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# Spatiotemporal patterns of particulate matter (PM) and associations between PM and mortality in Shenzhen, China

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## Abstract

**Background:** Most studies on air pollution exposure and its associations with human health in China have focused on the heavily polluted industrial areas and/or mega-cities, and studies on cities with comparatively low air pollutant concentrations are still rare. Only a few studies have attempted to analyse particulate matter (PM) for the vibrant economic centre Shenzhen in the Pearl River Delta. So far no systematic investigation of PM spatiotemporal patterns in Shenzhen has been undertaken and the understanding of pollution exposure in urban agglomerations with comparatively low pollution is still limited.

**Methods:** We analyze daily and hourly particulate matter concentrations and all-cause mortality during 2013 in Shenzhen, China. Temporal patterns of PM ($PM_{2.5}$ and $PM_{10}$) with aerodynamic diameters of 2.5 (10) μm or less (or less (including particles with a diameter that equals to 2.5 (10) μm) are studied, along with the ratio of $PM_{2.5}$ to $PM_{10}$. Spatial distributions of $PM_{10}$ and $PM_{2.5}$ are addressed and associations of $PM_{10}$ or $PM_{2.5}$ and all-cause mortality are analyzed.

**Results:** Annual average $PM_{10}$ and $PM_{2.5}$ concentrations were 61.3 and 39.6 μg/m$^3$ in 2013. $PM_{2.5}$ failed to meet the Class 2 annual limit of the National Ambient Air Quality Standard. $PM_{2.5}$ was the primary air pollutant, with 8.8 % of days having heavy $PM_{2.5}$ pollution. The daily $PM_{2.5}/PM_{10}$ ratios were high. Hourly $PM_{2.5}$ concentrations in the tourist area were lower than downtown throughout the day. $PM_{10}$ and $PM_{2.5}$ concentrations were higher in western parts of Shenzhen than in eastern parts. Excess risks in the number of all-cause mortality with a 10 μg/m$^3$ increase of PM were 0.61 % (95 % confidence interval [CI]: 0.50–0.72) for $PM_{10}$, and 0.69 % (95 % CI: 0.55–0.83) for $PM_{2.5}$, respectively. The greatest ERs of $PM_{10}$ and $PM_{2.5}$ were in 2-day cumulative measures for the all-cause mortality, 2-day lag for females and the young (0–65 years), and L02 for males and the elder (>65 years). $PM_{2.5}$ had higher risks on all-cause mortality than $PM_{10}$. Effects of high PM pollution on mortality were stronger in the elder and male.

**Conclusions:** Our findings provide additional relevant information on air quality monitoring and associations of PM and human health, valuable data for further scientific research in Shenzhen and for the on-going discourse on improving environmental policies.

**Keywords:** Temporal-spatial patterns, Particulate matter, Mortality, Shenzhen

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## Background

Airborne particulate matter (PM) consistently associated with adverse health effects at current levels of exposure in urban populations [1–4]. Air pollution has serious direct and indirect effects on public health in China [2, 5–8]. PM with aerodynamic diameters less than 2.5 μm ($PM_{2.5}$) has become the fourth prominent threat to the health of Chinese people [9].

The range of adverse health effects of air pollution is broad [2, 10, 11]. Susceptibility to pollution may vary depending on overall health condition and age [5, 6, 12–14]. Risk of various effects has been shown to increase with exposure, but there is little evidence to suggest a threshold below which no adverse health effects can be anticipated [15, 16]. The lowest concentration at which such effects begin to manifest is not much greater than the background concentration, which has been estimated at 3–5 μg/$m^3$ for $PM_{2.5}$ in the United States and western Europe [15]. Most studies on air pollution exposure and its effects on human health in China have focused on heavily polluted cities or mega-cities [8, 17–19], whereas studies on cities with relatively low air pollutant concentrations are rare.

Shenzhen is a major coastal city with a population of some 15 million. It is situated within the Pearl River Delta (PRD) and Guangdong Province, immediately north of Hong Kong. Shenzhen has become China's most crowded city and is the fifth most densely populated city in the world, with a population density of 17,150 per square kilometre. Shenzhen is listed as the fourth most important economic centre among Chinese cities. As China's first and still one of the most successful special economic zones the city has an important position in the PRD region and the country. Compared with other cities in China, air quality in Shenzhen is high. Nevertheless, the city has been experiencing elevated levels of PM pollution in recent years because of rapid economic development [20]. As one of the first-stage cities implementing the National Ambient Air Quality Standard (GB3095-2012) in 2013, Shenzhen provided real-time hourly monitoring concentrations of air pollutants to the general public since January 1 2013. According to air quality monitoring data from the China National Environmental Monitoring Center (CNEMC), respective annual average concentrations of $PM_{10}$ and $PM_{2.5}$ were 61.3 and 39.6 μg/$m^3$ in Shenzhen in 2013. The annual average $PM_{10}$ concentration was higher than in 2012 (52 μg/$m^3$). However, comprehensive studies on PM in Shenzhen have been rare and there have been no systematic investigations of PM spatiotemporal patterns in Shenzhen.

We carried out a time-series analysis on daily and hourly PM concentrations and daily number of all-cause mortality (excluding accidental deaths) during the first year (2013) of National Ambient Air Quality Standard implementation in Shenzhen. Daily and hourly patterns of $PM_{2.5}$ and $PM_{10}$ were summarized and the daily $PM_{2.5}/PM_{10}$ ratio was calculated. Spatial distributions of $PM_{10}$ and $PM_{2.5}$ were investigated. Associations of PM and all-cause mortality were analysed and the susceptibility differentiated according to gender and age were addressed. The objectives were to provide daily/hourly $PM_{10}$ and $PM_{2.5}$ monitoring information for Shenzhen during 2013 to the general public and scientific researchers, investigate spatiotemporal characteristics of $PM_{10}$ and $PM_{2.5}$, evaluate changes of $PM_{2.5}/PM_{10}$ ratio, and to discover potential relationships between daily exposure to $PM_{2.5}$ or $PM_{10}$ and all-cause mortality.

