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Original article

Spatiotemporal characteristics and health effects of air pollutants in Shenzhen

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ABSTRACT

In this study, spatiotemporal patterns and health effects in all-cause mortality of air pollutants (CO, NO₂, and SO₂) during 2013 in Shenzhen were investigated. Spatiotemporal characteristics of air quality index (AQI) and air quality are also addressed. The results show that daily averages were 10.9 µg/m³ for SO₂, 39.6 µg/m³ for NO₂, and 1.2 mg/m³ for CO. Daily AQI ranged from 24 to 179. There were approximately 39 days of air pollution in Shenzhen. NO₂ was the third major air pollutant. Monthly/hourly average AQI and concentrations of NO₂ and SO₂ in the city center area were higher than in tourist areas. Annual AQI and NO₂ concentration were higher in western parts of Shenzhen, whereas SO₂ was higher in eastern portions. The lowest CO concentration was in the Luohu District. Relative risks of mortality number increased with SO₂/NO₂ levels. When SO₂/NO₂ concentration changed, female individuals were more sensitive than male individuals, and people aged older than 65 years were more affected than younger people.

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1. Introduction

China has undergone very rapid economic growth since economic reforms in 1978. This growth has increased energy consumption, air pollution, and associated health effects (Wong et al., 2008; Hellgren et al., 2010; Cai et al., 2014; Li and Zhang, 2014). To improve air quality, protect the environment, and reduce the health burden of air pollution, the Chinese Government issued a new ambient air quality standard (GB3095-2012) (Ministry of Environmental Protection of the People's Republic of China and Administration of Quality Supervision Inspection and Quarantine (2012)) in 2012, replacing the old standard (GB3095-1996)

(Ministry of Environmental Protection of the People's Republic of China and Administration of Quality Supervision Inspection and Quarantine (1996)). The new standard will be implemented incrementally nationwide by 1 January 2016. Selected cities including Beijing-Tianjin-Hebei, the Yangtze River Delta, Pearl River Delta and provincial capitals began compliance with the GB3095-2012 on 1 January 2013.

Shenzhen is in southern China, spanning 113°46'–114°37'E and 22°27'–22°52'N, with a city area of 1991.64 km² (Simons, 2003). There is a subtropical oceanic climate, with warm weather and abundant rainfall, and annual average temperature is 22.4 °C. Shenzhen is a rapidly developing city in Guangdong Province, and is located at the mouth of the Pearl River Delta adjacent to Hong Kong. It is one of the original "Special Economic Zones" that was designed to attract foreign investment, promote exports, and evaluate various economic policies. Shenzhen is exemplary of China's urban revolution and shares many environmental and social equity concerns with numerous rapidly developing cities around the world (Skoner, 2001). From 1996 to 2006, the real gross domestic product of Shenzhen increased by nearly 400%, and the

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city is now the fourth richest in China (Simons, 2003). The rapid economic development and urbanization have also given rise to a number of environmental concerns and demands on natural resources, most notably the conversion of land and accompanying impacts on air and water quality (Maziak et al., 2003; Liu et al., 2007; Chen and Jiao, 2008). As one of the first-stage cities complying with GB3095-2012 since 2013, Shenzhen has released real-time hourly monitoring concentration data of six air pollutants to the general public since 1 January 2013. Annual SO₂ and NO₂ concentrations were 9 and 42 µg/m³ in 2012; and the air quality met the Grade II standard of GB3095-1996; relative to other cities in China, air quality in Shenzhen was good. Compared with previous years, however, the city is experiencing increasing air pollution (Ministry of Environmental Protection of the People's Republic of China, 2000–2013). However, there has been no comprehensive study of air pollutants (SO₂, NO₂, and CO) in Shenzhen, therefore studies on spatiotemporal patterns and health effects of those pollutants are needed.

We carried out a time-series analysis of daily/hourly air pollutant concentrations and daily number of all-cause (non-accidental) mortality during the first year (2013) of GB3095-2012 implementation in Shenzhen. Daily patterns of air quality index (AQI) and the three aforementioned air pollutants were determined, and their hourly patterns in different urban functional areas of the city were examined. Spatial distributions of the four variables were also investigated. Health effects of air pollutants on all-cause mortality were analyzed, considering various age and sex groups. The results of our analysis will help us to implement a control strategy for SO₂, NO₂, and other major pollutants in urban areas.

