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The effects of firework regulation on air quality and public health during the Chinese Spring Festival from 2013 to 2017 in a Chinese megacity

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ABSTRACT

Fireworks displays are a traditional form of celebration during the Chinese Spring Festival (Festival). In response to the heavy air pollution caused by fireworks, Shanghai, a megacity in China, has imposed regulatory measures on the use of fireworks in recent years. To investigate air quality trends before and after firework regulation was established and quantify its efficiency, gaseous pollutants, $PM_{2.5}$ levels, and $PM_{2.5}$ chemical composition were synchronously measured at 1 h time intervals at an urban site and a suburban site in Shanghai in the period during and around the Festival from 2013 to 2017. $PM_{2.5}$ concentrations at the urban site during the Festival over the five-year period were 79 (max: 524), 94 (290), 53 (163), 50 (146) and 32 (156) μg/m^3, respectively, presenting a decreasing trend at a rate of −13.8 μg/m^3/yr ($p = 0.05$). K^+ concentrations, which serve as a tracer of fireworks, were 8.2 (max: 159.4), 2.5 (14.6), 2.2 (10.4), 4.3 (44.2) and 0.8 (4.5) μg/m^3 during the Festival from 2013 to 2017, respectively, and thus decreased at a rate of −1.3 μg/m^3/yr ($p = 0.17$). Accordingly, fireworks contributed 41 (51.9%), 38 (36.5%), 6 (10.3%), 21 (35.6%), and 4 μg/m^3 (12.1%) to $PM_{2.5}$, respectively, implying the effectiveness of firework regulation in Shanghai. Health effects attributed to $PM_{2.5}$ pollution in Shanghai during the Festival were assessed based on Poisson regression. The number of premature deaths related to short-term $PM_{2.5}$ exposure in Shanghai during the Festival from 2013 to 2017 was 75 (95% CI: 27, 108), 92 (30, 129), 55 (18, 76), 49 (19, 70), and 31 (12, 45), respectively. Daily mortality due to $PM_{2.5}$ exposure during the Festival from 2013 to 2017 accounted for 1.4–3.8% of total daily mortality in Shanghai. This study provides scientific evidence of air quality improvement and the effectiveness of firework regulation in Shanghai.

1. Introduction

Fireworks displays are the most popular way to celebrate festivals in China, especially the Chinese Spring Festival (Festival hereafter). However, fireworks lead to severe air pollution and serious health hazards, produce large amounts of solid wastes, and can cause fires (Kumar et al., 2016; Lin, 2016). For example, pollution episodes in Beijing involving $PM_{2.5}$ concentrations even greater than on haze days were attributed to fireworks set off during the Festival (Zhang et al., 2017) and 24-h $PM_{2.5}$ levels at 315 monitoring sites in the United States were elevated on average by 42% due to Independence Day fireworks (Seidel and Birnbaum, 2015). Although particles emitted from fireworks only remain suspended in the atmosphere for hours, inhalation of fireworks smoke containing high levels of hazardous chemicals can harm human health due to frequent fireworks displays during the Festival. For example, fireworks burning was reported to be a major

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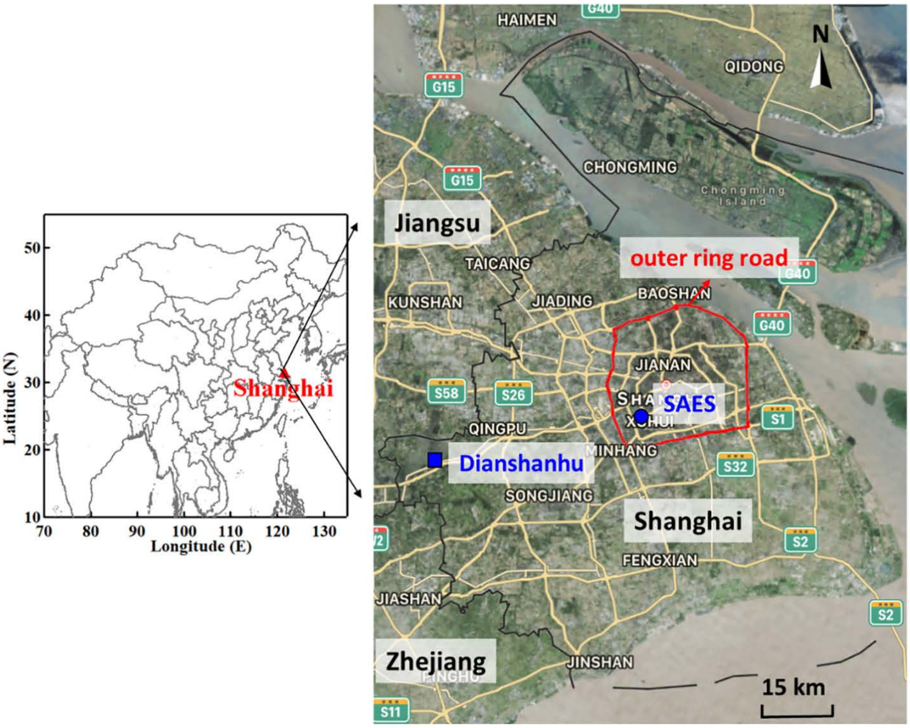

Fig. 1. Map of sampling sites in Shanghai.

source of polycyclic aromatic hydrocarbons (PAHs) during the Festival in Nanjing, and the cancer risks of PAHs were reported to be 0.68 and 3.3 per 100,000 children and adults exposed during the Festival (Kong et al., 2015a). A positive significant relationship has been found between particulate oxidative burden and individual trace metals associated with fireworks (Godri et al., 2010). Fireworks-related injuries (e.g. hand and eye injuries) have been reported around the world, including in the United States, India, Philippines, Columbia, and China (Chaparro-Narváez et al., 2017; Jing et al., 2010; John et al., 2015; Moore et al., 2014; Patel and Mukherjee, 2016; Roca et al., 2015; Wang et al., 2014a). Studies of fireworks-related injuries have reached a consistent conclusion: the largest number of injuries associated with fireworks occurs during festivals, such as the Festival in China (Wang et al., 2014a).

As a megacity, Shanghai has set out to regulate fireworks in recent years, and "Limited Fireworks" policies have been established. For example, fireworks displays were banned in some places in Shanghai during the Festival in 2014 and 2015 (http://sh.bendibao.com/news/2014126/97094.shtm and http://sh.bendibao.com/tour/201,529/124263.shtm). However, Shanghai still suffered from heavy air pollution during the Festival due to fireworks displays, especially on Festival Eve. Therefore, the Shanghai government announced stricter regulations on fireworks displays during the Festival as of January 1, 2016, which prohibited fireworks displays within the outer ring road area (urban area). Further regulatory measures were implemented over fireworks sales in 2017. For example, there were 66 points of sales with licenses for fireworks in Shanghai in 2016, whereas there were only 9 in 2017, leading to a sharp decrease in fireworks sales (http://sh.bendibao.com/news/20161222/174178.shtm).

The physicochemical profiles of fireworks have been extensively characterized, including gas-phase species (Attri et al., 2001; Drewnick et al., 2006; Huang et al., 2012a; Ravindra et al., 2003; Vecchi et al., 2008; Wang et al., 2007), chemical composition (Ambade and Ghosh, 2013; Chang et al., 2011; Cheng et al., 2014; Drewnick et al., 2006; Feng et al., 2012; Jiang et al., 2015; Jing et al., 2014; Kong et al., 2015b; Li et al., 2017; Moreno et al., 2007; Sarkar et al., 2010; Shi et al., 2014; Tian et al., 2014; Tsai et al., 2012; Wang et al., 2007; Yang et al., 2014; Zhang et al., 2017), particle size distribution (Jing et al., 2014; Joshi et al., 2016; Yang et al., 2014; Zhang et al., 2010), morphology (Agrawal et al., 2011; Li et al., 2013; Wang et al., 2007; Zheng et al., 2017), optical properties (Yu et al., 2013; Zheng et al., 2017), and source apportionment of $PM_{2.5}$ during fireworks displays (Feng et al., 2012; Huang et al., 2012a; Jiang et al., 2015; Kong et al., 2015b). Huang et al. (2012a) conducted an intensive study in Shanghai during the 2009 Festival and reported widespread usage of fireworks, causing heavy pollution due to extremely high aerosol concentrations, SO_2, and NOx. Zhang et al. (2010) investigated size distribution of particles during the 2009 Festival in Shanghai and found a clear shift of particles from nucleation and Aitken mode to small accumulation mode at the peak of the fireworks event. The chemical composition and sources of $PM_{2.5}$ during the 2009 Festival holiday in Shanghai were investigated by Feng et al. (2012). However, few studies have examined the effects of fireworks on air quality and the consequent effects on public health in a megacity using systematic observations over multiple years, to provide up-to-date information on the effectiveness of firework regulation during the Festival.