Rang of health effects of air pollution was broad [2, 10, 11]. Susceptibility to pollution may vary with health or age [5, 6, 12–14]. Risk of various effects has been shown to increase with exposure, but there is little evidence to suggest a threshold below which no adverse health effects can be anticipated [15, 16]. The lowest concentration at which such effects begin to manifest is not much greater than the background concentration, which has been estimated at 3–5 μg/$m^3$ for $PM_{2.5}$ in the United States and western Europe [15]. Most studies on air pollution exposure and its effects on human health in China have focused on heavily polluted cities or mega-cities [8, 17–19], whereas studies on cities with relatively low air pollutant concentrations are rare.

## Methods

### Study area

Shenzhen is in southern China, 113°46–114°37E and 22°27–22°52 N, with an area of 1991.64 $km^2$. There is a subtropical oceanic climate, with warm temperatures and abundant rainfall. Annual average temperature is 22.4 °C. The monthly average temperature in January is 15.4 °C, and 28.9 °C in July.

### Data sources

#### *Mortality data*

All non-accidental mortality data for calendar year 2013 were obtained from death certificates recorded at the Shenzhen Center for Disease Control and Prevention. In the death registry, causes are coded by the International Classification of Disease revision 10 (ICD10).

#### *Air pollutant monitoring data*

Daily air quality monitoring data were provided by the Shenzhen Environmental Monitoring Center and CNEMC. Daily $PM_{10}$ and $PM_{2.5}$ concentrations were derived from the average of available hourly data measured at 11 state-controlled monitoring stations across Shenzhen, the locations of which are presented in Fig. 1. According to Technical regulation for ambient air quality assessment

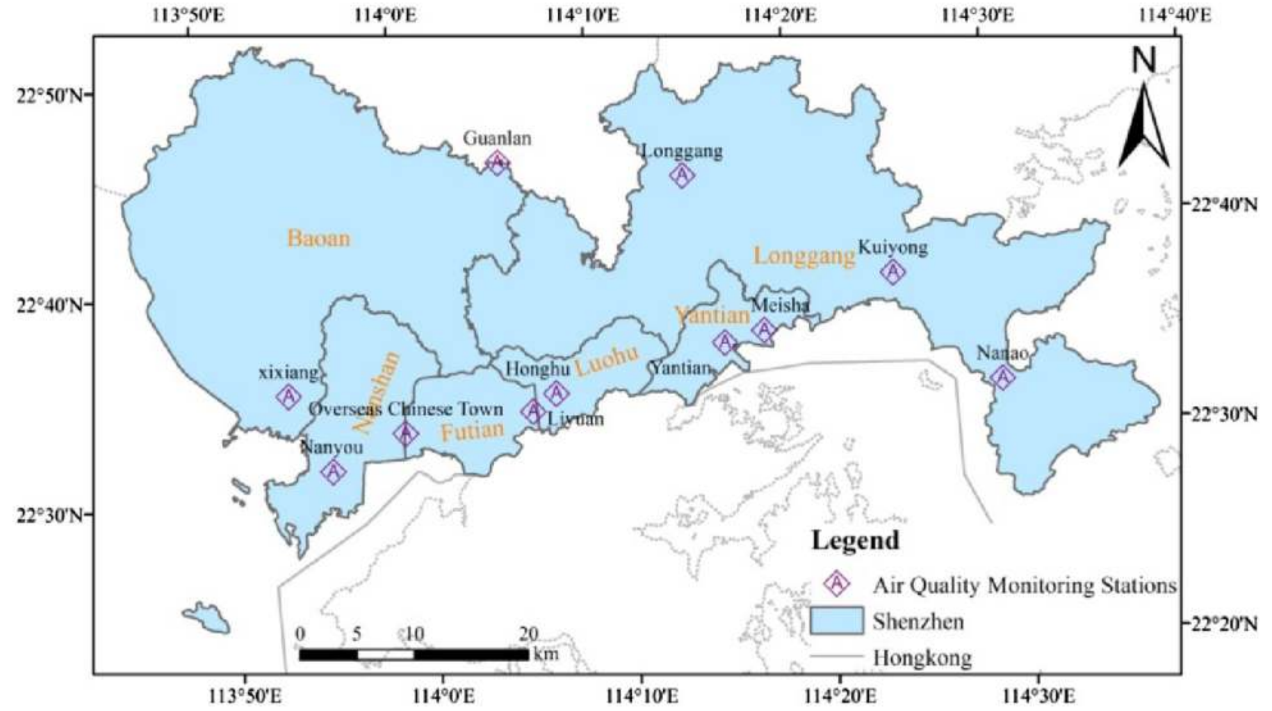

**Fig. 1** Distribution of 11 state-controlled air quality monitoring sites in Shenzhen

(on trial) (HJ 663—2013), when calculating daily means of a city, at least 75 % hourly concentrations from the monitoring stations of the city had to be available in a single day. If more than 25 % of the data in a monitoring station was missing in the whole study period, the entire station would be excluded. According to technical guidelines of the Chinese government, these locations must not be in the immediate vicinity of traffic intersections or major industrial polluters, and should be sufficiently distant from any other emission sources. Thus, the monitoring data reflect the general background urban air pollution level in our study area.

To discern spatiotemporal changes of hourly $PM_{2.5}$ and $PM_{10}$ concentrations, we acquired hourly monitoring data from 1 January through 30 November 2013 at two state-controlled monitoring stations. These stations were downtown (Huaqiaocheng, HQC) and in a tourist area (Nan'ao, NA). Hourly $PM_{2.5}$ and $PM_{10}$ monitoring data were from the National Real-Time Air Quality Monitoring Data Publishing Platform developed by CNEMC, which is publicly accessible via the website http://113.108.142.147:20035/emcpublish/.