2. Methodology

2.1. Data sources

2.1.1. Mortality data

All mortality data for the 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) (World Health Organization, 2010).

2.1.2. Air pollutant monitoring data

Air quality monitoring data were provided by the China National Environmental Monitoring Center (CNEMC). Daily AQI and SO₂, NO₂, and CO concentrations were provided as daily mean values measured at 11 state-controlled monitoring stations in Shenzhen. Station locations are presented in Fig. 1. According to technical guidelines of the Ministry of Environmental Protection, these locations must not be in the immediate vicinity of traffic intersections or major industrial polluters, and should have sufficient distance from any other emission source. Thus, the monitoring data reflect general urban air quality in Shenzhen.

To determine spatiotemporal changes of hourly AQI and SO₂, NO₂, and CO concentrations, we obtained hourly monitoring data from 1 January through 30 November 2013 at two stations, and hourly AQI at all stations. The two stations were Huaqiaocheng (HQC) and Nan'ao (NA). HQC is in the city center, and was used to assess regional air quality and its variations. NA is located in the east of Shenzhen, with the sea on three sides. Most of the area around NA has the original ecology and is undeveloped, and the station data were therefore used to quantify pollution concentrations unaffected by the urban environment. Hourly air pollutant monitoring data were from the National Real-Time Air Quality Monitoring Data Publishing Platform, developed by the CNEMC.

2.1.3. Meteorological data

Meteorological data (temperature, relative humidity, barometric pressure, and wind speed) were obtained from the Meteorological Bureau of Shenzhen Municipality. The data were measured at a fixed-site station in the study area, owned by that bureau. The monitoring standard of the station is consistent with that of the international World Meteorological Organization (World Meteorological Organization, 2013), and the data are representative of Shenzhen.

2.2. Data analysis

The objective of the data analysis was to quantify the association between daily number of mortality and air pollutant concentrations, while adjusting for weather and temporal factors in the multivariable modeling. Because number of mortality was small and typically followed a Poisson distribution (Wood, 2006; Box et al., 2013), the core analysis was a generalized additive model (GAM) with log link and Poisson error that accounted for fluctuations in daily numbers of deaths. Consistent with other time-series studies (Pope and Dockery, 2006; Zhang et al., 2012; Meng et al., 2013), we used the GAM with penalized splines to analyze the daily counts of mortality, air pollution, and covariates (meteorological factors, time trend, and day of the week).

Before conducting the model analyses, there were 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 air pollution variables to the final cause-specific best base model, assuming a linear relationship between the logarithmic mortality number and air pollutant concentration.

First, we constructed the basic pattern of mortality number excluding the air pollution variables. 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 modeling tool. Other covariates, such as day of the week, were also included in the basic models.

After we established the basic models, we introduced the pollutant variables and analyzed their effects on 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:

$$\log[E(Y_t)] = \alpha + \sum_{i=1}^q \beta_i(X_i) + \sum_{j=1}^p f_j(Z_j, df) + W_t(\text{week})$$

Here $E(Y_t)$ represents the expected number of mortality at day t ; β represents the log-relative rate of mortality associated with an unit increase of air pollutants; X_i indicates the concentrations of pollutants at day t ; $W_t(\text{week})$ is the dummy variable for day of the week. $\sum_{j=1}^p f_j(Z_j, df)$ is the non-parametric spline function of calendar time, temperature and humidity. A detailed introduction to the GAM is given in Wood's book (Wood, 2006).

Regarding the basic models, we also did some sensitivity analysis following Welty's method (Welty and Zeger, 2005). We initialized the df as 7 df /year for time, 3 df for temperature, barometric pressure and humidity. We fitted both single-pollutants models and multi-pollutant models (models with a different combination of two or three pollutants per model) to assess the stability of pollutants' effect.

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

To identify the potential time delay of air pollutant exposure on mortality, we analyzed lag effects. Change of RRs in the number of all-cause mortality with a 10 $\mu\text{g}/\text{m}^3$ increase of air pollutants as a single-day measure, 1–3 days prior to mortality (L0–L3), and moving averages from day 0 and day 1 to day 3 (L01–L03) prior to mortality were ascertained. Here, a lag of 0 day (L0) corresponds to current-day pollution, and a lag of 1 day refers to the previous-day concentration. In multi-day lag models, L03 corresponds to a 4-day moving average of pollutant concentration of the current and previous 3 days (Gasparrini et al., 2010; Greiner et al., 2011; Zhang et al., 2013).