In this study, we conducted a comprehensive and systematic campaign to investigate air quality trends and fireworks impacts in Shanghai during the Festival from 2013 to 2017. Hourly $PM_{2.5}$ and gaseous pollutants were monitored at an urban site and a suburban site to investigate air quality trends. The chemical composition of $PM_{2.5}$ in Shanghai was measured to quantitatively identify the impact of fireworks during the Festival over five consecutive years. Health effects and the corresponding economic cost related to $PM_{2.5}$ pollution during the Festival are also assessed.

2. Experimental methods

2.1. Sampling site

Measurements were simultaneously conducted at an urban and suburban site in Shanghai during the Festival, 2013–2017 (Fig. 1). The outer ring road is the boundary of urban and suburban areas in Shanghai. The urban site was located on the rooftop of a five-floor building in the Shanghai Academy of Environmental Science (31.17°N, 121.43°E, SAES), which represents a typical mixed residential-commercial-transportation area (Wang et al., 2015a). The suburban site was the Dianshanhu monitoring site (31.09°N, 120.98°E), which is located in the west of Shanghai. The two sites are 45 km apart.

2.2. *Description of the festival holiday*

The Festival is the most important holiday for the Chinese, and it typically involves family reunions. Before the Festival, numerous migrant residents return to their hometowns to celebrate with their families, which is especially obvious in China's megacities. After the Festival period, they return to the city for school and work. This phenomenon is known as "Chunyun" in Chinese, or the "spring travel rush." During the Festival, factories close down and a significant reduction of vehicle numbers is usually observed, leading to a sharp decrease in air pollutants, which has been termed the holiday effect (Huang et al., 2012a; Tan et al., 2009; Zhang et al., 2017). At the same time, fireworks displays become an important pollution source during the Festival.

2.3. *Measurements*

The sampling period was 13 days long, including 3 days before the Festival, 7 days during the Festival, and 3 days after it every year from 2013 to 2017. Accordingly, the sampling periods were February 6 to 18, 2013; January 27 to February 8, 2014; February 15 to 27, 2015; February 4 to 16, 2016; and January 24 to February 5, 2017. At the urban site, $PM_{2.5}$, trace gases (SO_2, NO_2 and CO), water-soluble ions, organic carbon (OC), and element carbon (EC) were measured in 2013. $PM_{2.5}$ and trace gases were measured from 2014 to 2017. At the suburban site, $PM_{2.5}$, trace gases, water-soluble ions, OC, and EC were measured from 2014 to 2017.

At the urban site, $PM_{2.5}$ mass concentration was measured using an online particulate monitor (FH 62 C14 series, Thermo Fisher Scientific Inc., USA), which utilizes the radiometric principle of beta-attenuation using a C_{14} source (https://www.environmental-expert.com/products/model-fh-62-c14-continuous-particulate-monitor-5454) with a time resolution of 1 min. Trace gases, including SO_2, NO_2, and CO, were measured with 1 min time resolution using an SO_2 Analyzer (EC9580B, Ecotech, Australia), NO–NO_2–NOx Analyzer (Thermo scientific 42i, USA), and CO Analyzer (EC9830B, Ecotech, Australia). At the suburban site, a Thermo Fisher Scientific TEOM (1405-D, Thermo Scientific Co., MA, USA) was utilized to monitor $PM_{2.5}$ with a time resolution of 5 min. Trace gases were measured using a set of gas analyzers (Thermo, USA i-series 49i, 43i). Concentrations of $PM_{2.5}$ and trace gases were averaged every hour.

The instruments used to detect water-soluble ions and OC and EC were the same at the urban and suburban sites. Hourly concentrations of water-soluble inorganic ions, including Cl^-, NO_3^-, SO_4^{2-}, Na^+, NH_4^+, K^+, Mg^{2+}, and Ca^{2+} were detected by a commercial instrument for online Monitoring of AeRosols and Gases (MARGA, model ADI 2080, Applikon, Netherlands) equipped with a $PM_{2.5}$ cyclone at a flow rate of 16.7 L/min. A solution of LiBr as an internal standard was periodically injected and mixed with the sample solutions for subsequent detection. Multi-point calibrations of target water-soluble ions were performed before and after the campaign. The detection limits of Cl^-, NO_3^-, SO_4^{2-}, Na^+, NH_4^+, K^+, Mg^{2+}, and Ca^{2+} were 0.01, 0.05, 0.04, 0.05, 0.05, 0.09, 0.06, and 0.1 μg/m^3, respectively (based on a 45 min sampling time). Detailed principles for detecting water-soluble ions can be found in our previous study (Wen et al., 2015).

Hourly OC and EC in $PM_{2.5}$ were measured using a semi-continuous OC/EC analyzer (model RT-4, Sunset Laboratory Inc., USA), with a flow rate of 8 L/min. The analysis followed the NIOSH method 5040 and the thermal-optical transmittance (TOT) protocol for gradient pyrolysis. A parallel plate denuder with a carbon impregnated filter (CIF) was designed to remove semi-volatile organic compounds. Particles were collected on a quartz fiber filter. The filter was replaced every 3–5 days because continuous backup of refractory substances (e.g. minerals) on the filter can affect the laser correction factor, leading to errors in OC and EC separation. Before and after the campaign, OC calibration was conducted using a series of standard sucrose solutions. The precision was found to be satisfactory, with a relative standard deviation below 5%. Field blanks were analyzed to calibrate samples. EC concentrations were negligible, whereas OC concentrations ranged from 0.1 to 1.0 μg/m^3 on field blanks. The detection limit of the semi-continuous OC/EC analyzer was 0.2 and 0.04 μg/m^3 for OC and EC, respectively (based on a 45 min sampling time). The detailed principles of the OC/EC analyzer can be found elsewhere (Chang et al., 2017).

Data on meteorological factors at the suburban site from 2014 to 2017, including temperature (T), relative humidity (RH), wind speed (WS), and precipitation, were provided by Shanghai Environmental Monitoring Center.

2.4. *Potential source contribution function (PSCF)*

Potential source contribution function (PSCF), which combines measurements with air mass backward trajectory analysis, has been widely used to identify source areas for a receptor site (Han et al., 2018; Jeong et al., 2017; Jeong et al., 2013; Yao et al., 2016). The PSCF value of a grid (*i*, *j*) is defined as follows:

$$PSCF_{ij} = \frac{m_{ij}}{n_{ij}} \tag{1}$$

where m_{ij} is the number of trajectory endpoints in the grid (*i*, *j*) that corresponds to the measured concentration of a pollutant greater than a threshold value, and n_{ij} is the total number of trajectory endpoints in that grid. Higher PSCF values indicate higher potential source contributions to the receptor site. In this study, the average concentration of a pollutant was used as the threshold value (Jeong et al., 2017). Given the short time-frame for fireworks pollution, the domain of PSCF was set from 30 to 32° N and from 120 to 123° E in 0.1 × 0.1 grid cells (600 grid cells). 72-h backward trajectories were calculated for every hour each day during the Festival from 2013 to 2017 using the Hybrid Single-Particle Lagrangian Integrated Trajectory model, obtaining a total of 12,096 endpoints (72 × 24 × 7). Thus, the average number of endpoints per cell was 20. To reduce the uncertainty caused by small trajectory endpoints, the PSCF values were multiplied by a weighting function (W_{ij}), described in Eq. (2) (Yao et al., 2016):

$$W_{ij} = \begin{Bmatrix} 1.0 & 3n_{ave} < n_{ij} \\ 0.7 & n_{ave} < n_{ij} \le 3n_{ave} \\ 0.4 & \frac{2}{3}n_{ave} < n_{ij} \le n_{ave} \\ 0.2 & 0 < n_{ij} \le \frac{2}{3}n_{ave} \end{Bmatrix} \tag{2}$$

where n_{ave} is the average number of endpoints for a grid cell.

2.5. *Estimate of health effects attributable to short-term $PM_{2.5}$ exposure*

Most epidemiologic studies of short-term effects use Poisson distribution to determine the relationship of health effects and $PM_{2.5}$ concentrations, which can be described as follows (Huang et al., 2012b; Wang et al., 2015b; Xue et al., 2018)

$$\Delta E = P \times IR\left[1 - \frac{1}{exp[\beta(c - c_0)]}\right] \tag{3}$$

where ΔE denotes the number of estimated cases of mortality and morbidity; *P* is the exposed population; *IR* represents the incidence rate of the mortality or morbidity endpoints; β is the coefficient of the exposure-response function (percentage change in number of cases per