### Meteorological data

To control for effects of weather on mortality, meteorological data (temperature, relative humidity, barometric pressure and wind speed) were obtained from the Meteorological Bureau of Shenzhen Municipality. The weather data was monitored at a weather station belonging to that bureau. The monitoring standard is consistent with the international WMO (World Meteorological Organization) standard. There were no missing meteorological data.

## Data analysis

### Statistical analysis

Spearman correlation coefficients were used to reflect the relationship between PM and meteorological factors during the study period.

### Spatial analysis

In the Macroscopic regional scale, spatial distribution of $PM_{2.5}$ concentration follow the basic assumption of 'the first law of geography', namely the regional concentrations in nearby areas are more similar than in the more distant areas. Therefore, inverse distance weighted model (Inverse Distance Weighted, IDW) interpolation analysis was used to analyze spatial distributions of $PM_{2.5}$ and $PM_{10}$.

### Associations between daily concentration of PM and mortality

Consistent with other time-series studies [21, 22], we used a generalized additive model (GAM) with penalized splines to analyze mortality, PM, and confounding factors (calendar time, day of week, temperature, barometric pressure, wind speed and humidity). Because the daily mortality number was small and typically followed a Poisson distribution [23, 24], the core analysis was via a GAM with log link and Poisson error that accounted for smooth fluctuations of that number.

In preparation for conducting the model analyses, we conducted two steps in the procedure of the model building and model fit: development of the best base model (without a pollutant) and development of the main model (with a pollutant). The latter is achieved by adding the PM to the final cause-specific best base model, assuming a linear relationship between the logarithmic mortality number and PM concentration.

First, we constructed the basic pattern of mortality number excluding PM. We incorporated smoothed spline functions of time and weather conditions, which can include non-linear and non-monotonic links between mortality and time/weather conditions, offering a flexible modelling tool. Day of the week was also included in the basic models.

After we established the basic models, we introduced the PM and analyzed their associations with mortality. To compare the relative quality of the mortality predictions across these non-nested models, Akaike's Information Criterion (AIC) was used as a measure of how well the model fitted the data. Smaller AIC values indicate the preferred model. Briefly, we fitted the following log-linear generalized additive models to obtain the estimated pollution log-relative rate β in the study district:

$$\log[\mathrm{E(Yt)}] = \alpha + \sum_{\mathrm{i}=1}^{\mathrm{q}} \beta\mathrm{i}(\mathrm{Xi}) + \sum_{\mathrm{j}=1}^{\mathrm{p}} \mathrm{fj}(\mathrm{Zj}, \mathrm{df}) + \mathrm{Wt}(\mathrm{week})$$

Here E(Yt) represents the expected number of mortality at day t; β represents the log-relative rate of mortality associated with an unit increase of PM; Xi indicates the concentrations of pollutants at day t; Wt(week) is the dummy variable for day of the week. $\sum_{\mathrm{j}=1}^{\mathrm{p}} \mathrm{fj}(\mathrm{Zj}, \mathrm{df})$ is the non-parametric spline function of calendar time, temperature, barometric pressure, wind speed and humidity. A detailed introduction to GAM is given in Wood [24]. We initialized the df as 7 df/year for time, 3 df for temperature, barometric pressure, wind speed and humidity [25].

Results were expressed as excess risk (ER) in mortality number per 10 μg/m$^3$ increases in PM concentrations (ER = ($e^{\beta x \Delta C}$-1) × 100, where $\Delta C$ is the incremental PM amount, which was 10 μg/m$^3$ here for comparison with similar studies in other locations of China).

Values of $p < 0.05$ were considered statistically significant.

We also examined PM effects with different lag (L) structures of single-day (distributed lag; L0–L3) and multi-day (moving average lag; L01–L03) lags. Here, a lag of 0 day (L0) corresponds to current-day pollution and a lag of 1 day to the previous-day concentration. In multi-day lag models, L03 corresponds to a 4-day moving average pollutant concentration of the current and previous 3 days [26, 27]. Meteorological factors used in the lag models (distributed and moving average) were from current-day data. While running the models we also considered lags of more than three days for each of the pollutants, but very few associations were identified and these results have been excluded from further analyses.

### *Software used*

Temporal changes of $PM_{2.5}$ and $PM_{10}$ were summarized by Origin 9.0 software, and their spatial differences were presented by ArcGIS 10.2 using Inverse distance weighted (IDW). Other statistical analyses were conducted in R3.1.0, and MGCV package in R3.1.0 was used for the GAM analysis.

# Results

## Descriptive results

Table 1 summarizes annual means and percentages of daily mortality number, $PM_{10}$ and $PM_{2.5}$ concentrations, and meteorological factors for Shenzhen in 2013.

During the study period, mean daily temperature and humidity were 23.1 °C and 74.8 %, respectively. Mean daily temperature was 9.8–31.2 °C and mean daily humidity ranged from 24–100 %, reflecting the subtropical oceanic climate of Shenzhen.

Annual average concentrations were 61.3 μg/m$^3$ for $PM_{10}$ and 39.6 μg/m$^3$ for $PM_{2.5}$. Averages were higher than median values for the two air pollutants. $PM_{2.5}/PM_{10}$ ratios ranged from 37.0 to 88.3 %, with a mean of 62.4 %.

A total mortality of 11,919 people from all causes was observed in 2013. Among these, 7494 were male and 4425 female. There were 6421 people in the 0–65 year age group and 5498 in the 65+ group. The daily number of all-cause mortality was between 9 and 51.

Spearman correlation coefficients for PM and meteorological factors are presented in Table 2. Significant positive correlations were found between PM and barometric pressure. Temperature was negatively and significantly correlated with PM. Similar patterns of correlations were also found for humidity and wind speed.

