly used for analyzing impacts of extreme weather on health risk (Qiu et al., 2016). While case-only analysis can be useful, one limitation of this method is that the selection of a control period is not as comprehensive as time-series analysis, and may induce statistical bias with poor selection.

In this study, we integrated a time-series analysis with a case-only analysis to estimate the mortality risk contributed by haze. We applied a Poisson regression of a generalized linear model to conduct this time-series case-only analysis:

$$LogE(D_t) = \beta_0 + \beta_1 Haze_{(t)} + \beta_2 RH_{(t)} + \beta_3 Tmean_{(t)} + \beta_4 O_{3(t)} + \beta_5 NO_{(t)} + \beta_6 SO_{(t)} + \beta_7 DOW_{(t)} + \beta_8 Month_{(t)}$$

where D_t is the daily count of cause-specific deaths on day t; *Haze* is a binary indicator of a day with or without a specific haze event on day t, *RH* is the relative humidity; *Tmean* is the daily average temperature; O_3 is the daily average O_3; NO_2 is the daily average NO_2; SO_2 is the daily average SO_2; *DOW* is a category variable of the day of the week; and *Month* is a continuous variable of the month of a year for controlling the seasonality. In brief, we examined the independent effect of haze events on daily mortality based on the odds ratio (OR) and its 95% confidence intervals (CI) estimated by the β_1 (Szumilas, 2010). *RH*, *Tmean*, O_3, NO_2, and SO_2 were the variables controlling for baseline influences of weather and air quality, *DOW* was a variable controlling for the weekday-weekend effect, and *Month* was used for controlling the effect of seasonality. All analyses were conducted in R software with the "glm2" package (Marschner et al., 2009). In addition, we did not use PM_{10} and $PM_{2.5}$ as confounders to reduce potential issue of multicollinearity with haze.

In order to evaluate the impact of haze events on cause-specific mortality, we examined four types of haze event based on their influences on daily mortality. These were 1) "regular haze day", defined by all haze events which occurred during the study period; 2) "hot hazy days", defined by haze events with daily average temperature >= 90th percentile of the study period; 3) "cold hazy days", for haze events with daily average temperature <= 10th percentile; and 4) "hazy days with higher ozone", for haze events with ground-level O_3 >= 90th percentile. We selected ground-level O_3 in this study because it is directly related to climate change and extreme weather with potential influence on health issues (Adam-Poupart et al., 2014; Bell et al., 2007; Ebi & McGregor, 2008; Kan et al., 2012), while other types of air pollutants (e.g. NO, NO_2, SO_2) are associated with traffic-related pollution. All types of haze events were compared with five groups of cause-specific mortality, including 1) all-cause mortality; 2) cardiorespiratory mortality (ICD-10 codes I00-I99 and J00-J99); 3) mental and behavioral disorders (F00-F99); 4) mortality associated with diseases of the nervous system (G00-G99); and 5) mortality caused by disease of the skin and subcutaneous tissue (L00-L99). These five groups of cause-specific mortality were defined based on previous studies. In brief, 1) and 2) were commonly found to be associated with extreme weather and air pollution (Ho et al., 2017; Tsangari et al., 2016; Wong et al., 2015), and 3) – 5) have recently found to have associations with air quality and extreme weather (Calderón-Garcidueñas et al., 2015; Dales & Cakmak, 2016; Ding et al., 2015; Krutmann et al., 2014; Yackerson et al., 2014). Taken together, these combinations can determine the difference in impacts of temperature and air quality on cause-specific mortality during a haze event.

Spatiotemporal Effects of Temperature, Air Quality and Built Environment

We investigated the spatiotemporal influences of urban environment on daily mortality, under different conditions of temperature and air pollution:

$$LogE(D\_identified\_regions_{(t)}) = \beta_0 + \beta_1 Haze_{(t)} + \beta_2 RH_{(t)} + \beta_3 Tmean_{(t)} + \beta_4 O_{3(t)} + \beta_5 NO_{(t)} + \beta_6 SO_{(t)} + \beta_7 DOW_{(t)} + \beta_8 Month_{(t)}$$

where $D\_identified\_regions_{(t)}$ represents the daily count of cause-specific deaths of areas identified based on the delineation of maps.

In this study, we adopted the method of Wong et al. (2008) to spatially delineate the maps, for estimating the additional effect of the urban environment on short-term mortality risk during a specific haze event. We identified four types of areas that may have potential influence on mortality risk based on where 50 percent of all decedents located, including: 1) TPUs with SVF <50th percentile representing districts with a high-density environment and poorer air ventilation; 2) TPUs with percentage of vegetation < 50th percentile indicating areas with less influence on air pollutant deposition and dispersion; 3) TPUs with higher anthropogenic heat (>= 50th percentile) that may be associated with haze formation; and 4) TPUs with $PM_{2.5}$ >= 50th percentile showing areas with higher air pollution exposure directly related to haze. We evaluated the influence of these four types of areas on the haze-mortality link by comparing their ORs and CIs to the corresponding ORs and CIs determined by all areas across Hong Kong, the latter being the baseline ORs. For an identified area with OR and CIs higher than the baseline, we reported that this result should be contributed by a significant added effect of the urban environmental factor.

Results

Data Summary

After exclusion of all data with a missing death date or missing location of residence, a total of 284,477 decedents were recorded in 2007 through 2014. Based on 50th percentiles of all decedents above, we identified TPUs with average SVF lower than 0.675 as areas with high-density environment (Figure 1). In addition, TPUs with percentage of vegetation < 49.57%, average anthropogenic heat flux >= 52.25 W/M^2, and average $PM_{2.5}$ >= 52.05ppm were the districts with low vegetation cover (Figure 2), high anthropogenic heat (Figure 3) and high $PM_{2.5}$ (Figure 4).

To minimize the bias from the delay in reporting deaths, decedents of the last two days of 2014 (Dec 30 and Dec 31) were excluded from this time-series case-only analysis. After further exclusion of decedents of Dec 30 and 31 of 2014, 284,446 death records were included in this study. There were 111 hazy days observed by the weather station at the headquarter of Hong Kong Observatory between Jan 1, 2007 and Dec 29, 2014, in which 11,365 decedents died on these hazy days (Table 5). Ten of these 111 haze days were days with average temperature higher than the 90th percentile (29.51°C) and 8 of these days had an average temperature lower than the

10th percentile (15.75°C); 19 of these hazy days had an average daily ground-level ozone higher than the 90th percentile (70.73ppm).