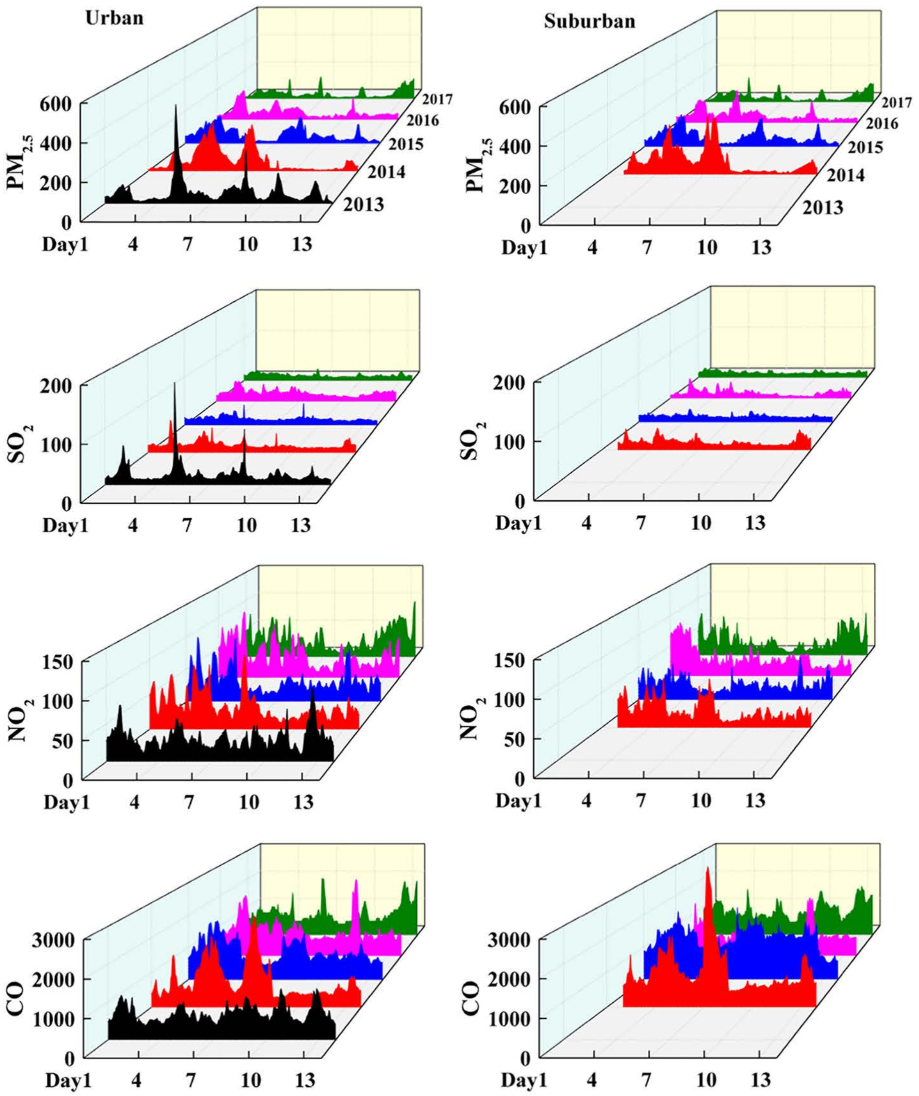

Fig. 2. Time series of $PM_{2.5}$ and trace gases at the urban site and suburban sites in Shanghai during the Festival from 2013 to 2017. Day 1 to Day 13 refer to 02/06/2013–02/18/2013, 01/27/2014–02/08/2014, 02/15/2015–02/27/2015, 02/04/2016–02/16/2016, 01/24/2017–02/05/2017, respectively.

person per 10 μg/m^3 change in $PM_{2.5}$); c is the observed $PM_{2.5}$ concentration during the Festival; and c_0 is the threshold concentration. In this study, we only accessed commonly studied health endpoints that can be quantified, including total non-accidental mortality, all-cause hospital admissions, and outpatient visits (pediatrics and internal medicine) caused by short-term $PM_{2.5}$ exposure.

3. Results and discussion

3.1. Air quality trends during the festival from 2013 to 2017

The Festival holiday is defined in this study as Festival Eve and the next six days. Time series of $PM_{2.5}$, SO_2, NO_2, and CO at the urban site and suburban site in Shanghai during the Festival from 2013 to 2017 are shown in Fig. 2. Annual average values and trends in $PM_{2.5}$, SO_2, NO_2, and CO at the urban and suburban sites are plotted in Fig. S1. The fitted lines are derived from the least square linear regression analysis and the significance levels (p) are annotated. $PM_{2.5}$ concentrations at the urban site during the Festival from 2013 to 2017 were 79 (max: 524), 94 (290), 53 (163), 50 (146), and 32 (156) μg/m^3, respectively. The annual average concentration of $PM_{2.5}$ at the urban site decreased at a rate of −13.8 μg/m^3/yr (equivalent to −17.5% per year, $p = 0.05$). Similarly, $PM_{2.5}$ concentrations at the suburban site during the Festival from 2014 to 2017 were 104 (max: 334), 58 (177), 59 (215), and 33 (174) μg/m^3, respectively, with a reduction rate of −21.2 μg/m^3/yr (equivalent to −20.4% per year, $p = 0.07$). Compared to $PM_{2.5}$, trace gases exhibited small interannual variation. For example, SO_2 at the urban and suburban sites presented a slight decreasing trend, with a rate of decrease of −2 μg/m^3/yr ($p = 0.13$) and − 1.4 μg/m^3/yr ($p = 0.16$), respectively. The maximum SO_2 concentration of 182 μg/m^3 was observed on Festival Eve in 2013. No significant variations in NO_2 and CO concentrations at the two sites were observed during the Festival during the five-year period.

Generally, high-intensity fireworks displays occurred on Festival Eve. Thus, average $PM_{2.5}$ and gas species at the urban and suburban sites in Shanghai on Festival Eve (from 18:00 to 06:00 in the next day) from 2013 to 2017 were analyzed, as shown in Fig. S2. $PM_{2.5}$ concentrations were 256, 226, 34, 89, and 17 μg/m^3 at the urban site on Festival Eve from 2013 to 2017, respectively, and 193, 49, 116, and 23 μg/m^3 at the suburban site on Festival Eve from 2014 to 2017, respectively. Linear regression results indicate that $PM_{2.5}$ at the urban site on Festival Eve from 2013 to 2017 significantly decreased, at a rate of −61.5 μg/m^3/yr ($p = 0.05$), whereas the decreasing trend of $PM_{2.5}$ was not significant at the suburban site (−44.0 μg/m^3/yr, $p = 0.25$). This difference can be largely attributed to the different firework regulation policies in urban and suburban areas in Shanghai. SO_2 was relatively high (62 μg/m^3) at the urban site on Festival Eve in 2013 and remained stable from 2014 on. For gaseous species, no significant variation trend in SO_2, NO_2, or CO was observed at the two sites.

Feng et al. collected daily $PM_{2.5}$ samples at Shanghai Environmental Monitoring Center and investigated the chemical composition of $PM_{2.5}$ on Festival Eve and Festival Day (FE&FD) in 2009 (Feng et al., 2012). Shanghai Environmental Monitoring Center is only 0.8 km away from the urban site in this study. Thus, the results presented in Feng's study are comparable to those in this study. We averaged hourly concentrations of $PM_{2.5}$ and its chemical composition at the urban site for the same sampling period as Feng's study. $PM_{2.5}$ in urban Shanghai was 255.3 μg/m^3 on FE&FD in 2009, which is 2.1 times greater than in 2013 (122 μg/m^3). Similarly, OC, EC, and inorganic ions in 2009 (21.5, 3.7 and 134.5 μg/m^3) were 2.0, 2.1, and 1.7 times the levels in 2013, respectively. Cl^- and K^+, which are closely related to fireworks displays, were 59.4 μg/m^3 and 15.7 μg/m^3, accounting for 44.2% and 20.1% of total inorganic ions during FE&FD in 2009 and 2013, respectively. Huang et al. (2012a) utilized an online instrument to measure $PM_{2.5}$ in Shanghai and observed a maximum hourly $PM_{2.5}$ concentration of over 900 μg/m^3 during the 2009 Festival, which was much higher than in 2013 (524 μg/m^3). In summary, air pollution in Shanghai during the 2009 Festival was much more serious than in 2013, and fireworks displays were definitely a dominant source of $PM_{2.5}$ during the 2009 Festival.

3.2. Overview of fireworks displays and regional impact

A large number of studies have reported a sharp increase in potassium concentrations during fireworks displays (Wang et al., 2007; Feng et al., 2012; Yang et al., 2014; Kong et al., 2015b). Thus, K^+ was used as an indicator of fireworks during the study period. K^+ concentrations in Shanghai during Festival and non-Festival periods from 2013 to 2017 are plotted in Fig. 3. K^+ was measured at the urban site in 2013 and at the suburban site from 2014 to 2017. The K^+ concentration during the non-Festival period is the average of concentrations before and after the Festival. Annual average concentrations of K^+ in Shanghai during the Festival from 2013 to 2017 were 8.2, 2.5, 2.2, 4.3, and 0.8 μg/m^3, respectively, with maximum hourly concentrations of 159.4, 14.6, 10.4, 44.2, and 4.5 μg/m^3, respectively. As shown in Fig. 3, K^+ during the Festival presented a decreasing trend with a rate of −1.3 μg/m^3/yr (p = 0.17) during the five-year period studied, whereas K^+ before and after the Festival did not show a significant decreasing or increasing trend. We compared K^+ during the Festival with the non-Festival period by the mass ratio of Festival/non-Festival concentrations, which were 6.3, 2.8, 1.6, 2.9, and 1.0 during 2013–2017, respectively. As stated earlier, the Shanghai government issued new regulations to restrict the use of fireworks in 2016; however, the K^+ concentration seems to have increased during the 2016 Festival. Thus, it is worth paying close attention to the impact of fireworks during the 2016 Festival.