## Temporal changes

### *Daily concentrations of $PM_{10}$ and $PM_{2.5}$*

Figure 2 shows temporal characteristics of $PM_{10}$ and $PM_{2.5}$. Daily $PM_{10}$ and $PM_{2.5}$ concentrations showed significant similar temporal trends, with relatively high levels during October–December and low levels for May–September.

**Table 1** Statistical characteristics of air pollutants, meteorological factors, and daily mortality number

| Items | Average | SD | Min | 25 % | Mid | 75 % | Max |
|---|---|---|---|---|---|---|---|
| All-cause mortality[a] | 32.7 | 6.5 | 9 | 28 | 32 | 36 | 51 |
| Male[a] | 20.5 | 4.9 | 5 | 17 | 20 | 24 | 36 |
| Female[a] | 12.1 | 3.7 | 1 | 10 | 12 | 14 | 25 |
| Young (0–65years)[a] | 17.6 | 4.5 | 3 | 15 | 17 | 20 | 32 |
| Elder (> 65 years)[a] | 15.1 | 4.4 | 4 | 12 | 15 | 18 | 29 |
| Temperature (°C) | 23.1 | 5.2 | 9.8 | 19.4 | 24.2 | 27.7 | 31.2 |
| Humidity (%) | 74.8 | 15.6 | 24 | 67 | 78 | 87 | 100 |
| Pressure (hPa) | 1005.2 | 6.2 | 986.8 | 1000.5 | 1005.1 | 1010.8 | 1019.2 |
| Wind speed (m/s) | 2.1 | 0.8 | 0.3 | 1.6 | 2 | 2.5 | 5.5 |
| $PM_{10}$ (μg/m$^3$) | 61.3 | 33.5 | 10 | 34 | 53 | 81 | 179 |
| $PM_{2.5}$ (μg/m$^3$) | 39.6 | 24.8 | 9 | 20 | 35 | 52 | 135 |
| $PM_{2.5}/PM_{10}$ (%) | 62.4 | 10.7 | 37 | 54.4 | 63.2 | 69.6 | 100 |

[a] daily number. Pressure is barometric

Daily $PM_{10}$ concentrations were 10–179 μg/m$^3$ with an average of 61.3 μg/m$^3$, and $PM_{2.5}$ concentrations were 9–135 μg/m$^3$ with an average of 39.6 μg/m$^3$. $PM_{10}$ and $PM_{2.5}$ concentration ranges were wide, and their maxima were twice the Class 2 limits of National Ambient Air Quality Standard.

### *Ratios of $PM_{2.5}$ to $PM_{10}$*

Temporal characteristics of daily $PM_{2.5}/PM_{10}$ ratios are shown in Fig. 2. The ratios peaked during December–February and April–May, with low values from June to August, which mean high fine particulate ratio in December–February and April–May. The ratios ranged from 37.0 to 88.3 %, with an average of 62.4 %.

### *Temporal trends of daily mortality number*

Daily trends on number of mortality for all-cause, male, female, young and elder are also summarized in Fig. 2. Daily mortality number for all-cause was 9–51 with an average of 33, 5–36 for male with an average of 21, 1–25 for female with an average of 12, 3–32 for young with an average of 18, 4–29 for elder with an average of 15.

### Spatial differences

Figure 3 presents spatial distributions of $PM_{10}$ and $PM_{2.5}$ in Shenzhen during 2013. $PM_{10}$ and $PM_{2.5}$ concentrations were higher in western parts of Shenzhen than in eastern parts. According to National Ambient Air Quality Standard, annual average $PM_{2.5}$ concentrations at five monitoring stations named Nan'ao, Liyuan, Kuiyong, Meisha and Yantian were within Class 2 limits (annual average $PM_{2.5}$ concentration < 35 μg/m3), but exceeded these limits at the other six stations.

To represent spatial differences of PM in Shenzhen more directly, we analysed monthly and hourly concentrations of $PM_{10}$ and $PM_{2.5}$ at HQC and NA sites, in the downtown and tourist areas of Shenzhen, respectively. These two parts of the city serve distinct and quite different urban functions, and differences in air quality might indicate that they are affected by different pollutant emission sources.

### *Monthly differences*

Figure 4 shows average monthly $PM_{10}$ and $PM_{2.5}$ concentrations at HQC and NA from January through November. The results show that $PM_{10}$ and $PM_{2.5}$ had

**Table 2** Spearman correlation coefficients between air pollutants and meteorological factors

| | Temperature | Humidity | pressure | Wind speed | $PM_{10}$ | $PM_{2.5}$ |
|---|---|---|---|---|---|---|
| Temperature | 1 | 0.250[a] | | | | |
| Humidity | 0.250[a] | 1 | | | | |
| Pressure | −0.831[a] | −0.516[a] | 1 | | | |
| Wind speed | 0.006 | −0.048 | −0.054 | 1 | | |
| $PM_{10}$ | −0.475[a] | −0.624[a] | 0.578[a] | −0.188[a] | 1 | |
| $PM_{2.5}$ | −0.559[a] | −0.556[a] | 0.624[a] | −0.170[a] | 0.973[a] | 1 |