Temporal change of air pollutants was determined by Origin 9.0 software. Spatial differences of AQI and air pollutants were expressed by ArcGIS 10.0. All other statistical analyses were conducted in R3.1.0 using the MGCV package. Results were expressed as RR percentage change in mortality number per certain increases of air pollutant concentrations ($\text{RR} = e^{\beta \times \Delta c}$, where Δc is the increased amount of air pollutants, for comparison to similar studies in other locations of China; in the present study, we used 10 $\mu\text{g}/\text{m}^3$ for SO_2 and NO_2 , and 1 mg/m^3 for CO).

3. Results

3.1. Statistical results

Table 1 summarizes annual means and percentages of daily all-cause mortality number, AQI, and concentrations of air pollutants in Shenzhen during 2013.

During the study period, annual temperature and humidity were 23.1 $^{\circ}\text{C}$ and 74.8%, respectively. Mean daily temperature ranged from 9.8 to 31.2 $^{\circ}\text{C}$, and mean daily humidity from 24% to 100%, reflecting the subtropical oceanic climate.

The daily range of SO_2 was 4–51 $\mu\text{g}/\text{m}^3$, with an average of 10.9 $\mu\text{g}/\text{m}^3$. NO_2 concentration was 14–111 $\mu\text{g}/\text{m}^3$, with an annual average of 39.6 $\mu\text{g}/\text{m}^3$, and the daily CO concentration was 0.7–2.0 mg/m^3 , with an annual average of 1.2 mg/m^3 . According to GB3095–2012 and the Technical Regulation on Ambient Air Quality Index (on trial) HJ633–2012, annual levels of these pollutants met Grade II limits of GB3095–2012 (annual SO_2 concentration $\leq 60 \mu\text{g}/\text{m}^3$, annual NO_2 concentration $\leq 40 \mu\text{g}/\text{m}^3$). NO_2 was the third major air pollutant in Shenzhen, with 61 days as the primary pollutant and 3 days as a non-attainment pollutant. There were no polluted days for SO_2 and CO.

A total mortality number of 11,919 for all causes was observed in 2013; among these, the male: female ratio was 7494:4425, and that of the young group (age 0–65 years) to older group (age >65 years) was 6421:5498. The daily all-cause mortality number ranged from 9 to 51, with an average of 32.7.

Pearson coefficients for the air pollutants and meteorological factors are listed in Table 2. Significant positive correlations were found among $\text{SO}_2/\text{NO}_2/\text{CO}$ and barometric pressure. There were significant negative correlations among SO_2/NO_2 and other meteorological factors (temperature, humidity, and wind speed). There was no significant correlation between CO and wind speed. There were significant positive correlations among the air pollutants.

3.2. Temporal changes

Daily AQI and pollutant levels are presented in Fig. 2. During 2013, daily AQI was 24–179, and it was >100 on 39 days. According to HJ633–2012, those days had air pollution, and most were in December (18 days), October (8 days), and January (7 days).

Daily NO_2 and CO concentrations showed significant temporal differences. There were higher concentrations during December to

Table 1
Statistics of air pollutants, AQI, and daily mortality number.

	All-cause	Male	Female	Young	Old	$\text{SO}_2 \mu\text{g}/\text{m}^3$	$\text{NO}_2 \mu\text{g}/\text{m}^3$	$\text{CO mg}/\text{m}^3$	AQI
Average	32.7	20.5	12.1	17.6	15.1	10.9	39.6	1.2	64.4
SD	6.5	4.9	3.7	4.5	4.4	5.7	15.7	0.2	28.5
Minimum	9	5	1	3	4	4	14	0.7	24
25%	28	17	10	15	12	7	28	1.0	42
Mid	32	20	12	17	15	10	36	1.2	58
75%	36	24	14	20	18	13	47	1.3	81.3
Maximum	51	36	25	32	29	51	111	2	179

Table 2

Correlation coefficients for air pollutants and meteorological factors.

	Temperature	Humidity	Pressure	Wind speed	SO ₂	NO ₂	CO
Temperature	1						
Humidity	0.377 ^a	1					
Pressure	−0.818 ^a	−0.530 ^a	1				
Wind speed	0.009	−0.003	−0.100	1			
SO ₂	−0.413 ^a	−0.635 ^a	0.433 ^a	−0.152 ^a	1		
NO ₂	−0.381 ^a	−0.270 ^a	0.341 ^a	−0.471 ^a	0.614 ^a	1	
CO	−0.493 ^a	−0.295 ^a	0.475 ^a	−0.077	0.451 ^a	0.345 ^a	1

^a Correlation is significant at the 0.01 level (two-tailed test). Pressure: barometric pressure.