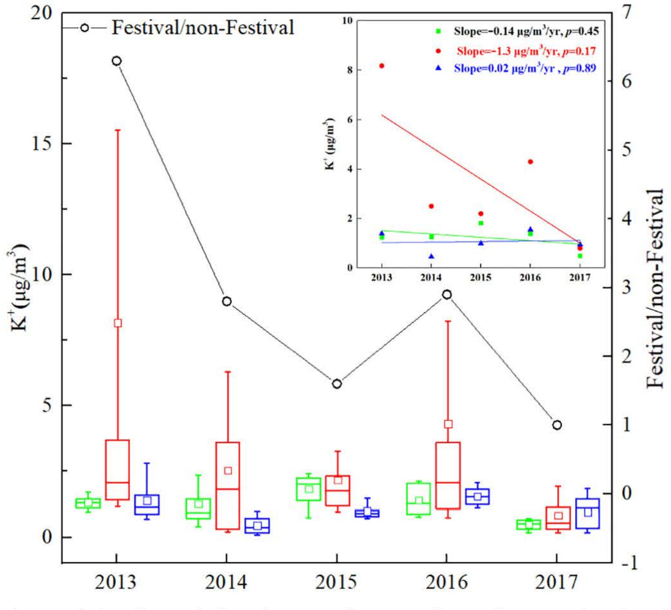

Fig. 3. K^+ distribution before the Festival (green), during the Festival (red) and after the Festival (blue) in Shanghai from 2013 to 2017. The horizontal lines show the median values, blocks show mean values, boxes show the 25th- and 75th percentile values, and whiskers show the 10th- and 90th percentile values. The fitted lines are derived from the least square linear regression analysis of average K^+ concentrations and the significance levels (p) are annotated. K^+ in 2013 was measured at the urban site and at the suburban site from 2014 to 2017. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The spatial and temporal distribution of $PM_{2.5}$ in Shanghai on Festival Eve (February 7) and Festival Day (February 8) in 2016 was investigated to compare the air quality in urban and suburban areas, as illustrated in Fig. 4. $PM_{2.5}$ concentrations in both urban and suburban areas were at low levels (mostly < 50 μg/m^3) at 18:00, February 7. After 2 h, $PM_{2.5}$ in almost all suburban areas had increased to levels exceeding the national air quality standard (75 μg/m^3), especially in north suburban areas of Shanghai ($PM_{2.5}$ > 250 μg/m^3), whereas $PM_{2.5}$ in most urban areas remained < 55 μg/m^3. As $PM_{2.5}$ concentrations in suburban areas continued to increase, $PM_{2.5}$ in urban areas exceeded 75 μg/m^3 due to transportation of pollutants from suburban areas to urban areas. For example, $PM_{2.5}$ in most suburban areas exceeded 150 μg/m^3 at 02:00, February 8, influencing $PM_{2.5}$ concentrations in urban areas, which exceeded 85 μg/m^3 (Fig. 4). It is clear that $PM_{2.5}$ in suburban areas was much higher than in urban areas in Shanghai on Festival Eve. Similar results were observed on Festival Eve in Beijing and Shenzhen (Lai and Brimblecombe, 2017). The time series of $PM_{2.5}$ and its chemical composition, gases, and meteorological parameters at the suburban site in Shanghai on Festival Eve and Festival Day in 2016 is given in Fig. S3. $PM_{2.5}$ concentrations, ranging from 44 μg/m^3 to 70 μg/m^3, were relatively low before 18:00, February 7, and NO_3^- was the most abundant $PM_{2.5}$ ingredient. Concentrations of $PM_{2.5}$ began to increase after 18:00, February 7, and reached their maximum at 07:00–09:00, February 8; the $PM_{2.5}$ chemical composition also changed. During this time, K^+ became the most abundant $PM_{2.5}$ component, followed by SO_4^{2-} and Cl^-, with maximum values of 44.2, 31.2, and 20.5 μg/m^3, respectively. It is clear that urban areas in Shanghai were affected by fireworks, despite fireworks being prohibited in urban areas in 2016.

Why was higher K^+ observed at the suburban site during the 2016 Festival compared to 2014 and 2015, given that stricter regulations on fireworks were in place in 2016? We suggest two possible reasons. Fireworks displays started to shift from urban areas to suburban areas in Shanghai in 2016, which may have led to increased fireworks display intensity in suburban areas compared to previous years, as fireworks were only allowed in suburban areas. For example, people living in urban areas may have gone to suburban areas to set off fireworks. Meteorological conditions probably played a role in the heavy pollution during the 2016 Festival Eve, because stagnant weather (very low WS, Fig. S3) is favorable for the accumulation of pollutants.

Fireworks displays are a nationwide form of entertainment during the Festival holiday. Thus, the regional impact of fireworks was studied using PSCF, because particles related to fireworks in surrounding areas may be transported to Shanghai. PSCF analyses of K^+ and $PM_{2.5}$ in Shanghai during the Festival from 2013 to 2017 are plotted in Fig. 5. Areas with PSCF values higher than 0.8 indicate significant potential source areas, and the area with a value of 0.6 indicates a moderate source area. PSCF values of K^+ and $PM_{2.5}$ were relatively low and agreed well during the 2013 Festival, which indicates that Shanghai was scarcely influenced by regional fireworks displays (Fig. 5(a) and

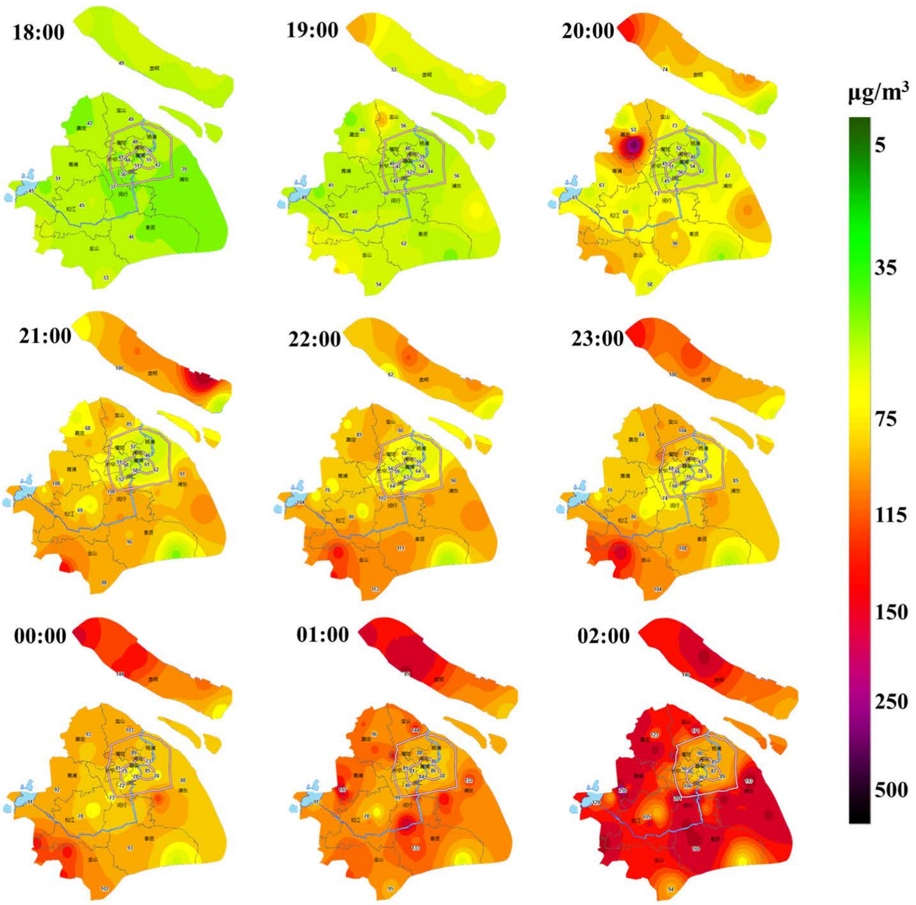

Fig. 4. Spatial and temporal distribution of $PM_{2.5}$ in Shanghai on Festival Eve (February 7) in 2016 (downloaded from Yangtze River Delta regional air quality forecast business platform).

(f)). PSCF maps of K^+ and $PM_{2.5}$ during the 2014 Festival show large differences, and the same is true for 2015 and 2016 (Fig. 5(b–d) and (g–i)). Compared to K^+, higher PSCF values (> 0.8) of $PM_{2.5}$ indicate a significant regional transportation contribution to $PM_{2.5}$ in Shanghai during the Festival in 2014–2016. Jiangsu and Anhui were significant potential source areas of $PM_{2.5}$ in Shanghai during the Festival from 2014 to 2016. PSCF maps of K^+ in 2014, 2016, and 2017 show some areas with PSCF values larger than 0.6, which implies that Shanghai was affected to some extent by fireworks from surrounding areas (Jiangsu and Anhui).