[a]Correlation significant at 0.01 level (2-tailed test). Pressure is barometric

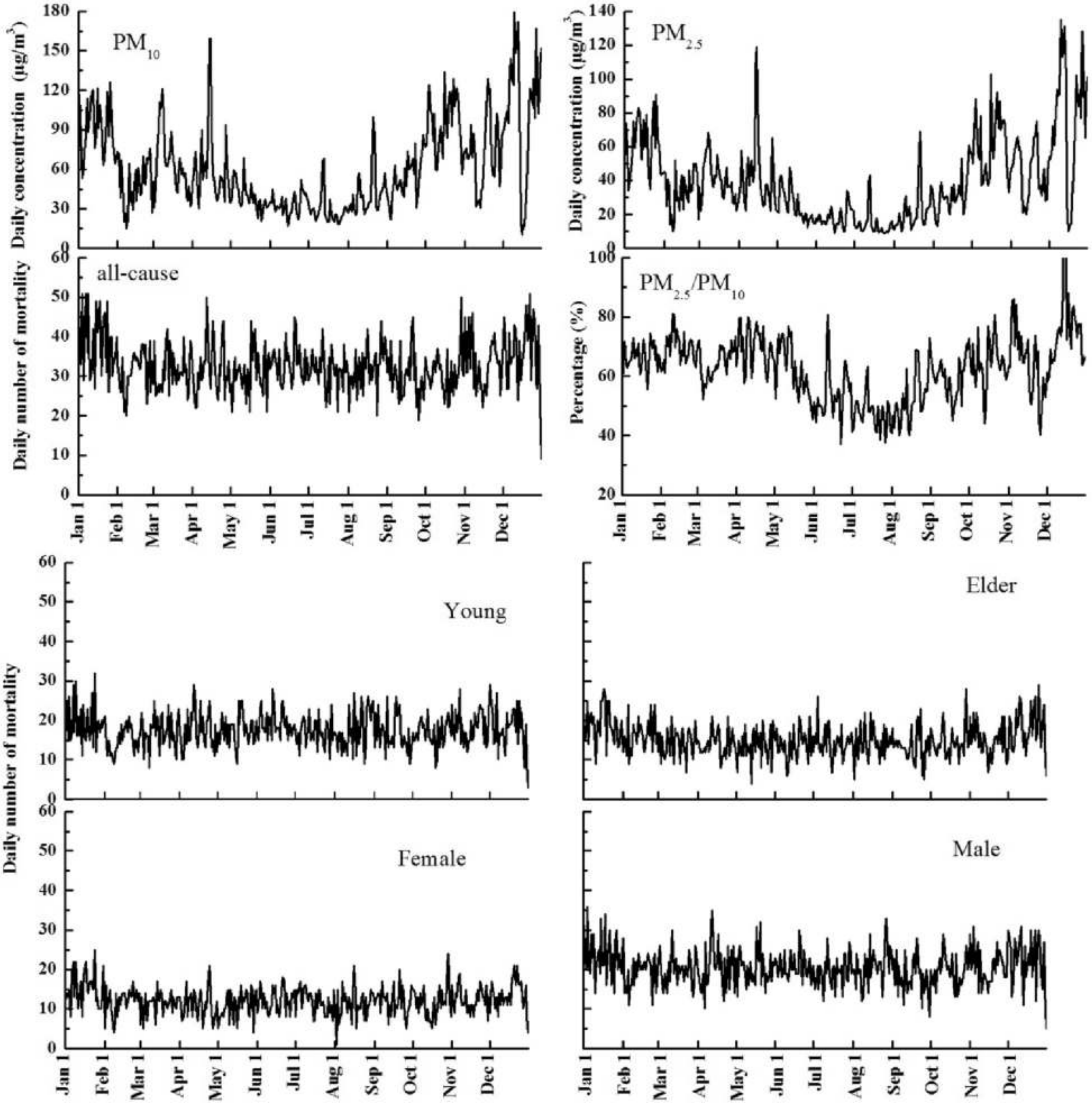

**Fig. 2** Daily concentrations of $PM_{10}$ and $PM_{2.5}$ and daily number of mortality

similar hourly trends at HQC, which had higher concentrations in January and October and lower concentrations in July. At the NA monitoring station, both $PM_{10}$ and $PM_{2.5}$ had higher concentrations in January and October, and lower concentrations in May for $PM_{10}$ and June for $PM_{2.5}$. Concentrations of $PM_{10}$ at HQC were higher than at NA during January–May and September–November, and lower than at NA during May–September. Concentrations of $PM_{2.5}$ at HQC were higher than at NA during January–June and September–November, and lower than at NA during June–September.

### *Hourly differences*

Hourly average $PM_{10}$ and $PM_{2.5}$ concentrations at HQC and NA in 2013 are also presented in Fig. 4. Changes in hourly concentrations of $PM_{10}$ and $PM_{2.5}$ had similar patterns at NA, which had maxima at 20:00 and secondary maxima at 9:00. Minima were from 3:00 to 4:00.

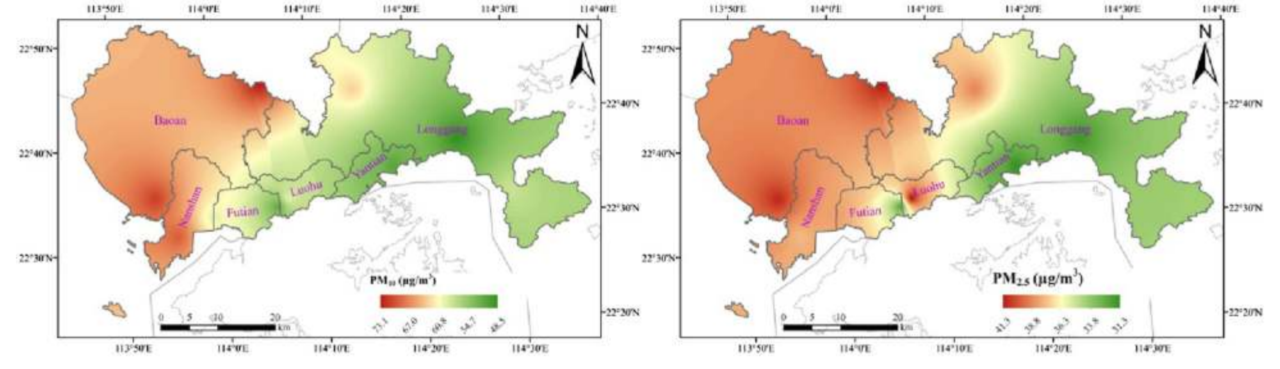

**Fig. 3** Spatial distributions of $PM_{10}$ and $PM_{2.5}$ in Shenzhen

Changes in hourly concentration of $PM_{10}$ and $PM_{2.5}$ did not show patterns common with HQC, which may be related to changes of pollution source over a day in the downtown area. Hourly concentrations of $PM_{2.5}$ at NA were lower than at HQC throughout the day, but the hourly $PM_{10}$ concentration did not show this pattern.