January and March to April for NO₂, and December through February for CO. There were relatively low concentrations from June to August for NO₂ and July through September for CO. Although daily SO₂ had some peaks in 2013, there was no obvious temporal variation.

3.3. Spatial differences

Spatial distributions of AQI, SO₂, NO₂, and CO in Shenzhen are shown in Fig. 3. Annual AQI and NO₂ concentrations were greater in western parts of the city than in eastern parts. SO₂ level showed the highest value in east parts of Shenzhen. The lowest CO concentration was in Luohu (central business) District. According to GB3095-2012 and HJ633-2013, annual SO₂ concentrations met the grade I limit of GB3095-2012 (annual SO₂ concentration $\leq 20 \mu\text{g}/\text{m}^3$) at all monitoring stations. Annual NO₂ concentrations met the above grade I limit at seven stations (annual NO₂ concentration $\leq 40 \mu\text{g}/\text{m}^3$), and the grade II limit at the other four stations.

3.3.1. Monthly changes

Fig. 4 shows monthly average SO₂/NO₂/CO concentrations at HQC and NA from January through November. The NO₂ and SO₂ concentrations had similar temporal trends at the two stations, with higher concentrations in January and lower ones in July. Monthly average NO₂/SO₂ concentrations at HQC were higher than at NA. CO concentrations at HQC were higher than at NA during January–March and October–November; and lower than NA during April–September. Monthly average AQI peaked in January,

and there was a secondary peak in October. The AQI at HQC was smaller than at NA during May–September, and larger in other months.

3.3.2. Hourly differences

Hourly average AQI and pollutant concentrations are also presented in Fig. 4. Hourly NO₂ concentration at HQC had a peak at 21:00 and a second on at 9:00; the lowest concentration appeared around 5:00–6:00. At NA, hourly NO₂ concentration was high at 8:00 and was low during 1:00–6:00. SO₂ concentration at HQC had different hourly variations than NA; there were large values during 12:00–21:00 and small ones during 3:00–8:00. NA had a maximum at 11:00, with an increase during 0:00–11:00, and a decrease over 12:00–22:00. Hourly AQI patterns were similar to SO₂ in the two areas. All hourly average AQI and SO₂/NO₂ concentrations were greater at the city center than in the tourist areas, which may reflect different pollution sources in those areas. In contrast with the above three variables, hourly CO data showed a maximum at 1:00 at NA and at 9:00 at HQC.

3.4. Health effects

Table 3 presents RRs (95% confidence interval, CI) of daily all-cause mortality number with every $10 \mu\text{g}/\text{m}^3$ increase in SO₂/NO₂ concentration. RRs of mortality with every $1 \text{ mg}/\text{m}^3$ increase of CO concentration are not listed, because the health effects of CO were not significant.

The greatest RRs of SO₂ were found in 2-day cumulative measures (L02) for all-cause mortality, L01 for female individuals and

Fig. 2. Daily AQI and concentration of air pollutants.

Fig. 3. Spatial distribution of AQI and ambient air pollutants in Shenzhen during 2013.

older individuals, L02 for male individuals, and L02 for young individuals. Greatest RRs of NO_2 were in L03 for all-cause mortality, L01 for female individuals, L03 for male individuals and young individuals, and L1 for older individuals. With the SO_2/NO_2 concentration increase, RRs of female individuals were greater than for male individuals, and those of older individuals were greater than for young individuals.

Given the high correlation coefficients among CO, SO_2 , and NO_2 in our study, we did not consider multi-pollutant exposure mortality. Additionally, unlike cities in northern China, temperature differences in Shenzhen are not great; therefore we did not use seasonal models.

4. Discussion

The objective of this study was to provide air quality status and environmental monitoring information to the general public and scientific research community, determine spatiotemporal characteristics of AQI, CO, NO_2 , and SO_2 , evaluate Shenzhen air quality during 2013, and ascertain any health effects of air pollutants on human health.