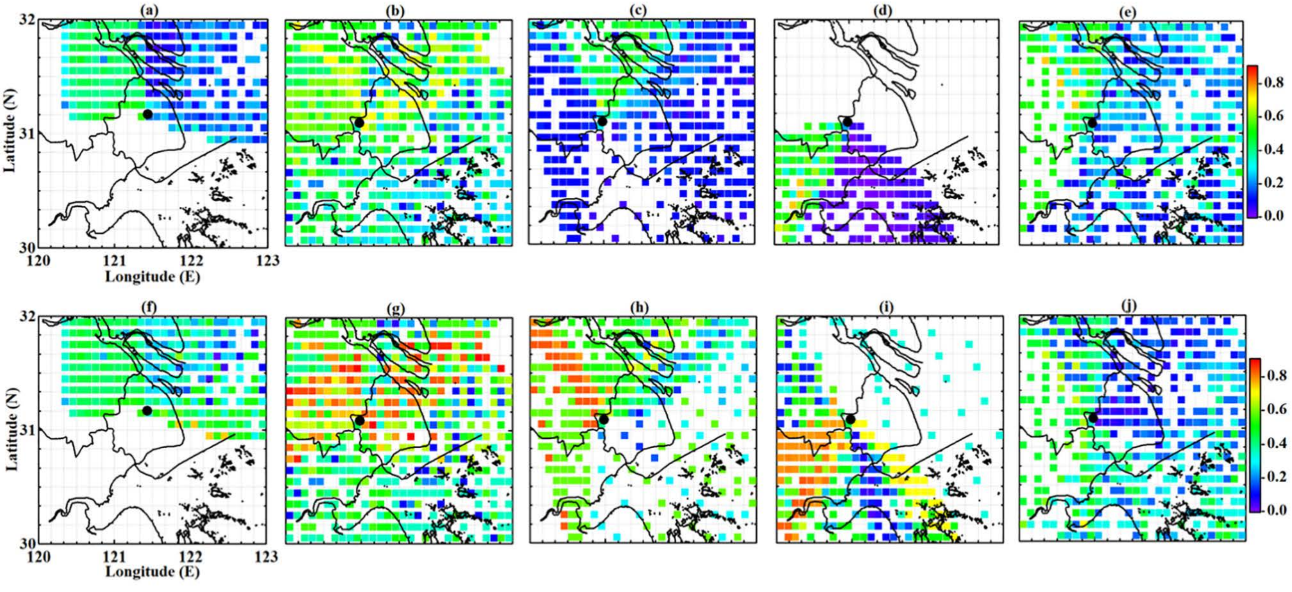

Fig. 5. PSCF analysis of K^+ (a–e) and $PM_{2.5}$ (f–j) in Shanghai during the Festival from 2013 to 2017 (dot in black indicates Shanghai).

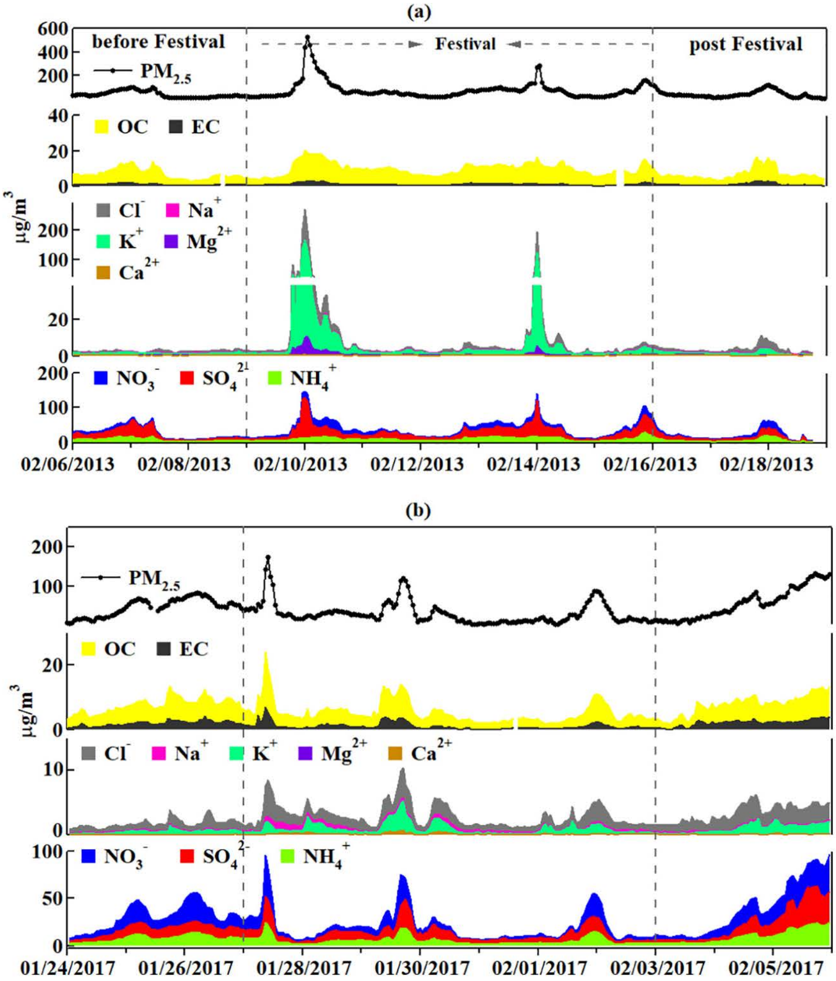

Fig. 6. Time series of $PM_{2.5}$ and its chemical composition (a) at the urban site during the Festival in 2013 and (b) at the suburban site during the Festival in 2017.

3.3. Fireworks effect and the holiday effect

As discussed previously, despite reduced industry and vehicle emissions during the Festival, Shanghai suffered serious air pollution during the 2013 Festival holiday mainly due to intensive fireworks displays (high K^+), and air quality in Shanghai significantly improved in 2017 compared to 2013. Thus, we selected the 2013 and 2017 Festivals as typical cases to investigate the fireworks effect and holiday effect, respectively. The time series of hourly $PM_{2.5}$ and its chemical composition in Shanghai around the 2013 and 2017 Festivals is presented in Fig. 6.

3.3.1. Fireworks effect

As can be seen in Fig. 6(a), $PM_{2.5}$ and its chemical components show two major peaks on February 10 (Festival Eve) and February 14 (the God of Wealth's birthday) in 2013, due to intense fireworks displays in celebration. Several small peaks of $PM_{2.5}$, K^+, and other related species were observed, indicating frequent fireworks activity during the 2013 Festival. The $PM_{2.5}$ concentration was 42 μg/m^3 at 17:00, February 9, with Cl^- of 1.6 μg/m^3 and K^+ of 2.0 μg/m^3, indicating less fireworks display activity. However, concentrations of Cl^- and K^+ at 18:00 were both 3.5 times those at 17:00. $PM_{2.5}$ concentrations continued to increase > 10-fold, with a maximum value of 524 μg/m^3 after 7 h (at 00:00, February 10). Concentrations of Cl^-, K^+, SO_4^{2-}, and Mg^{2+} simultaneously raised to their maximum, which were 100.2, 159.4, 117.5, and 10.3 μg/m^3, respectively. During the 7 h, concentrations of Mg^{2+}, K^+, Cl^-, and SO_4^{2-} increased by a factor of 124.4, 77.3, 62.2 and 12.8, respectively. Similar variations of $PM_{2.5}$ and its chemical components occurred on the God of Wealth's birthday. During the period from 17:00, February 13, to 00:00, February 14, sharp increases in $PM_{2.5}$ (from 69 to 280 μg/m^3), K^+ (from 2.0 to 118.9 μg/m^3), SO_4^{2-} (from 27.1 to 104.4 μg/m^3), Cl^- (from 0.3 to 69.0 μg/m^3), and Mg^{2+} (from 0.3 to 5.2 μg/m^3) were observed due to fireworks displays. A comparison of $PM_{2.5}$ mass balance at 17:00, February 9, and 00:00, February 10, is plotted in Fig. S4. A factor of 1.8 was adopted to convert the mass of OC into the mass of organic matter (OM) in Shanghai during winter (Xing et al., 2013). SO_4^{2-} (16.4%), NO_3^- (20.2%), NH_4^+ (13.1%), and OM (19.4%) were major chemical components of $PM_{2.5}$, at 17:00, February 9, whereas Cl^- and K^+ only accounted for 3.8% and 4.8% of $PM_{2.5}$ at this point. $PM_{2.5}$ chemical composition significantly changed due to fireworks displays. K^+, SO_4^{2-}, and Cl^- were the dominant constituents of $PM_{2.5}$ at 00:00, February 10, 2013, contributing 30.4%, 22.4%, and 19.1% of $PM_{2.5}$, respectively, whereas NO_3^-, NH_4^+, and OM accounted for relatively small proportions of $PM_{2.5}$, which were 3.5%, 2.1% and 5.9%, respectively.