## Associations with all-cause mortality

Table 3 presents ER percentages(ERs) (95 % confidence interval [CI]) of daily all-cause mortality number with every 10-μg/m³ increase in $PM_{10}$ or $PM_{2.5}$ concentration.

To identify possible time delay of $PM_{10}$ or $PM_{2.5}$ pollution exposure and daily mortality number, we analyzed

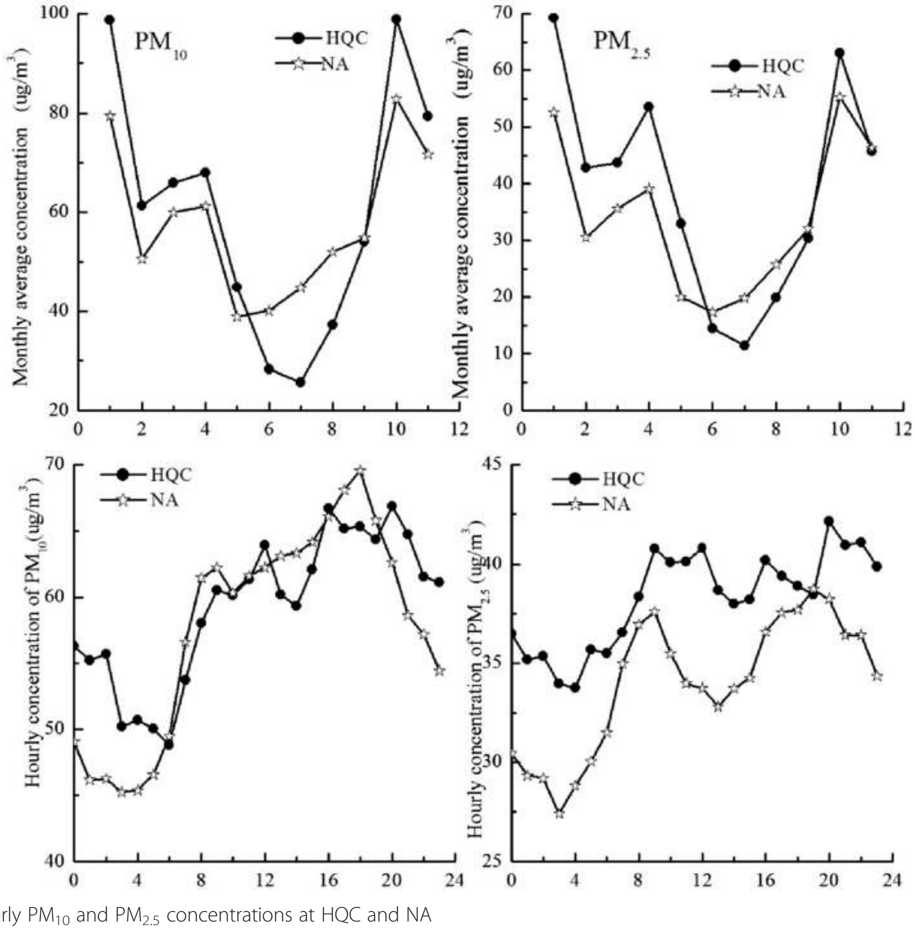

**Fig. 4** Monthly/hourly $PM_{10}$ and $PM_{2.5}$ concentrations at HQC and NA

**Table 3** Excess risk (ER) percentage for daily all-cause mortality number with every 10-μg/m3 increase in PM concentration

| Items | | All-cause | Female | Male | Elder | Young |
|---|---|---|---|---|---|---|
| | | ER (95 % CI) | ER (95 % CI) | ER (95 % CI) | ER (95 % CI) | ER (95 % CI) |
| $PM_{10}$ | L0 | 0.22(0.12 ~ 0.32) | −0.32(−0.48 ~ 0.17) | 0.54(0.42 ~ 0.67) | 1.35(1.21 ~ 1.49) | −0.79(−0.92 ~ 0.65) |
| | L1 | 0.37(0.28 ~ 0.46) | 0.33(0.19 ~ 0.47) | 0.40(0.29 ~ 0.51) | 1.05(0.92 ~ 1.17) | −0.24(−0.36 ~ 0.12) |
| | L2 | 0.51(0.43 ~ 0.60) | 0.33(0.21 ~ 0.46) | 0.62(0.52 ~ 0.73) | 0.85(0.74 ~ 0.97) | 0.21(0.10 ~ 0.33) |
| | L3 | −0.02(-0.10 ~ 0.06) | −0.47(−0.59 ~ 0.34) | 0.25(0.15 ~ 0.35) | 0.41(0.29 ~ 0.53) | −0.41(−0.52 ~ 0.29) |
| | L01 | 0.42(0.31 ~ 0.52) | 0.05(−0.12 ~ 0.22) | 0.64(0.51 ~ 0.77) | 1.54(1.39 ~ 1.69) | −0.57(−0.71 ~ 0.42) |
| | L02 | 0.61(0.50 ~ 0.72) | 0.23(0.06 ~ 0.40) | 0.85(0.71 ~ 0.98) | 1.55(1.4 ~ 1.71) | −0.22(−0.37 ~ 0.07) |
| | L03 | 0.45(0.34 ~ 0.57) | −0.07(−0.25 ~ 0.10) | 0.77(0.64 ~ 0.91) | 1.39(1.24 ~ 1.55) | −0.38(−0.54 ~ 0.23) |
| $PM_{2.5}$ | L0 | 0.12(−0.01 ~ 0.24) | −0.35(−0.54 ~ 0.15) | 0.40(0.24 ~ 0.56) | 1.67(1.48 ~ 1.85) | −1.26(−1.44 ~ 1.09) |
| | L1 | 0.46(0.35 ~ 0.58) | 0.76(0.58 ~ 0.94) | 0.29(0.15 ~ 0.44) | 1.39(1.22 ~ 1.55) | −0.37(−0.53 ~ 0.21) |
| | L2 | 0.68(0.57 ~ 0.79) | 0.75(0.57 ~ 0.92) | 0.65(0.51 ~ 0.78) | 1.13(0.97 ~ 1.28) | 0.28(0.12 ~ 0.43) |
| | L3 | −0.23(−0.34 ~ 0.12) | −0.63(−0.80 ~ 0.45) | 0.01(−0.13 ~ 0.15) | 0.55(0.39 ~ 0.71) | −0.94(−1.1 ~ 0.79) |
| | L01 | 0.41(0.28 ~ 0.55) | 0.31(0.10 ~ 0.52) | 0.48(0.31 ~ 0.65) | 1.92(1.73 ~ 2.11) | −0.92(−1.11 ~ 0.73) |
| | L02 | 0.69(0.55 ~ 0.83) | 0.62(0.40 ~ 0.84) | 0.74(0.56 ~ 0.91) | 1.97(1.77 ~ 2.16) | −0.45(−0.64 ~ 0.25) |
| | L03 | 0.44(0.29 ~ 0.58) | 0.19 (−0.04 ~ 0.42) | 0.59(0.41 ~ 0.76) | 1.82(1.62 ~ 2.03) | −0.80(−1.00 ~ 0.60) |