Heavy air pollution was observed on these hazy days. PM_{10}, SO_2, NO_2, and O_3 were on average 47.6ppm, 10.5ppm, 21.5ppm and 10.7ppm higher than days without haze. Among all types of air pollutants, PM_{10} was the most significant, with an average concentration on hazy days 105% higher than days without a haze event. Therefore, mortality risk during a hazy day can be contributed by high air pollution, especially an exponential increase in particulate matters. In addition, we observed disparities of all-cause mortality during haze events across Hong Kong (Figure 5). This implies that the urban environment may have additional influence of mortality risk during hazy days in Hong Kong.

Mortality Risk of Haze Events

In general, a hazy day (lag 0) has higher all-cause mortality than a day without haze (OR: 1.029 [CI: 1.009, 1.049]), controlling for seasonal effects (Table 2). During a hazy day with lower temperature, the OR of all-cause mortality is 1.131 [CI: 1.061, 1.204]; and on the lag 1, 2, and 3 days of this colder hazy day, the ORs of all-cause mortality are respectively 1.095 [1.027, 1.167], 1.074 [1.007, 1.145], and 1.098 [1.034, 1.166]. This indicates a generally higher risk of all-cause mortality during a haze event on cold days than the other days of a year. In contrast, higher temperature only significantly contributes to a higher mortality risk on a lag 2 day after a haze event (OR: 1.074 [1.006, 1.147]), indicating a much weaker combined effect of heat and haze on mortality compared with the cold effect. In addition, ground-level ozone pollution also shows a significant interaction with short-term mortality risk. On lag 1, lag 2, and lag 3 days of a haze event with higher ozone pollution, the ORs of all-cause mortality are 1.060 [1.012, 1.110], 1.058 [1.010, 1.111], and 1.096 [1.047, 1.147], respectively.

We also found a shift in the relative contribution of haze events to cause-specific mortality. For cardiorespiratory mortality, our results indicated a significant increase in risk during the lag 2 day (OR: 1.043 [1.012, 1.074]) and lag 3 day (OR: 1.037 [1.006, 1.068]) of a hazy day. We also observed a higher mortality risk between lag 0 - 3 days of a haze event with lower temperature, with the highest OR of 1.167 [1.066, 1.277] on the hazy day (lag 0). These results indicate that a combination of cold weather and a haze event has a significant adverse effect on cardiorespiratory mortality. There were also influences of hotter temperature and higher ozone on cardiorespiratory mortality, showing that cardiorespiratory issues should be one of the major causes of death during a haze event.

Another significant impact on cause-specific mortality that we should note is the severe influence of haze events on mental and behavioral disorders. Although a hazy day generally has 2.9% higher risk than a day without haze, a very intense adverse effect is found on the mortality associated with mental and behavior disorders, for which the ORs of lag 0 and 1 days are 1.164 [1.008, 1.344] and 1.265 [1.101, 1.454]. Influenced by the high ozone of a hazy day, the ORs of lag 0, 1 and 3 days can be up to 1.789 [1.206, 2.652], 1.545 [1.130, 2.112], and 1.480 [1.082, 2.023], respectively. The second day of a haze event with higher temperature (lag 1) is also associated with a peak in short-term mortality (OR: 1.789 [1.206, 2.652]). This evidence pinpoints the necessity of targeting members of the population with mental and behavioral disorders for public health prevention during a haze event, especially on days also affected by other types of extreme meteorological phenomena.

We have also observed significant mortality risk associated with the nervous system on the lag 1 day of a haze event (OR: 1.297 [1.051, 1.600]) and on the lag 3 day of a hazy day with higher ozone (OR: 1.887 [1.250, 2.850]). There is no association between haze and mortality caused by diseases of the skin and subcutaneous tissue.

Spatiotemporal Effects of Urban Environment on Cause-Specific Mortality

We observed a distinctive spatiotemporal pattern of cause-specific mortality associated with haze. In brief, a cold hazy day was the only event with spatiotemporal influence on all-cause mortality contributed by a high-density environment, low vegetation cover, high anthropogenic heat and high $PM_{2.5}$ across a district (Table 3). Areas with lower vegetation and higher $PM_{2.5}$ had significantly higher all-cause mortality during the lag 2 day of a hot hazy day, with ORs of 1.118 [1.021, 1.224] and 1.135 [1.039, 1.241] respectively. There were also influences of low vegetation cover and high anthropogenic heat on the lag 2 day of a haze event with higher ozone (ORs: 1.097 [1.028, 1.171] and 1.083 [1.015, 1.154]), while a regular hazy day showed no significant additional effect contributed by the urban environment. These results imply that urban environmental factors have different contributions to cause-specific mortality during a specific type of haze event.

The difference in additional effects was clearer when we compared cardiorespiratory mortality to mortality associated with mental and behavioral disorders. During a regular hazy day, only areas with higher $PM_{2.5}$ had significantly higher cardiorespiratory mortality risk (Table 4), with an OR on a lag 3 day of 1.051 [1.008, 1.095]; and during a hazy day with higher ozone, only low vegetation cover was a significant factor for cardiorespiratory mortality (OR: 1.139 [1.035, 1.254]).

However, for a hot hazy day, areas with higher $PM_{2.5}$, as well as areas with lower vegetation, contributed to higher cardiorespiratory mortality risk; and for a cold hazy day, all environmental factors significantly influenced cardiorespiratory mortality. These were very different from the results of mortality associated with mental and behavioral disorders, as a high-density environment had no contribution to mental issues during all haze events (Table 5). For a regular hazy day, the mortality associated with mental and behavioral disorders was highly influenced by the spatial variability of $PM_{2.5}$ and vegetation; the ORs of areas with higher $PM_{2.5}$ on lag 0 and 1 days are 1.274 [1.052, 1.542] and 1.471 [1.229, 1.760], and the OR of areas with lower vegetation on a lag 1 day is 1.387 [1.155, 1.666]. The additional effects contributed by the urban environment on the mortality associated with mental and behavioral disorders can be more extreme during specific hazy events. On a lag 3 day of a hot hazy day, OR of areas with higher $PM_{2.5}$ is 1.783 [1.042, 3.049]; on a lag 1 day of a hazy day with higher ozone, ORs of areas with lower vegetation and higher anthropogenic heat are 1.922 [1.298, 2.846] and 1.781 [1.195, 2.655]; and on a lag 1 day of a cold hazy day, the ORs of areas with lower vegetation, higher anthropogenic heat and higher $PM_{2.5}$ can reach up to 1.873 [1.122, 3.124], 1.729 [1.019, 2.937], and 2.189 [1.370, 3.496], respectively. These results are particularly important because we have not observed significant results for mortality associated with mental and behavioral disorders during a cold hazy day across all areas of Hong Kong. This analysis indicates that spatial variability of the urban environment can enhance the adverse health effect, resulting in an excessive increase in mental-related mortality in specific neighborhoods.