Quantifying the contribution of fireworks displays to $PM_{2.5}$ is helpful for understanding the overall impact of fireworks displays during the Festival. Wang et al. developed a reliable method to quantify $PM_{2.5}$ emissions from fireworks in Beijing based on the mass ratio of $PM_{2.5}$ to CO (Wang et al., 2014b). In this study, Eq. (4) is used to calculate the contribution of fireworks to $PM_{2.5}$ in Shanghai during the Festival, as follows (Wang et al., 2014b):

$$PM_{2.5}^{f} = PM_{2.5} - PM_{2.5}^{nf} = PM_{2.5} - CO \times (PM_{2.5}/CO)_{nf} \qquad (4)$$

where $PM_{2.5}^{f}$ and $PM_{2.5}^{nf}$ are $PM_{2.5}$ concentrations attributed to fireworks and non-fireworks activities during the Festival, respectively.

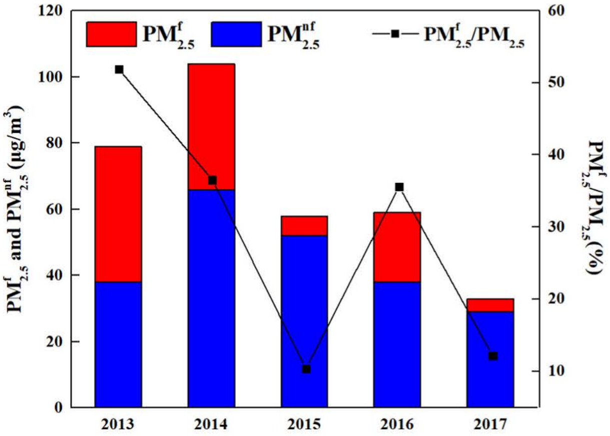

Fig. 7. Fireworks contribution to $PM_{2.5}$ in Shanghai during the Festival from 2013 to 2017.

$PM_{2.5}$ and CO are the measured concentrations of $PM_{2.5}$ and CO during Festival. $(PM_{2.5}/CO)_{nf}$ refers to the average mass ratio of $PM_{2.5}$ to CO during the non-fireworks display period (the average value before and post-Festival). Time series of the calculated $PM_{2.5}{}^{f}$ and the related species during the 2013 Festival are illustrated in Fig. S5, and the average $PM_{2.5}{}^{f}$ in Shanghai during the Festival from 2013 to 2017 are plotted in Fig. 7. It is clear from Fig. S5 that $PM_{2.5}{}^{f}$ is highly consistent with the variation in K^+, with a correlation coefficient (r^2) of 0.7. For example, similar to K^+, $PM_{2.5}{}^{f}$ concentrations peaked on Festival Eve and the God of Wealth's birthday, with concentrations of 474 μg/m^3 and 227 μg/m^3, respectively, accounting for 90.5% and 80.9% of total $PM_{2.5}$, respectively. The Festival holiday lasted for 7 days, and 168 effective hourly $PM_{2.5}$ samples were obtained during the 2013 Festival. 73% of these samples were affected by fireworks displays (Fig. S5). The average $PM_{2.5}$ concentration attributed to fireworks was 41 μg/m^3, accounting for 51.9% of total $PM_{2.5}$ in Shanghai during the 2013 Festival. Similarly, fireworks' contributions to $PM_{2.5}$ in Shanghai during the Festival in 2014, 2015, 2016, and 2017 were 38, 6, 21, and 4 μg/m^3, accounting for 36.5%, 10.3%, 35.6%, and 12.1% of $PM_{2.5}$, respectively (Fig. 7). Fireworks contributed less to $PM_{2.5}$ during the 2015 and 2017 Festivals. A high level of precipitation (13.5 mm) during the 2015 Festival may have helped to disperse fireworks pollutants, and stronger winds (Table S1) are also favorable for the diffusion of pollutants. The meteorological conditions were unfavorable for pollutant cleanup in 2017, however, because no precipitation was recorded during the Festival, and relatively low wind speeds occurred. Thus, the decreased fireworks contribution in 2017 was mainly due to the more stringent firework regulation policy.

We compared $PM_{2.5}$ and its chemical composition in Shanghai during the 2013 Festival with those in the non-Festival period in the same year. Sources of air masses during the Festival and non-Festival periods were explored by determining 72 h backward trajectories, as seen in Fig. S6. Air masses during the periods before, during, and post Festival in 2013 were similar, which indicates that the impact of meteorological factors on air pollution was comparable during these three periods. Therefore, the elevated concentrations of $PM_{2.5}$ and its chemical composition during the Festival were mainly caused by fireworks displays despite reduced industry and vehicular emissions during the Festival. Compared to the non-Festival period, $PM_{2.5}$ in Shanghai increased by 47.5% during the 2013 Festival. Similarly, increases in $SO_4{}^{2-}$ (41.4%), $NO_3{}^{-}$ (44.8%), $NH_4{}^{+}$ (40.4%), Cl^- (71.4%), and K^+ (84.1%) concentrations were observed during the 2013 Festival. EC concentrations were similar (One-Way ANOVA, $p = 0.26$) in the three periods before, during, and post Festival (0.9, 1.0, and 1.0 μg/m^3, respectively), whereas OC concentrations during the Festival (8.9 μg/m^3) were significantly higher than before (6.1 μg/m^3, One-Way ANOVA, $p \ll 0.01$) and post Festival (6.0 μg/m^3, One-Way ANOVA, $p \ll 0.01$), which may imply that more OC than EC was emitted by fireworks during the Festival. In terms of gaseous species, SO_2 increased by 27.3%, while NO_2 showed a slight decrease of 16.7% during the Festival, implying the decrease in NO_2 emissions due to a sharp decline in traffic was stronger than the increase in NO_2 emissions due to fireworks (Fig. 2) during the Festival. CO levels, which are not closely related to fireworks displays, were similar during the Festival and non-Festival periods.

3.3.2. Holiday effect

As Fig. 6(b) shows, no noticeable increase in $PM_{2.5}$ was observed at parallel points in time on Festival Eve and the God of Wealth's birthday in 2017 compared to 2013. $PM_{2.5}$ concentrations in Shanghai were < 50 μg/m^3 during these two periods. Three brief pollution episodes ($PM_{2.5}$ > 75 μg/m^3), only lasting from 4 to 6 h, were observed, with a maximum $PM_{2.5}$ of 174 μg/m^3 in Shanghai during the 2017 Festival. The three episodes, two of them peaking on Festival Eve and the God of Wealth's birthday, agreed well with K^+ variation, which may indicate individual fireworks displays during the 2017 Festival. Compared to the non-Festival period, the $PM_{2.5}$ concentration in Shanghai during the 2017 Festival decreased by 39.0%, due to a $PM_{2.5}$ of 54 μg/m^3 and 33 μg/m^3 during non-Festival and Festival periods, respectively. $NO_3{}^{-}$ and its precursor NO_2 both decreased by 58% during the 2017 Festival due to the reduction of vehicular emissions, suggesting the importance of controlling vehicle emissions to mitigate air pollution in megacities (Huang et al., 2012a). Compared to $NO_3{}^{-}$, $SO_4{}^{2-}$ decreased less (29.6%) during the Festival, which is partly because $SO_4{}^{2-}$ was mainly produced from secondary formation over a regional scale and was less affected by local formation (Jiang et al., 2015). $NH_4{}^{+}$ presented a reduction (39.8%) between $NO_3{}^{-}$ and $SO_4{}^{2-}$, which can be easily explained by noting that ammonium primarily existed in the form of $(NH_4)_2SO_4$ and NH_4NO_3.

In terms of carbonaceous species, EC (45.0%) decreased by a larger percentage than OC (23.9%) during the 2017 Festival. OC/EC ratios during, before, and post Festival were 4.9, 3.2, and 2.9, respectively. Results from One-way ANOVA indicate that the OC/EC ratio during the Festival was significantly higher than in the non-Festival period ($p < 0.01$). OC/EC ratios are influenced by emission sources, secondary organic aerosol formation, and different OC/EC deposition rates. The higher OC/EC ratio during the Festival is unlikely to be associated with secondary formation, due to weak photochemical reaction during winter. It possibly resulted from large variation in emission sources during the Festival and non-Festival periods. Cao et al. (2005) report that the average OC/EC ratio is 12.0 for coal-combustion, 4.1 for vehicle exhaust, and 60.3 for biomass burning. However, OC/EC ratios of 2.7 for coal-combustion, 1.1 for motor vehicles, and 9.0 for biomass burning have been reported elsewhere (Watson et al., 2001). Despite differences in absolute OC/EC values, it is clear that vehicular sources lead to lower OC/EC ratios. Thus, higher OC/EC ratios during the Festival may be due to a sharp decline in vehicle emissions.