lag effects of air pollutants. ER in the all-cause mortality number with a 10 μg/$m^3$ increase of pollutants for single-day measures, 1–3 days prior to mortality (L0–L3), and moving averages from day 0 and day 1 to day 3 prior to the mortality are also listed in Table 3. When running the models, lag effects of more than 3 days for $PM_{10}$ and $PM_{2.5}$ were also considered. However, as little to no relationship was found, the results of that analysis were not included. Gender and age differences were also considered. Unlike cities in northern China, temperature differences in Shenzhen were not significant. Therefore, we did not run seasonal models.

The results showed that the greatest ERs of $PM_{10}$ and $PM_{2.5}$ were in 2-day cumulative measures (L02) for the all-cause mortality group, 2-day lag (L2) for females and the young (0–65 years), and L02 for males and the elder (> 65 years). The greatest ERs in the mortality number with a 10-μg/$m^3$ increase of $PM_{10}$ were 0.61, 0.33, 0.85, 1.55 and 0.21 % for the all-cause mortality group, females, males, elder and young, respectively. The greatest ERs in the mortality number with a 10-μg/$m^3$ increase of $PM_{2.5}$ were 0.69, 0.76, 0.74, 1.97 and 0.28 % for the same respective groups. ERs of males with increases in $PM_{10}$ or $PM_{2.5}$ concentration were greater than those of females, and ERs of the elder were greater than the young with concentration increases of $PM_{10}$ or $PM_{2.5}$.

## Discussion

This study focused on spatiotemporal patterns and possible associations of $PM_{10}$ and $PM_{2.5}$ with all-cause mortality during the first year (2013) of National Ambient Air Quality Standard implementation in Shenzhen, a relatively clean city compared to other cities in China. The objectives were to provide 2013 PM monitoring information of Shenzhen to the general public, to discover possible associations between PM and mortality in a comparatively clean city, and to provide scientific results to researchers in other areas. We also intend to encourage health services and public health policy-makers in Shenzhen to consider ideas for real-time public health alerts for air quality, so that vulnerable groups and others affected by air pollution can be appropriately advised. The present study was unique in the following aspects: 1) we analysed daily patterns of PM and air quality during the first year (2013) of National Ambient Air Quality Standard implementation in Shenzhen; 2) based on reliable data sources, hourly/monthly patterns of PM in two functional areas of Shenzhen were addressed; 3) spatial patterns of PM were determined; and 4) to our knowledge, the study is the first to investigate associations between PM and all-cause mortality in Shenzhen.

During 2013, annual average $PM_{10}$ and $PM_{2.5}$ concentrations were 61.3 and 39.6 μg/$m^3$, respectively; averages were higher than the median values for the two air pollutants. According to National Ambient Air Quality Standard and the Technical Regulation on Ambient Air Quality Index (on trial) (HJ633-2012), $PM_{2.5}$ was the major air pollutant in Shenzhen, with 104 days as the primary pollutant and 32 days as a "non-attainment" pollutant. The latter indicates 32 days with heavy $PM_{2.5}$ pollution. Annual average $PM_{10}$ and $PM_{2.5}$ concentrations were 108 and 89 μg/$m^3$ in Beijing, and 72 and 53 μg/$m^3$ in Guangzhou [28]. Compared with heavy PM-polluted cities in China (Beijing, Guangzhou, and others), Shenzhen has good air quality [9, 19, 29].

Shenzhen was ranked 7th among 74 first-stage cities, but its annual average $PM_{2.5}$ concentration exceeded the Class 2 limit of National Ambient Air Quality Standard [28, 30].

The annual average ratio of $PM_{2.5}$ to $PM_{10}$ was 62.4 %, which indicates a high percentage of $PM_{2.5}$ in ambient air pollution of Shenzhen. $PM_{2.5}/PM_{10}$ maximized in December–February and April–May, with lower values in June–August. Compared with Beijing the $PM_{2.5}/PM_{10}$ ratio in Shenzhen was higher than Beijing autumn normal days and lower than haze days and winter normal days in Beijing; the average $PM_{2.5}/PM_{10}$ ratios in Beijing were correspondingly 0.63, 0.32, 0.70, and 0.66 in autumn haze, autumn normal, winter haze and winter normal days, respectively [31]. The $PM_{2.5}/PM_{10}$ ratio is 0.575 in Taiwan [32]. These findings may be related to meteorological conditions and pollution sources in the city. $PM_{2.5}$ concentrations can be affected by both local emissions and contributions of meso-scale origin [33]. Further studies on concentrations and ratios of PM at intercity level should be conducted.