We also observed additional effects of the effect of haze on mortality associated with disease of the nervous system due to spatial variability of the urban environment (Table 6). For areas with a high-density environment, lower vegetation and higher anthropogenic heat, ORs on the lag 1 day of a regular hazy day are 1.558 [1.172, 2.070], 1.580 [1.195, 2.090], and 1.585 [1.204, 2.088], respectively. Although we did not find a significant association between mortality of nervous system disease and hot hazy days across all areas of Hong Kong, there was an extremely high mortality risk during a hotter day with haze across the areas with higher $PM_{2.5}$ (OR: 2.551 [1.242, 5.237]). In contrast, we did not observe a significant additional effect influenced by the urban environment on the mortality associated with diseases of the skin and subcutaneous tissue (Table 7).

Discussion

In this study, we examined the effect of haze on cause-specific mortality in Hong Kong. We found that a regular hazy day (lag 0) has significant association with higher all-cause mortality (OR: 1.029 [1.009, 1.049]). We also found that the effects of haze on short-term mortality varied for days with different temperatures and air quality, and these specific hazy events can particularly affect cause-specific mortality. While a haze event, especially a cold hazy day, significantly increased the cardiovascular mortality in Hong Kong, the increase of mortality associated with mental and behavioral disorders during a hazy day was more severe. A hazy day with higher ozone (lag 0) created fatal events (OR: 1.789 [1.341, 2.388]); in such cases, public health surveillance should be developed in advance to reduce the natural hazard risk to urban populations. We also found spatiotemporal variability in mortality risk due to the impact of the urban environment, particularly, a neighborhood with specific urban form during a day with extremes in temperature or air quality severely increased the cause-specific mortality. These additional effects of the urban environment were more significant for mortality associated with mental and behavioral disorders, and for mortality associated with diseases of the nervous system.

Our findings are consistent with previous studies. For example, dust-haze increased the mortality from 3.4% -10.4% on lag 0 – 6 days across Guangzhou, China (Liu et al., 2014); and a 3.46 increase in excessive risk of total hospital admission has also observed in Guangzhou during a day with a haze event (Zhang et al., 2014). A pooled relative risk of 1.05 [1.01, 1.09] across Chinese cities was also observed during a day with dust-haze (Yang et al., 2016). In some Chinese cities, a day with a smog episode had a 19.26% increase in overall mortality (Zhou et al., 2015). Since the air pollution risk is location-specific and there may exist intra-urban variability (Kheirbek et al., 2014), the baseline result of our study (OR: 1.021 [1.002, 1.039]) is comparable with these other studies.

By targeting a specific event of haze across different urban areas in order to evaluate mortality risk, our study has added more evidence to existing literature. For example, previous studies have widely found an interaction between high urban temperature and haze (Cao et al., 2016), while there is no study pinpointing how this interaction can affect urban health risk. In the present study, our finding of a severe increase in mortality associated with the nervous system during a hot hazy day across a higher $PM_{2.5}$ area (OR: 2.551 [1.242, 5.237]) can address the impact of heat-haze interaction on health, especially since diseases of the nervous system have been found to have a positive association with both extreme hot weather and air pollution (Calderón-Garcidueñas et al., 2015; Khalaj et al., 2010). It is important that our study evaluates five different cause-specific mortality types associated with air pollution for the relative risk in a haze event. While generally a higher mortality risk during a haze event has been found in this study, not all types of cause-specific mortality associated with air pollution can induce significant mortality risk during a hazy day. There is no association between haze events and mortality related to skin disease. This result is particularly valuable, because common environmental health studies have generally classified haze studies as a sub-type of air pollution/health research (Liu et al., 2014), while in reality, the influences of haze and general air pollution are different. For example, the impact of haze in Hong Kong is a mixing effect of visibility and air pollution, while previous studies have found different contributions of visibility and air pollution to mortality in Hong Kong (Thach et al., 2010; Wong et al., 2008b). Therefore, future studies should make more efforts to analyze the morbidity/mortality effect of haze in cities around the world, in order to achieve a holistic view to understand how adverse weather can influence health risk across different regions.

Environmental Policy Implications

Based on our study, better guidelines for disaster risk management and health warning system development should be implemented. It has been recognized that urban policy can sufficiently reduce air pollution risk (Slovic et al., 2016), while there is a lack of environmental policy targeting haze events, even though they are a common natural hazard in Asian countries. Thus, disaster risk reduction should be conducted in the following two phases: establishment of emergency plans and health warning systems for disaster management, and development of sustainability plans and policies for mitigation. Based on our results, the first step could be developing a health warning system for haze events, while emergency planning should be conducted for urban areas which generally have higher air pollution. Specific sub-types of health warnings should also be implemented for days with extreme weather and air quality, and as shown by our study (Hong Kong), cold hazy days should be targeted, with more care on cardiorespiratory issues for the population in all areas, and more support for mental health patients in areas with lower environmental quality (lower vegetation, higher anthropogenic heat and higher $PM_{2.5}$). In a second phase of disaster risk reduction, environmental policy should be introduced to increase urban greenery in urban areas, along with guidelines to improve the high-density environment to allow more air ventilation, with promotion of clean energy to reduce anthropogenic heat, in order to minimize local air pollution through long-term mitigation. Social policy should also be developed to promote health education for vulnerable segments of the population, and to increase the number of emergency facilities and health centers to minimize excessive increases in health risk during a hazy day.

The protocol for disaster risk reduction can also extended by targeting more extreme scenarios. For example, the present study has followed common environment health research by applying time-series analysis with the 10th percentile or the 90th percentile as thresholds to define extreme temperatures that can influence mortality (Gasparrini et al., 2015). However, recent studies have also applied very extreme scenarios (e.g. the 99.9th percentile) to understand potential catastrophic scenarios (Ho et al., 2017; Krstic et al., 2017). Integrated with the epidemiological design for very extreme cases, such as case-crossover analysis, the protocol for disaster risk reduction can progressively build up to a "multi-level" system that can target days with different weather for planning and emergency management, as well as establishing policies with greater flexibility.