3.4. Health effects of $PM_{2.5}$ during the festival

Given that $PM_{2.5}$ was only measured at two sites in this study, we used the average $PM_{2.5}$ concentration from 10 monitoring sites distributed in urban and suburban areas in Shanghai as the value of c in Eq. (3) to estimate health effects related to $PM_{2.5}$ exposure in Shanghai during the Festival. Data on daily $PM_{2.5}$ in Shanghai during the Festival from 2013 to 2017 were downloaded from the official website of Shanghai Environmental Monitoring Center (http://www.semc.gov.cn/aqi/home/Index.aspx), as listed in Table S2. Previous studies found that relatively low levels of ambient particles were consistently associated with daily mortality and hospital admissions, indicating that there may be no health effect threshold concentration for $PM_{2.5}$ (Morgan et al., 2003; Pope III, 2000). Thus, we set c_0 at zero (Huang et al., 2012b;

Table 1

Exposure-response coefficients of health outcomes due to short-term $PM_{2.5}$ exposure.

Health endpoints	β (%)	95% CI	References
Total non-accidental mortality	0.17	(0.02, 0.35)	(Chen et al., 2013)
	0.30	(0.06, 0.54)	(Huang et al., 2009)
	0.85	(0.32, 1.39)	(Song et al., 2008)
	0.36	(0.11, 0.61)	(Kan et al., 2007)
	0.47	(0.22, 0.72)	(Chen et al., 2011)
	0.43[a]	(0.18, 0.82)[a]	
All-cause hospital admissions	0.19	(0.18, 0.20)	(Liu et al., 2018)
Outpatient visits			
Internal medicine	0.49	(0.27, 0.7)	(Xie et al., 2014)
Pediatrics	0.56	(0.2, 0.9)	(Xie et al., 2014)

CI: Confidence intervals.

[a] Average value, presented as % change per 10 μg/m^3 increase in $PM_{2.5}$ concentration.

Wang et al., 2015b). The Festival holiday is usually in the early part of the year (January or February); thus, *P* and *IR* refer to data from 2012 to 2016, respectively. The population of Shanghai was 23.8 million in 2012, 24.15 million in 2013, 24.26 million in 2014, 24.15 million in 2015, and 24.2 million in 2016 (China Statistical Yearbook 2013, 2014, 2015, 2016, 2017).

The exposure-response coefficient, β, is a significant parameter for estimating health effects. The principle of selecting β related to short-term $PM_{2.5}$ exposure gives priority to studies performed in Shanghai, then Yangtze River Delta and megacities in China, because large differences in results have been reported in China and abroad. The exposure-response coefficients used in this study are listed in Table 1. The annual incidence rate of the selected health endpoints in each year in Shanghai was sourced from the National Health and Family Planning Yearbook (NHFPC, 2013, 2014, 2015, 2016, 2017). Given that accidental death is not related to $PM_{2.5}$ exposure, total non-accidental mortality rate was calculated based on total mortality rate and accidental death rate (NHFPC, 2013, 2014, 2015, 2016, 2017). Daily incidence rate was obtained from the annual incidence rate, divided by 365 (Table S3). Next, the health outcomes were calculated each day based on daily $PM_{2.5}$ in Shanghai during the Festival. The sum of daily health effects indicated the health effects during the seven-day Festival each year from 2013 to 2017.

Table 2 lists the calculated health effects related to $PM_{2.5}$ exposure in Shanghai during the Festival from 2013 to 2017 based on Poisson regression. The number of premature deaths related to short-term $PM_{2.5}$ exposure in Shanghai during the Festival from 2013 to 2017 was 75 (95% CI: 27, 108), 92 (30, 129), 55 (18, 76), 49 (19, 70), and 31 (12, 45), respectively. Taking 2013 as an example, the total number of deaths in Shanghai was 126,546 in 2013, which is calculated as the population multiplied by the total mortality rate (NHFPC, 2014). Thus, daily average deaths were 347 in Shanghai, 2013. The number of daily deaths related to $PM_{2.5}$ exposure during the Festival therefore accounted for 3.1% of total daily deaths in Shanghai, 2013. Similarly, the percentage ranged from 1.3% to 3.8% in 2014–2017. Linear regression results indicate that the number of premature deaths during the Festival from 2013 to 2017 shows a decreasing trend, at a rate of −13.1 cases/yr ($p = 0.05$), which is equivalent to two cases/day, accounting for 5.8‰ of daily total deaths in Shanghai (in 2013). 794 (755, 835), 985 (934, 1035), 607 (576, 641), 611 (580, 642), and 408 (384, 429) cases of hospital admission were associated with short-term $PM_{2.5}$ exposure in Shanghai during the Festival from 2013 to 2017, respectively. Statistically, there were 2,910,404 cases of hospital admission in Shanghai in 2013, which averages to 7974 per day (NHFPC, 2014). Thus, daily hospital admissions related to $PM_{2.5}$ pollution during the Festival accounted for 1.4% of daily total hospital admissions in Shanghai. $PM_{2.5}$-associated internal medicine and pediatrics outpatient visits ranged from 2908 (1610, 4137) to 7695 (4312, 10,828) cases and from 956 (346, 1524) to 2577 (946, 4038) cases during the Festival from 2013 to 2017, respectively.

The average economic cost was 1,510,000 Chinese Yuan (CNY) for deaths (Chen et al., 2010), 17,112 CNY for hospital admissions (NHFPC, 2017), and 340 CNY for outpatient visits per case in Shanghai (NHFPC, 2017). Thus, the consequent health-based economic loss in Shanghai during the Festival from 2013 to 2017 was 129.7, 159.3, 95.6, 86.6, and 55.1 million CNY, respectively. The economic loss related to premature deaths accounted for 86% of total economic loss associated with $PM_{2.5}$ exposure during the Festival. In 2013, Shanghai's GDP (gross domestic product) was 2,180,000 million CNY, with a daily GDP of 5972 million CNY. Thus, daily economic loss due to $PM_{2.5}$ exposure during the Festival accounted for 3.1‰ of the daily GDP of Shanghai in 2013, and ranged from 1.3 to 3.8‰ from 2014 to 2017.

The estimates of health effects made in this study have some limitations. Only health effects that can be quantified were considered, leading to an underestimate of the actual economic benefits of firework regulation. It is noteworthy that $PM_{2.5}$ was closely related to fireworks during the Festival in this study. $PM_{2.5}$ emitted from fireworks may be more toxic than $PM_{2.5}$ examined in epidemiological studies, which may lead to underestimates of health and economic benefits. As a cultural phenomenon, a number of people left Shanghai and returned to their hometown to celebrate the Festival. Thus, the actual exposed population is less than the population reported in the statistical yearbook, causing an overestimation of health effects. The threshold concentration of $PM_{2.5}$ is still undetermined, and has been thus set differently in previous studies. For example, c_0, the threshold concentration, was set at zero in some previous studies due to the lack of a health effect threshold concentration for atmospheric $PM_{2.5}$ (Huang et al., 2012b; Wang et al., 2015b). c_0 ranged from 5.8 μg/m^3 to 8.8 μg/m^3 in the Global Burden of Disease Study (Burnett et al., 2014; Lim et al., 2012) and World Health Organization Air Quality Guidelines (10 μg/m^3) have also been widely used as the threshold value of $PM_{2.5}$ (Jahn et al., 2011). In this study, c_0 was set as zero, which may overestimate the health and economic benefits of firework regulation. Poisson regression model assumed that the population in Shanghai was exposed to the same $PM_{2.5}$ concentrations. However, $PM_{2.5}$ concentrations actually exhibited large differences in spatial distribution, as shown in Fig. 4.

Table 2

Health effects attributed to short-term $PM_{2.5}$ exposure in Shanghai during the Festival, 2013–2017, mean value (95% CI).

Health outcomes	2013	2014	2015	2016	2017
Total non-accidental mortality	75 (27,108)	92 (30,129)	55 (18,76)	49 (19,70)	31 (12,45)
All-cause hospital admissions	794 (755,835)	985 (934,1035)	607 (576,641)	611 (580,642)	408 (384,429)
Outpatient visits					
Internal medicine	6306 (3516,8911)	7695 (4312,10,828)	4800 (2668,6806)	4774 (2649,6774)	2908 (1610,4137)
Pediatrics	2116 (770,3339)	2577 (946,4038)	1577 (572,2501)	1579 (572,2508)	956 (346,1524)

The population distribution also exhibited significant spatial variation. Population-weighted average $PM_{2.5}$ concentrations should therefore be used in future studies to estimate $PM_{2.5}$-related health effects.

4. Conclusions

This study made use of online measurements of $PM_{2.5}$ and its chemical composition to investigate the effect of firework regulation on air quality and the consequent health effects in Shanghai during the Festival from 2013 to 2017. Its conclusions are as follows.

Significant air quality improvement was revealed by a decreasing trend of $PM_{2.5}$ concentrations in Shanghai during Festivals from 2013 to 2017. $PM_{2.5}$ concentrations at the urban site were 79 (max: 524), 94 (290), 53 (163), 50 (146), and 32 (156) $\mu g/m^3$, with a reduction rate of $-13.8\,\mu g/m^3/yr$ ($p = 0.05$). Similarly, $PM_{2.5}$ concentrations at the suburban site presented a downward trend beginning in 2014 ($-21.3\,\mu g/m^3/yr$, $p = 0.07$).