NO_2 has been used as a marker for a cocktail of combustion-related pollutants. In particular, air pollutants emitted by road traffic or indoor combustion sources and NO_2 can have greater spatial variation than other traffic-related pollutants (Gupta et al., 2004; Cyrys et al., 2012). Annual NO_2 concentration was higher in western Shenzhen, which can be related to greater traffic or indoor combustion emissions there. SO_2 is a traditional pollutant of industrial origin related to combustion of coal and other fossil fuels (Kan et al., 2010). SO_2 had greater concentrations in eastern Shenzhen, and the lowest CO concentrations were in the Luohu District. These findings may be related to land use or industrial structure.

Monthly average NO_2/SO_2 concentrations had similar temporal trends in the city center and tourist area, and the monthly CO level did not show any pattern in common between the two areas. Consistent with the correlation coefficients among the three air pollutants, NO_2/SO_2 may have more similar emission sources than NO_2/CO or SO_2/CO . Monthly average NO_2/SO_2 concentrations in the commercial area were higher than in the tourist area, which indicates greater emissions from traffic or human activities. Hourly NO_2/SO_2 concentrations had no pattern in common between the commercial and tourist area, which may be related to different pollution sources and emission variation through the day. Further studies are needed on associations between regional air quality, traffic, pollution sources, land use, industrial structure, and meteorological factors.

Relative to heavily polluted Chinese cities (Guangzhou, Beijing, and others), Shenzhen has clean air quality, and annual NO_2 and SO_2 concentrations met grade II of GB3095-2012. However, there was significant association between NO_2/SO_2 and mortality in our study, consistent with similar investigations (Meng et al., 2013; Shang et al., 2013; Guarnieri and Balmes, 2014). RRs in the number of all-cause mortality increased with NO_2/SO_2 concentration.

A variety of health effects have been associated with exposure to NO_2 (The; Meng et al., 2013; Shang et al., 2013; Guarnieri and Balmes, 2014). Effects of NO_2 on mortality were also found in Shenzhen. RRs in mortality number with a $10 \mu\text{g}/\text{m}^3$ increase of NO_2 were 1.195, 1.439, 1.059, 0.428, and 1.916 for all-cause mortality, female individuals, male individuals, older and young individuals, respectively.

SO_2 is a ubiquitous air pollutant. Gaseous SO_2 is released into the atmosphere from the combustion and processing of sulfur-containing fossil fuels (Guarnieri and Balmes, 2014). The long-term effect of exposure to low-concentration SO_2 is similar to the short-term effect of exposure to high-concentration SO_2 in many industrial settings and chemical industries. Numerous epidemiological studies have suggested that SO_2 exposure is associated with health risk and mortality caused by respiratory tract diseases, lung cancer, and cardiovascular diseases (Meltzer et al., 2009; Kan et al., 2010; Meng et al., 2013; Guarnieri and Balmes, 2014). The greatest RRs in mortality number with a $10 \mu\text{g}/\text{m}^3$ increase of SO_2 were

Fig. 4. AQI and air pollutant concentrations at sites HQC and NA.

2.157, 2.494, 1.999, 0.024, and 0.652 for all-cause mortality, female individuals, male individuals, older and young individuals, respectively.

CO is a colorless, tasteless, odorless, and nonirritating gas that is a product of incomplete combustion of carbon-containing fuels

(Nathan, 2007; Chen et al., 2011). It has direct effects on blood and other tissues, and indications of these effects are in the form of organ function change (Nathan, 2007; Chen et al., 2011). In the present study, 1 mg/m³ concentration change was selected in CO exposure-mortality models, and there was no significant

Table 3

RR all-cause mortality with every 10 µg/m³ increase in air pollutant concentration.