Limitations and Future Directions

In this study, we examined the adverse effect of haze on five types of cause-specific mortality, while other types of health risks such as influenza and traffic-related deaths have not been evaluated. It is believed that effect of haze on both influenza and traffic-related health risks should be studied in the future because of their interaction with air quality and extreme weather (im Kampe et al., 2016; Wang et al., 2017). However, the quality of spatial data so far has been a limitation to apply a spatial approach to analyze influenza and traffic-related health risks. For example, the current dataset for influenza in Hong Kong does not incorporate location-related information. In addition, mortality records of Hong Kong were reported based on location of residence, but the daily mobility of its urban population should highly influence traffic-related deaths; as a result, using only home addresses for such a study is not appropriate. An alternative solution to improve data quality is to conduct a cohort study with a large sample size in the future, in order to analyze the impact of haze on influenza and traffic-related health risks.

In order to examine the spatiotemporal influence of the urban environment on haze mortality, we applied a spatial delineation technique to study the additional effects on mortality risk. This method and similar techniques (e.g. spatial clustering) are commonly used in environmental health studies (Ho et al., 2017b; Li et al., 2012; Wong et al., 2008), while the limitation of this delineation method is lack of consideration of spatial autocorrelation between areas. An alternative technique to analyze spatial variability of health risk is the spatial regression approach (Marotta, 2017; Yeh et al., 2017), but this approach is controlled by the district boundary, resulting in a modifiable areal unit problem (MAUP) or ecological fallacy (Chan et al., 2012; Ho et al., 2015; Schuurman et al., 2007). To minimize the issues of MAUP and ecological fallacy while at the same time maintaining large sample sizes to reduce statistical bias, our current approach of spatial delineation of the mortality data by characteristics of the urban environment is appropriate.

In addition, we have followed other studies by applying multiple annually averaged maps for analyzing mortality risk across urban environment (Ho et al., 2017; Krstic et al., 2017; Wong et al., 2017). While these maps can demonstrate the spatial variability of environmental deprivation, they cannot be used to indicate spatiotemporal change in the urban environment, although such change may also enhance the effect of haze on health risk. An alternative solution is to combine multiple scenes of satellite images for more information to describe spatiotemporal changes, but this alternative strategy is generally limited by the local weather. For example, cloud coverage across a sub-tropical city can be an obstacle of satellite observation, resulting in only a few images which are useful from a satellite within a year (Wong et al., 2015). Thus, annually averaged maps are the only dataset that can be used with relatively high accuracy in the present study. This fact implies that some potentially relevant meteorological factors which are highly affected by urban morphology and spatiotemporal change (e.g. wind speed, wind direction and pressure) cannot be applied in this study. Future study should target developing a holistic model to reconstruct daily or hourly datasets for mapping urban environments, in order to improve the spatiotemporal model for estimating environmental health risk.

Finally, we have examined the impact of haze events on cause-specific mortality. However, we did not evaluate the effect of haze intensity (e.g. hours of haze) on mortality, which may also contribute to health risk during a hazy day. We believe such a study will be worth conducting once haze intensity data with better spatiotemporal quality can be retrieved. The current data on haze are based on one weather station in Hong Kong, which may not be able to demonstrate the spatial variability of haze on an hourly basis across the city. It is expected that the hours of haze should differ distinctly between urban and rural areas because of the characteristics of geophysical landscapes. Therefore, it is better to develop a monitoring network with multiple triggers across urban and rural areas, in order to subsequently utilize the environmental data for examining the spatiotemporal variability of haze hours on health risks.

Conclusions

We developed a time series case-only analysis with a spatial delineation approach to examine the effects of different types of haze events on short-term mortality, and the additional effect on mortality during a haze event associated with urban environmental factors. We found that haze has significant influences on mortality risk, especially for populations with mental and behavioral disorders or diseases of the nervous system. We also found that extreme weather can interact with haze mortality, while hazy days with colder temperature and higher ground-level ozone pollution have higher increases in mortality. We observed that a high-density environment, lower vegetation cover, higher anthropogenic heat and higher $PM_{2.5}$ of an area can somewhat influence mortality risk during a hazy day, while for areas with higher $PM_{2.5}$, higher association with cardiorespiratory mortality and mental disorders was found during a regular hazy day. To target vulnerable populations, emergency plans and sustainable development (e.g. greenery and community centers) should be developed along with health warning systems and environmental policy to reduce the adverse effects of haze on urban health.

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Table 1. Summary statistics for the mortality records of the analytic dataset. Summaries are presented for cases who a) died on a hazy day, and controls b) who died on a day without haze event. Values in bold indicate a statistically significant difference between means (t-test with alpha = 0.05)

Summary	*Cases who died on a hazy day*	*Controls who died on a day without haze event*
Total of all-cause deaths	11,365	284,446
Total of cardiorespiratory deaths	5,049	118,863
Total of mental-related deaths	214	5,327
Total of nervous-related deaths	91	2,173
Total of skin-related deaths	61	1,509
Mean (SD) all-cause deaths per day	**102.4 (16.9)**	**97.2 (14.7)**
Mean (SD) PM_{10} (ppm)	**92.86 (48.11)**	**45.30 (21.24)**
Mean (SD) SO_2 (ppm)	**25.26 (13.29)**	**14.77 (7.85)**
Mean (SD) NO_2 (ppm)	**71.19 (17.00)**	**49.66 (14.21)**
Mean (SD) O_3 (ppm)	**51.80 (18.29)**	**41.08 (21.19)**

Table 2. Short-term risk of cause-specific mortality during a specific haze event.