Hourly concentrations of $PM_{10}$ and $PM_{2.5}$ had similar patterns in the tourist area (NA monitoring station) but did not have any patterns in common in the downtown area. This may be related to changes of pollution source like traffic emission in downtown over a single day. Hourly concentrations of $PM_{2.5}$ in the tourist area were lower than downtown throughout the day, which may be attributed to more intensive human activities downtown. $PM_{10}$ and $PM_{2.5}$ concentrations were higher in western parts of Shenzhen than eastern parts, which may be related to land use, pollution sources, industrial structure, traffic conditions, and other factors [34]. There should be further study of relationships between driving factors (e.g., spatial distribution of pollutant emissions, pollutant emission intensity, and regional industrial structure) and pollutant concentrations.

Time-series studies estimate that a 10 μg/$m^3$ increase in mean 24-hour $PM_{2.5}$ concentration increases the ERs of daily cardiovascular mortality by ~0.4 to 1.0 % [35]. Consistent with other studies [2, 11, 12, 36, 37], we found a statistically significant association between $PM_{10}$ or $PM_{2.5}$ and daily mortality number. There were lag effects in all the study groups, and ERs of $PM_{2.5}$ were greater than $PM_{10}$ in all study groups with concentration increases. ERs in the all-cause mortality number with a 10-μg/$m^3$ increase of $PM_{10}$ and $PM_{2.5}$ were 0.61 % (95 % CI: 0.50 %–0.72 %) and 0.69 % (95 % CI: 0.55 %–0.83 %), respectively. A study in Beijing for 2005–2009 showed that a 10 μg/$m^3$ increase in $PM_{2.5}$ was associated with a 0.65 % rise in all-cause mortality, whereas the same increase in $PM_{10}$ was associated with an increase of 0.15 % [38]. During 2006–2009 in Guangzhou, increments of 10 μg/$m^3$ in $PM_{10}$ were associated with a ER of 1.26 % for total non-accidental deaths, and 1.79 % for cardiovascular deaths [39]. During 2007 to 2009 in Tianjin, the effect estimates per 10 μg/$m^3$ increase in $PM_{10}$ concentrations at the moving average of lags 0 and 1 day in high temperature level were 0.62 % for non-accidental mortality [40]. ERs in our study were greater than those reported for Beijing and smaller than those for Guangzhou. Such inter-city variability in ER estimates may have been influenced by a number of factors, such as demographic and socioeconomic variables, culture, air pollution sources, and geographical and weather conditions [39]. Both temperature and particulate air pollution are associated with increased death risk; and extreme high temperature increased the associations of $PM_{10}$ with daily mortality [41]. ERs in the all-cause mortality number with 10-μg/$m^3$ increase of $PM_{10}$ and $PM_{2.5}$ were 0.33 and 0.76 % for females, respectively, 0.85 and 0.77 % for males, 1.55 and 1.97 % for the elder, and 0.21 and 0.28 % for the young. Males were more sensitive to $PM_{10}$ or $PM_{2.5}$ concentration changes than females. The elder appeared to be more affected than the young by $PM_{10}$ or $PM_{2.5}$ concentration increase. These findings indicate that PM effects on mortality were stronger among the elderly and on male. Because the seasonal difference was not significant in Shenzhen, we did not consider seasonal associations among PM and mortality in this study. The present study has certain limitations. We considered the target population to be relatively homogeneous and did not consider residence or work location of deaths, owing to a lack of data. Pollutant exposure levels were derived from 11 fixed-site monitoring stations. However, because air pollution varies spatially within a city, averages drawn from these stations may not reflect actual exposure levels. Accurate exposure assessment and a homogeneous target population are important factors to consider in future studies estimating mortality risk from air pollution [39]. Further in-depth studies should require air pollutant composition, pollution emission sources, pollutant emission patterns, time-series of human activity, individual exposure to pollutants, social economy, and human health at the city level.

## Conclusion

During 2013, annual average $PM_{10}$ and $PM_{2.5}$ concentrations were 61.3 and 39.6 μg/$m^3$ in Shenzhen. $PM_{2.5}$ failed to meet the Class 2 annual limit of National Ambient Air Quality Standard and was the major air pollutant, with 8.8 % of days having heavy $PM_{2.5}$ pollution. The annual average $PM_{2.5}/PM_{10}$ ratio was 62.4 %. Hourly $PM_{2.5}$ concentrations in the tourist area were lower than downtown throughout the day. $PM_{10}$ and $PM_{2.5}$ concentrations were higher in western parts than eastern parts. ERs in the all-cause mortality number increased with $PM_{10}$ and $PM_{2.5}$.

$PM_{2.5}$ had higher risks than $PM_{10}$. PM effects on mortality were stronger among male and the elderly. Our findings provide additional information on air quality monitoring and associations between PM and all-cause mortality, and valuable data for scientific research in Shenzhen. It also contributes to the discussion on further developing environmental health policies in urban China.

### Competing interests

The authors declare that they have no competing interest.

### Authors' contribution

FYZ led the study, carried out the time-series studies, analyzed the data and wrote the first draft of the manuscript. XJL participated in all-cause mortality date in Shenzhen. LZ and YY conducted PM monitoring/ meteorological data collecting and spatial analysis. LW and JML assisted with statistical analysis and language editing. WYW and TK helped to conceptualize the study, provided intellectual advice, contributed to data interpretation and helped to revise various drafts of the manuscript. All authors read and approved the final manuscript.

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