Items		All	Female	Male	Elder	Young
		RRs (95% CI)	RRs (95% CI)	RRs (95% CI)	RRs (95% CI)	RRs (95% CI)
SO ₂	L0	2.157(1.623–2.69)	2.494(1.667–3.320)	1.999(1.341–2.657)	5.724(4.981–6.466)	–0.933(–1.673–0.192)
	L1	2.149(1.667–2.632)	1.552(0.803–2.301)	2.523(1.931–3.116)	7.268(6.599–7.937)	–2.312(–2.984–1.640)
	L2	1.254(0.802–1.706)	0.111(–0.591–0.814)	1.942(1.388–2.496)	1.893(1.255–2.531)	0.652(0.032–1.272)
	L3	–1.069(–1.511–0.628)	–1.132(–1.810–0.453)	–1.012(–1.557–0.466)	0.024(–0.598–0.647)	–2.033(–2.640–1.426)
	L01	3.306(2.704–3.908)	2.717(1.784–3.650)	3.695(2.955–4.434)	9.695(8.855–10.535)	–2.073(–2.906–1.241)
	L02	3.564(2.916–4.212)	2.151(1.144–3.157)	4.447(3.651–5.243)	8.609(7.696–9.521)	–0.697(–1.588–0.193)
	L03	2.162(1.532–2.791)	0.904(–0.145–1.953)	2.953(2.120–3.786)	6.916(5.959–7.872)	–1.847(–2.774–0.919)
NO ₂	L0	1.195(0.993–1.396)	1.439(1.129–1.750)	1.059(0.809–1.308)	0.428(0.141–0.716)	1.916(1.642–2.190)
	L1	2.412(2.245–2.578)	2.300(2.041–2.560)	2.478(2.272–2.684)	2.914(2.677–3.151)	1.989(1.759–2.218)
	L2	2.412(2.245–2.578)	0.878(0.636–1.120)	2.513(2.325–2.701)	1.330(1.110–1.550)	2.435(2.225–2.645)
	L3	1.907(1.753–2.061)	–0.237(–0.476–0.002)	2.079(1.892–2.266)	0.191(–0.028–0.410)	2.153(1.945–2.361)
	L01	2.664(2.451–2.877)	2.718(2.386–3.050)	2.638(2.375–2.902)	2.635(2.330–2.940)	2.733(2.441–3.025)
	L02	3.290(3.068–3.512)	2.610(2.263–2.958)	3.698(3.425–3.971)	2.856(2.538–3.174)	3.715(3.412–4.019)
	L03	3.404(3.174–3.634)	2.010(1.648–2.372)	4.230(3.948–4.513)	2.440(2.109–2.771)	4.305(3.991–4.619)

relationship between CO and mortality in Shenzhen. Our results vary from the research of Chen et al. (Chen et al., 2011), whose exposure–response relationship between CO and mortality in three Chinese cities generally supported a linear association without a threshold. The authors found significant associations of CO with all-cause and cardiovascular mortality with a 1 mg/m³ increase of CO concentration in single-pollutant models. Our results were consistent with Nathan's study (Nathan, 2007), which showed that health effects of low concentrations such as in ambient air are much more subtle and considerably less threatening to the general public.

There were lag effects, and RRs of SO₂ were greater than NO₂ with increasing concentrations. Female individuals were more sensitive to NO₂/SO₂ concentration changes than male individuals, and the older individuals were more affected by NO₂/SO₂ concentration increases than the young individuals.

This study had some limitations. Although we had hourly air pollutant concentrations from monitoring data of 11 state-controlled monitoring stations across Shenzhen, average values from the 11 stations were used as exposure concentrations because of a lack of personal information. Accurate exposure assessment and catchment boundaries of monitoring stations are important factors to consider in the future. Given the high correlation among the air pollutants, it is difficult to rule out contributing effects of other co-pollutants. Further studies at the district level are required on relationships between meteorological factors, various air pollutants, human time-series activity, personal pollutant exposure, socioeconomics, and human health.

5. Conclusions

During 2013, annual concentrations in Shenzhen were 10.9 µg/m³ for SO₂, 39.6 µg/m³ for NO₂, and 1.2 mg/m³ for CO. The daily AQI was 24–179. Approximately 39 days had air pollution, largely in December. Monthly NO₂/SO₂ concentrations at site HQC were higher than at NA. All hourly average AQI and SO₂/NO₂ concentrations were higher in the city center than in the tourist area. Annual AQI and NO₂ concentrations were higher in western Shenzhen. SO₂ had higher concentrations in eastern portions. The lowest CO concentration was in the Luohu District. Significant relationships between SO₂/NO₂ and all-cause mortality were found, as were lag effects of the two air pollutants. The correlation between CO and mortality was not significant. Female individuals were more sensitive to concentration changes of SO₂/NO₂ than male individuals, and those individuals aged older than 65 years appeared more affected than younger people.

Our study provides first-hand monitoring information on AQI, CO, NO₂, and SO₂ in Shenzhen to the general public for 2013, and scientific findings on possible human health effects of air pollutants (CO, NO₂, and SO₂) in a relatively clean Chinese city. The study should encourage health service policymakers in Shenzhen to consider the results for real-time public health alerts on ambient air quality, so people affected can be appropriately advised.

Conflicts of interest

All authors declare they have no conflict of interest to disclose in the context of this study.

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