*** indicates significant result with P-value < 0.05.**

Cause of death	Classification of hazy events	Lag 0 (95th CIs)	Lag 1 (95th CIs)	Lag 2 (95th CIs)	Lag 3 (95th CIs)
All-cause	regular hazy days	1.029 [1.009, 1.049]*	1.024 [1.004, 1.045]*	1.022 [1.002, 1.042]*	1.009 [0.989, 1.029]
	hot hazy days	1.032 [0.967, 1.102]	1.014 [0.949, 1.084]	1.074 [1.006, 1.147]*	1.017 [0.951, 1.088]
	cold hazy days	1.131 [1.061, 1.204]*	1.095 [1.027, 1.167]*	1.074 [1.007, 1.145]*	1.098 [1.034, 1.166]*
	hazy days with higher ozone	1.044 [0.997, 1.094]	1.060 [1.012, 1.110]*	1.058 [1.010, 1.111]*	1.096 [1.047, 1.147]*
Cardiorespiratory diseases	regular hazy days	1.024 [0.994, 1.055]	1.024 [0.994, 1.055]	1.043 [1.012, 1.074]*	1.037 [1.006, 1.068]*
	hot hazy days	0.995 [0.897, 1.104]	0.979 [0.882, 1.088]	1.109 [1.003, 1.226]*	0.968 [0.869, 1.078]
	cold hazy days	1.167 [1.066, 1.277]*	1.118 [1.019, 1.225]*	1.100 [1.003, 1.207]*	1.158 [1.064, 1.261]*
	hazy days with higher ozone	1.035 [0.964, 1.111]	1.032 [0.961, 1.107]	1.017 [0.947, 1.093]	1.103 [1.029, 1.182]*
Mental and behavioral disorders	regular hazy days	1.164 [1.008, 1.344]*	1.265 [1.101, 1.454]*	1.017 [0.874, 1.182]	1.037 [0.894, 1.202]
	hot hazy days	1.229 [0.768, 1.966]	1.789 [1.206, 2.652]*	0.997 [0.597, 1.667]	1.473 [0.962, 2.257]
	cold hazy days	1.088 [0.664, 1.781]	1.448 [0.950, 2.208]	1.191 [0.748, 1.898]	1.134 [0.720, 1.783]
	hazy days with higher ozone	1.789 [1.341, 2.388]*	1.545 [1.130, 2.112]*	1.031 [0.715, 1.488]	1.480 [1.082, 2.023]*
Diseases of the nervous system	regular hazy days	1.131 [0.906, 1.411]	1.297 [1.051, 1.600]*	1.064 [0.850, 1.331]	1.139 [0.916, 1.416]
	hot hazy days	1.276 [0.630, 2.586]	0.923 [0.410, 2.078]	1.115 [0.950, 1.307]	1.299 [0.667, 2.533]
	cold hazy days	0.607 [0.227, 1.624]	1.702 [0.936, 3.093]	1.716 [0.944, 3.119]	0.974 [0.462, 2.054]
	hazy days with higher ozone	1.357 [0.829, 2.220]	0.885 [0.483, 1.621]	1.225 [0.749, 2.004]	1.887 [1.250, 2.850]*
Diseases of the skin and subcutaneous tissue	regular hazy days	0.971 [0.740, 1.273]	0.796 [0.591, 1.073]	0.949 [0.716, 1.258]	0.852 [0.636, 1.142]
	hot hazy days	1.369 [0.671, 2.793]	0.382 [0.095, 1.543]	0.563 [0.179, 1.768]	0.585 [0.186, 1.835]
	cold hazy days	0.668 [0.214, 2.084]	1.360 [0.606, 3.050]	0.920 [0.343, 2.468]	1.213 [0.541, 2.722]
	hazy days with higher ozone	1.012 [0.563, 1.822]	0.460 [0.189, 1.121]	0.729 [0.358, 1.486]	0.905 [0.462, 1.772]

Table 3. Short-term risk of all-cause mortality during a specific haze event in different identified areas. * indicates significant result with P-value < 0.05. Results with bold text indicate result significantly higher than the baselines (all areas).

Cause of death	Classification of hazy events	Identified Areas	Lag 0 (95th CIs)	Lag 1 (95th CIs)	Lag 2 (95th CIs)	Lag 3 (95th CIs)
All-cause	regular hazy days	All areas	1.029 [1.009, 1.049]*	1.024 [1.004, 1.045]*	1.022 [1.002, 1.042]*	1.009 [0.989, 1.029]
		SVF < 50th percentile	1.025 [0.997, 1.055]	1.014 [0.986, 1.043]	1.022 [0.993, 1.051]	1.003 [0.975, 1.032]
		vegetation < 50th pctl	1.021 [0.993, 1.051]	1.018 [0.990, 1.048]	1.019 [0.990, 1.048]	1.003 [0.975, 1.032]
		anthro. heat >= 50th pctl	1.023 [0.995, 1.052]	1.024 [0.996, 1.053]	1.014 [0.986, 1.043]	0.999 [0.972, 1.027]
		$PM_{2.5}$ >= 50th percentile	1.023 [0.995, 1.052]	1.024 [0.995, 1.053]	1.013 [0.985, 1.042]	1.013 [0.984, 1.041]
	hot hazy days	All areas	1.032 [0.967, 1.102]	1.014 [0.949, 1.084]	1.074 [1.006, 1.147]*	1.017 [0.951, 1.088]
		SVF < 50th percentile	0.974 [0.885, 1.072]	0.960 [0.871, 1.058]	1.079 [0.984, 1.183]	0.992 [0.901, 1.093]
		vegetation < 50th pctl	0.966 [0.878, 1.063]	0.984 [0.895, 1.083]	**1.134 [1.037, 1.241]***	1.030 [0.937, 1.132]
		anthro. heat >= 50th pctl	0.954 [0.868, 1.049]	0.980 [0.892, 1.076]	1.081 [0.988, 1.183]	1.044 [0.952, 1.145]
		$PM_{2.5}$ >= 50th percentile	0.981 [0.893, 1.079]	1.039 [0.947, 1.140]	**1.135 [1.039, 1.241]***	1.030 [0.937, 1.131]
	cold hazy days	All areas	1.131 [1.061, 1.204]*	1.095 [1.027, 1.167]*	1.074 [1.007, 1.145]*	1.098 [1.034, 1.166]*
		SVF < 50th percentile	**1.197 [1.096, 1.306]***	1.123 [1.027, 1.229]*	1.054 [0.961, 1.156]	1.117 [1.026, 1.216]*
		vegetation < 50th pctl	**1.202 [1.102, 1.311]***	**1.148 [1.058, 1.255]***	1.072 [0.978, 1.174]	**1.167 [1.075, 1.268]***
		anthro. heat >= 50th pctl	**1.198 [1.100, 1.305]***	**1.143 [1.048, 1.247]***	1.041 [0.951, 1.140]	1.111 [1.022, 1.207]*
		$PM_{2.5}$ >= 50th percentile	1.136 [1.039, 1.241]*	**1.143 [1.047, 1.248]***	1.063 [0.971, 1.164]	**1.162 [1.071, 1.262]***
	hazy days with higher ozone	All areas	1.044 [0.997, 1.094]	1.060 [1.012, 1.110]*	1.058 [1.010, 1.111]*	1.096 [1.047, 1.147]*
		SVF < 50th percentile	1.009 [0.943, 1.079]	1.017 [0.951, 1.087]	1.065 [0.997, 1.138]	1.056 [0.988, 1.128]
		vegetation < 50th pctl	0.973 [0.909, 1.042]	1.041 [0.974, 1.112]	**1.098 [1.029, 1.171]***	1.070 [1.002, 1.142]*
		anthro. heat >= 50th pctl	0.980 [0.917, 1.048]	1.066 [1.000, 1.137]	**1.083 [1.015, 1.154]***	1.062 [0.995, 1.133]
		$PM_{2.5}$ >= 50th percentile	0.970 [0.907, 1.038]	1.065 [0.998, 1.136]	1.055 [0.988, 1.126]	1.090 [1.022, 1.163]*

Table 4. Short-term risk of cardiorespiratory mortality during a specific haze event in different identified area. * indicates significant result with P-value < 0.05. Results with bold text indicate result significantly higher than the baselines (all areas).

Cause of death	Classification of hazy events	Identified Areas	Lag 0 (95th CIs)	Lag 1 (95th CIs)	Lag 2 (95th CIs)	Lag 3 (95th CIs)
Cardiorespir. diseases	regular hazy days	All areas	1.024 [0.994, 1.055]	1.024 [0.994, 1.055]	1.043 [1.012, 1.074]*	1.037 [1.006, 1.068]*
		SVF < 50th percentile	1.025 [0.983, 1.069]	1.014 [0.972, 1.057]	1.031 [0.988, 1.075]	1.035 [0.992, 1.079]
		vegetation < 50th pctl	1.029 [0.987, 1.073]	1.020 [0.978, 1.063]	1.046 [1.003, 1.090]*	1.044 [1.002, 1.088]*
		anthro. heat >= 50th pctl	1.037 [0.996, 1.080]	1.022 [0.981, 1.065]	1.035 [0.994, 1.078]	1.029 [0.988, 1.072]
		$PM_{2.5}$ >= 50th percentile	1.017 [0.975, 1.060]	0.999 [0.958, 1.042]	1.040 [0.997, 1.084]	**1.051 [1.008, 1.095]***
	hot hazy days	All areas	0.995 [0.897, 1.104]	0.979 [0.882, 1.088]	1.109 [1.003, 1.226]*	0.968 [0.869, 1.078]
		SVF < 50th percentile	0.976 [0.842, 1.131]	0.947 [0.816, 1.099]	1.120 [0.974, 1.287]	0.905 [0.775, 1.058]
		vegetation < 50th pctl	0.972 [0.840, 1.126]	0.947 [0.816, 1.099]	**1.194 [1.043, 1.367]***	0.976 [0.840, 1.134]
		anthro. heat >= 50th pctl	1.011 [0.878, 1.163]	0.927 [0.800, 1.073]	1.090 [0.950, 1.250]	0.962 [0.830, 1.115]
		$PM_{2.5}$ >= 50th percentile	0.946 [0.814, 1.099]	0.934 [0.804, 1.085]	**1.178 [1.028, 1.349]***	0.958 [0.823, 1.114]
	cold hazy days	All areas	1.167 [1.066, 1.277]*	1.118 [1.019, 1.225]*	1.100 [1.003, 1.207]*	1.158 [1.064, 1.261]*
		SVF < 50th percentile	**1.240 [1.096, 1.404]***	**1.169 [1.029, 1.327]***	1.060 [0.928, 1.210]	1.169 [1.037, 1.317]*
		vegetation < 50th pctl	**1.289 [1.142, 1.455]***	1.151 [1.013, 1.307]*	1.108 [0.974, 1.261]	**1.213 [1.080, 1.364]***
		anthro. heat >= 50th pctl	**1.267 [1.125, 1.428]***	1.150 [1.015, 1.302]*	1.074 [0.946, 1.221]	1.149 [1.022, 1.292]*
		$PM_{2.5}$ >= 50th percentile	1.133 [0.996, 1.289]	1.128 [0.992, 1.283]	1.069 [0.937, 1.219]	**1.219 [1.085, 1.370]***
	hazy days with higher ozone	All areas	1.035 [0.964, 1.111]	1.032 [0.961, 1.107]	1.017 [0.947, 1.093]	1.103 [1.029, 1.182]*
		SVF < 50th percentile	1.057 [0.958, 1.167]	1.000 [0.904, 1.105]	0.997 [0.901, 1.103]	1.124 [1.020, 1.238]*
		vegetation < 50th pctl	0.977 [0.882, 1.082]	1.035 [0.938, 1.143]	1.013 [0.916, 1.120]	**1.134 [1.030, 1.248]***
		anthro. heat >= 50th pctl	1.005 [0.911, 1.109]	1.028 [0.933, 1.132]	0.988 [0.895, 1.090]	1.094 [0.995, 1.203]
		$PM_{2.5}$ >= 50th percentile	0.972 [0.877, 1.077]	1.035 [0.937, 1.143]	1.040 [0.942, 1.148]	1.125 [1.022, 1.239]*

Table 5. Short-term risk of mortality associated with mental and behavioral disorders during a specific haze event in different identified areas. * indicates significant result with P-value < 0.05. Results with bold text indicate result significantly higher than the baselines (all areas).

Cause of death	Classification of hazy events	Identified Areas	Lag 0 (95th CIs)	Lag 1 (95th CIs)	Lag 2 (95th CIs)	Lag 3 (95th CIs)
Mental and behavioral disorders	regular hazy days	All areas	1.164 [1.008, 1.344]*	1.265 [1.101, 1.454]*	1.017 [0.874, 1.182]	1.037 [0.894, 1.202]
		SVF < 50th percentile	1.137 [0.922, 1.403]	1.253 [1.020, 1.538]*	1.012 [0.813, 1.259]	1.024 [0.824, 1.274]
		vegetation < 50th pctl	1.138 [0.934, 1.387]	**1.353 [1.121, 1.634]***	0.993 [0.804, 1.226]	0.951 [0.770, 1.175]
		anthro. heat >= 50th pctl	1.100 [0.904, 1.339]	1.245 [1.031, 1.505]*	0.987 [0.803, 1.213]	1.003 [0.820, 1.226]
		$PM_{2.5}$ >= 50th percentile	**1.274 [1.052, 1.542]***	**1.471 [1.229, 1.760]***	1.061 [0.866, 1.301]	0.995 [0.810, 1.222]
	hot hazy days	All areas	1.229 [0.768, 1.966]	1.789 [1.206, 2.652]*	0.997 [0.597, 1.667]	1.473 [0.962, 2.257]
		SVF < 50th percentile	1.253 [0.644, 2.437]	1.762 [0.987, 3.146]	1.328 [0.706, 2.500]	1.438 [0.764, 2.707]
		vegetation < 50th pctl	1.129 [0.581, 2.193]	1.762 [1.010, 3.074]*	1.263 [0.672, 2.373]	1.411 [0.772, 2.578]
		anthro. heat >= 50th pctl	1.179 [0.628, 2.214]	1.599 [0.917, 2.787]	1.161 [0.618, 2.181]	1.538 [0.882, 2.680]
		$PM_{2.5}$ >= 50th percentile	1.070 [0.530. 2.162]	1.961 [1.166, 3.297]*	1.129 [0.581, 2.192]	**1.783 [1.042, 3.049]***
	cold hazy days	All areas	1.088 [0.664, 1.781]	1.448 [0.950, 2.208]	1.191 [0.748, 1.898]	1.134 [0.720, 1.783]
		SVF < 50th percentile	0.872 [0.390, 1.951]	1.733 [0.978, 3.070]	1.532 [0.843, 2.782]	1.445 [0.796, 2.625]
		vegetation < 50th pctl	0.770 [0.345, 1.721]	**2.061 [1.255, 3.386]***	1.388 [0.765, 2.519]	1.037 [0.537, 2.002]
		anthro. heat >= 50th pctl	0.751 [0.336, 1.678]	**1.729 [1.019, 2.937]***	1.324 [0.730, 2.404]	1.102 [0.590, 2.058]
		$PM_{2.5}$ >= 50th percentile	0.876 [0.416, 1.846]	**2.189 [1.370, 3.496]***	1.373 [0.757, 2.493]	1.367 [0.772, 2.420]
	hazy days with higher ozone	All areas	1.789 [1.341, 2.388]*	1.545 [1.130, 2.112]*	1.031 [0.715, 1.488]	1.480 [1.082, 2.023]*
		SVF < 50th percentile	1.676 [1.086, 2.587]*	1.632 [1.037, 2.569]*	0.956 [0.548, 1.666]	1.305 [0.800, 2.130]
		vegetation < 50th pctl	1.775 [1.190, 2.648]*	1.709 [1.119, 2.609]*	1.234 [0.768, 1.984]	1.221 [0.759, 1.963]
		anthro. heat >= 50th pctl	1.731 [1.169, 2.562]*	**1.781 [1.195, 2.655]***	1.006 [0.610, 1.661]	1.457 [0.955, 2.223]
		$PM_{2.5}$ >= 50th percentile	1.691 [1.126, 2.540]*	1.651 [1.090. 2.499]*	1.514 [0.992, 2.311]	1.477 [0.959, 2.275]

Table 6. Short-term risk of mortality associated with diseases of the nervous system during a specific haze event in different identified areas. * indicates significant result with P-value < 0.05. Results with bold text indicate result significantly higher than the baselines (all areas).

Cause of death	**Classification of hazy events**	**Identified Areas**	**Lag 0 (95^{th} CIs)**	**Lag 1 (95^{th} CIs)**	**Lag 2 (95^{th} CIs)**	**Lag 3 (95^{th} CIs)**
Diseases of the nervous system	regular hazy days	All areas	1.131 [0.906, 1.411]	1.297 [1.051, 1.600]*	1.064 [0.850, 1.331]	1.139 [0.916, 1.416]
		SVF < 50^{th} percentile	1.235 [0.912, 1.671]	**1.558 [1.172, 2.070]***	0.927 [0.659, 1.303]	1.037 [0.746, 1.442]
		vegetation < 50^{th} pctl	1.120 [0.817, 1.537]	**1.583 [1.195, 2.097]***	0.962 [0.687, 1.347]	0.961 [0.686, 1.344]
		anthro. heat >= 50^{th} pctl	1.103 [0.807, 1.508]	**1.585 [1.204, 2.088]***	0.988 [0.711, 1.372]	0.917 [0.653, 1.287]
		$PM_{2.5}$ >= 50^{th} percentile	1.264 [0.940, 1.699]	1.391 [1.045, 1.853]*	0.989 [0.717, 1.363]	0.923 [0.663, 1.286]
	hot hazy days	All areas	1.276 [0.630, 2.586]	0.923 [0.410, 2.078]	1.115 [0.950, 1.307]	1.299 [0.667, 2.533]
		SVF < 50^{th} percentile	1.609 [0.655, 3.952]	1.717 [0.699, 4.218]	1.262 [0.464, 3.432]	0.951 [0.301, 3.001]
		vegetation < 50^{th} pctl	1.734 [0.706, 4.260]	1.717 [0.699, 4.214]	1.653 [0.673, 4.063]	0.939 [0.298, 2.963]
		anthro. heat >= 50^{th} pctl	1.233 [0.454, 3.348]	1.579 [0.644, 3.874]	1.556 [0.633, 3.822]	0.909 [0.288, 2.867]
		$PM_{2.5}$ >= 50^{th} percentile	**2.551 [1.242, 5.237]***	1.577 [0.643, 3.868]	1.121 [0.413, 3.043]	0.561 [0.138, 2.272]
	cold hazy days	All areas	0.607 [0.227, 1.624]	1.702 [0.936, 3.093]	1.716 [0.944, 3.119]	0.974 [0.462, 2.054]
		SVF < 50^{th} percentile	0.589 [0.146, 2.368]	0.936 [0.299, 2.922]	0.974 [0.312, 3.045]	0.287 [0.040, 2.045]
		vegetation < 50^{th} pctl	0.287 [0.040, 2.043]	1.477 [0.609, 3.582]	1.544 [0.636, 3.747]	0.837 [0.268, 2.615]
		anthro. heat >= 50^{th} pctl	0.287 [0.043, 2.049]	1.479 [0.610, 3.586]	1.546 [0.638, 3.751]	0.831 [0.266, 2.594]
		$PM_{2.5}$ >= 50^{th} percentile	0.865 [0.277, 2.700]	1.748 [0.778, 3.928]	1.779 [0.791, 3.999]	1.120 [0.417, 3.007]
	hazy days with higher ozone	All areas	1.357 [0.829, 2.220]	0.885 [0.483, 1.621]	1.225 [0.749, 2.004]	1.887 [1.250, 2.850]*
		SVF < 50^{th} percentile	1.549 [0.810, 2.964]	1.131 [0.527, 2.431]	1.032 [0.480, 2.217]	1.225 [0.598, 2.511]
		vegetation < 50^{th} pctl	1.097 [0.510, 2.357]	1.513 [0.767, 2.983]	1.013 [0.472, 2.175]	0.899 [0.396, 2.043]
		anthro. heat >= 50^{th} pctl	1.015 [0.473, 2.179]	1.241 [0.606, 2.541]	1.316 [0.667, 2.594]	1.039 [0.485, 2.227]
		$PM_{2.5}$ >= 50^{th} percentile	1.617 [0.871, 3.000]	1.436 [0.729, 2.831]	1.139 [0.556, 2.332]	1.462 [0.766, 2.788]

Table 7. Short-term risk of mortality associated with diseases of the skin and subcutaneous tissue during a specific haze event in different identified areas. * indicates significant result with P-value < 0.05. Results with bold text indicate result significantly higher than the baselines (all areas).

Cause of death	Classification of hazy events	Identified Areas	Lag 0 (95th CIs)	Lag 1 (95th CIs)	Lag 2 (95th CIs)	Lag 3 (95th CIs)
Diseases of the skin and subcutaneous tissue	regular hazy days	All areas	0.971 [0.740, 1.273]	0.796 [0.591, 1.073]	0.949 [0.716, 1.258]	0.852 [0.636, 1.142]
		SVF < 50th percentile	1.167 [0.823, 1.654]	0.959 [0.649, 1.417]	1.304 [0.920, 1.848]	0.989 [0.677, 1.445]
		vegetation < 50th pctl	0.866 [0.586, 1.281]	0.925 [0.626, 1.368]	1.277 [0.904, 1.803]	1.009 [0.691, 1.473]
		anthro. heat >= 50th pctl	1.060 [0.746, 1.506]	0.972 [0.669, 1.411]	1.225 [0.872, 1.722]	1.081 [0.759, 1.539]
		$PM_{2.5}$ >= 50th percentile	0.916 [0.628, 1.336]	0.685 [0.445, 1.055]	0.991 [0.682, 1.440]	0.744 [0.487, 1.136]
	hot hazy days	All areas	1.369 [0.671, 2.793]	0.382 [0.095, 1.543]	0.563 [0.179, 1.768]	0.585 [0.186, 1.835]
		SVF < 50th percentile	0.967 [0.305, 3.068]	0.402 [0.056, 2.894]	0.735 [0.180, 2.997]	0.715 [0.175, 2.910]
		vegetation < 50th pctl	0.605 [0.148, 2.463]	0.731 [0.179, 2.977]	0.995 [0.313, 3.156]	1.078 [0.340, 3.417]
		anthro. heat >= 50th pctl	0.579 [0.142, 2.357]	0.714 [0.175, 2.905]	0.917 [0.289, 2.908]	0.951 [0.300, 3.008]
		$PM_{2.5}$ >= 50th percentile	1.277 [0.468, 3.487]	0.690 [0.170, 2.808]	0.964 [0.304, 3.054]	1.108 [0.350, 3.509]
	cold hazy days	All areas	0.668 [0.214, 2.084]	1.360 [0.606, 3.050]	0.920 [0.343, 2.468]	1.213 [0.541, 2.722]
		SVF < 50th percentile	0.842 [0.209, 3.397]	0.851 [0.211, 3.432]	0.000 [0.000, ∞]	1.090 [0.348, 3.414]
		vegetation < 50th pctl	0.000 [0.000, ∞]	0.888 [0.220, 3.582]	0.000 [0.000, ∞]	1.940 [0.797, 4.724]
		anthro. heat >= 50th pctl	0.819 [0.203, 3.302]	1.229 [0.393, 3.849]	0.000 [0.000, ∞]	1.041 [0.332, 3.260]
		$PM_{2.5}$ >= 50th percentile	0.000 [0.000, ∞]	0.889 [0.221, 3.585]	0.444 [0.062, 3.171]	0.786 [0.195, 3.169]
	hazy days with higher ozone	All areas	1.012 [0.563, 1.822]	0.460 [0.189, 1.121]	0.729 [0.358, 1.486]	0.905 [0.462, 1.772]
		SVF < 50th percentile	1.354 [0.653, 2.808]	0.622 [0.196, 1.973]	1.078 [0.469, 2.476]	0.932 [0.378, 2.299]
		vegetation < 50th pctl	1.146 [0.529, 2.481]	0.575 [0.182, 1.824]	1.188 [0.548, 2.579]	0.954 [0.387, .2351]
		anthro. heat >= 50th pctl	1.049 [0.485, 2.270]	0.727 [0.267, 1.984]	1.033 [0.477, 2.236]	1.189 [0.552, 2.565]
		$PM_{2.5}$ >= 50th percentile	1.604 [0.807, 3.188]	0.529 [0.167, 1.674]	1.189 [0.550, 2.571]	0.971 [0.394, 2.391]

Captions of Figures

Figure 1 – Areas with high-density environment across Hong Kong based on a threshold estimated by all decedents of 2007 through 2014 with a quantile function. Brown regions indicate TPUs with high-density environment (SVF < 50th percentile), and yellow regions represent TPUs with lower density of environment (SVF >= 50th percentile).

Figure 2 – Areas with lower vegetation across Hong Kong based on a threshold estimated by all decedents of 2007 through 2014 with a quantile function. Light green regions indicate TPUs with low vegetation (percentage of vegetation < 50th percentile), and dark green regions represent TPUs with larger coverage of vegetation (percentage of vegetation >= 50th percentile).

Figure 3 – Areas with higher anthropogenic heat across Hong Kong based on a threshold estimated by all decedents of 2007 through 2014 with a quantile function. Dark red regions indicate TPUs with higher anthropogenic heat (>= 50th percentile), and light red regions represent TPUs with less anthropogenic heat (< 50th percentile).

Figure 4 – Areas with higher air pollution exposure across Hong Kong based on a threshold estimated by all decedents of 2007 through 2014 with a quantile function. Dark blue regions indicate TPUs with higher $PM_{2.5}$ (>= 50th percentile), and light blue regions represent TPUs with less $PM_{2.5}$ (< 50th percentile).

Figure 5 – Total all-cause deaths in TPUs across Hong Kong during haze events.