Fireworks were a significant source of $PM_{2.5}$ in Shanghai during the Festival. $PM_{2.5}$ concentrations in Shanghai increased over 10-fold within a few hours on Festival Eve, due to fireworks displays. Fireworks made an average contribution of 51.9% to $PM_{2.5}$ in Shanghai during the 2013 Festival, with a maximum hourly contribution of 90.5%. The Festival holiday lasted for 168 h, and 73% of this duration was impacted by fireworks.

Fireworks displays in Shanghai were effectively controlled during the Festival in 2017. K^+ levels, an indicator of fireworks displays, were 8.2 (max: 159.4), 2.5 (14.6), 2.2 (10.4), 4.3 (44.2), and 0.8 (4.5) $\mu g/m^3$ during Festivals from 2013 to 2017, respectively, presenting a downward trend at a rate of $-1.3\,\mu g/m^3/yr$ ($p = 0.17$). Similarly, fireworks contributed 41, 38, 6, 21, and 4 $\mu g/m^3$ to $PM_{2.5}$, respectively. A significant holiday effect was observed during the 2017 Festival largely due to a decrease in fireworks displays and a reduction in industry and vehicular emissions, as revealed by a 39% reduction in $PM_{2.5}$ during the Festival compared to the non-Festival period.

The improved air quality during the Festival in Shanghai resulted in less health burden. The number of premature deaths in Shanghai during the Festival for the period 2013–2017 was 75 (95% CI: 27, 108), 92 (30, 129), 55 (18, 76), 49 (19, 70), and 31 (12, 45), respectively, showing a decreasing trend at a rate of −13.1 cases/yr (equivalent to 2 cases/day, $p = 0.05$).

This study has some limitations. For example, meteorological parameters were not measured at the urban site. Health effects assessment based on Poisson regression involves some uncertainties, as discussed in Section 3.4. Nevertheless, the findings provide scientific evidence for the effectiveness of firework regulation for improving air quality and thus public health in Shanghai during the Festival. Shanghai's successful experience in improving air quality during the Festival can serve as a reference point for other cities' efforts to curb air pollution due to fireworks.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2019.01.037.

References

Agrawal, A., Upadhyay, V.K., Sachdeva, K., 2011. Study of aerosol behavior on the basis of morphological characteristics during festival events in India. Atmos. Environ. 45, 3640–3644. https://doi.org/10.1016/j.atmosenv.2011.04.006.

Ambade, B., Ghosh, S., 2013. Characterization of PM_{10} in the ambient air during Deepawali festival of Rajnandgaon district. India. Nat. Hazards 69, 589–598. https://doi.org/10.1007/s11069-013-0725-8.

Attri, A.K., Kumar, U., Jain, V.K., 2001. Formation of ozone by fireworks. Nature 411, 1015. https://doi.org/10.1038/35082634.

Burnett, R.T., Arden Pope III, C., Ezzati, M., Olives, C., Lim, S.S., Mehta, S., et al., 2014. An integrated risk function for estimating the global burden of disease attributable to ambient fine particulate matter exposure. Environ. Health Perspect. 122, 397–403. https://doi.org/10.1289/ehp.1307049.

Cao, J.J., Wu, F., Chow, J.C., Lee, S.C., Li, Y., Chen, S.W., et al., 2005. Characterization and source apportionment of atmospheric organic and elemental carbon during fall and winter of 2003 in Xi'an, China. Atmos. Chem. Phys. 5, 3127–3137. https://doi.org/10.5194/acp-5-3127-2005.

Chang, S.C., Lin, T.H., Young, C.Y., Lee, C.T., 2011. The impact of ground-level fireworks (13 km long) display on the air quality during the traditional Yanshui Lantern Festival in Taiwan. Environ. Monit. Assess. 172, 463–479. https://doi.org/10.1007/s10661-010-1347-1.

Chang, Y.H., Deng, C.R., Cao, F., Cao, C., Zou, Z., Liu, S.D., et al., 2017. Assessment of carbonaceous aerosols in Shanghai, China - part 1: long-term evolution, seasonal variations, and meteorological effects. Atmos. Chem. Phys. 17, 9945–9964. https://doi.org/10.5194/acp-17-9945-2017.

Chaparro-Narváez, P., Cotes-Cantillo, K., Castañeda-Orjuela, C., De la Hoz-Restrepo, F., 2017. Injuries due to fireworks use: a surveillance data analysis in Colombia, 2008–2013. Burns 43, 149–156. https://doi.org/10.1016/j.burns.2016.07.005.

Chen, R.J., Chen, B.H., Kan, H.D., 2010. Health impact assessment of surface ozone pollution in Shanghai. China Environ. Sci. 30, 603–608 (in Chinese).

Chen, R.J., Li, Y., Ma, Y.J., Pan, G.W., Zeng, G., Xu, X.H., et al., 2011. Coarse particles and mortality in three Chinese cities: the China air pollution and health effects study (CAPES). Sci. Total Environ. 409, 4934–4938. https://doi.org/10.1016/j.scitotenv.2011.08.058.

Chen, R., Wang, X., Meng, X., Hua, J., Zhou, Z., Chen, B., et al., 2013. Communicating air pollution-related health risks to the public: An application of the Air Quality Health Index in Shanghai, China. Environ. Int. 51, 168–173. https://doi.org/10.1016/j.envint.2012.11.008.

Cheng, Y., Engling, G., He, K.B., Duan, F.K., Du, Z.Y., Ma, Y.L., Liang, L.L., Lu, Z.F., Liu, J.M., Zheng, M., Weber, R.J., 2014. The characteristics of Beijing aerosol during two distinct episodes: impacts of biomass burning and fireworks. Environ. Pollut. 185, 149–157. https://doi.org/10.1016/j.envpol.2013.10.037.

Drewnick, F., Hings, S.S., Curtius, J., Eerdekens, G., Williams, J., 2006. Measurement of fine particulate and gas-phase species during the New Year's fireworks 2005 in Mainz, Germany. Atmos. Environ. 40, 4316–4327. https://doi.org/10.1016/j.atmosenv.2006.03.040.

Feng, J., Sun, P., Hu, X., Zhao, W., Wu, M., Fu, J., 2012. The chemical composition and sources of $PM_{2.5}$ during the 2009 Chinese New Year's holiday in Shanghai. Atmos. Res. 118, 435–444. https://doi.org/10.1016/j.atmosres.2012.08.012.

Godri, K.J., Green, D.C., Fuller, G.W., Dall'Osto, M., Beddows, D.C., Kelly, F.J., et al., 2010. Particulate oxidative burden associated with firework activity. Environ. Sci. Technol. 44, 8295–8301. https://doi.org/10.1021/es1016284.

Han, T., Yao, L., Liu, L., Xian, A., Chen, H., Dong, W., Chen, J., 2018. Baosteel emission control significantly benefited air quality in Shanghai. J. Environ. Sci. https://doi.org/10.1016/j.jes.2018.01.014.

Huang, W., Tan, J.G., Kan, H.D., Zhao, N., Song, W.M., Song, G.X., et al., 2009. Visibility, air quality and daily mortality in Shanghai, China. Sci. Total Environ. 407, 3295–3300. https://doi.org/10.1016/j.scitotenv.2009.02.019.

Huang, K., Zhuang, G., Lin, Y., Wang, Q., Fu, J.S., Zhang, R., et al., 2012a. Impact of anthropogenic emission on air quality over a megacity-revealed from an intensive atmospheric campaign during the Chinese Spring Festival. Atmos. Chem. Phys. 12, 11631–11645. https://doi.org/10.5194/acp-12-11631-2012.

Huang, D.S., Xu, J.H., Zhang, S.Q., 2012b. Valuing the health risks of particulate air pollution in the Pearl River Delta, China. Environ. Sci. Pol. 15, 38–47. https://doi.org/10.1016/j.envsci.2011.09.007.

Jahn, H.J., Schneider, A., Breitner, S., Eißner, R., Wendisch, M., Krämer, A., 2011. Particulate matter pollution in the megacities of the Pearl River Delta, China – a systematic literature review and health risk assessment. Int. J. Hyg. Environ. Health 214, 281–295. https://doi.org/10.1016/j.ijheh.2011.05.008.

Jeong, U., Lee, H., Kim, J., Kim, W., Hong, H., Song, C.K., 2013. Determination of the inter-annual and spatial characteristics of the contribution of long-range transport to SO_2 levels in Seoul between 2001 and 2010 based on conditional potential source contribution function (CPSCF). Atmos. Environ. 70, 307–317. https://doi.org/10.1016/j.atmosenv.2013.01.009.

Jeong, U., Kim, J., Lee, H., Lee, Y.G., 2017. Assessing the effect of long-range pollutant transportation on air quality in Seoul using the conditional potential source contribution function method. Atmos. Environ. 150, 33–44. https://doi.org/10.1016/j.atmosenv.2016.11.017.

Jiang, Q., Sun, Y.L., Wang, Z., Yin, Y., 2015. Aerosol composition and sources during the Chinese Spring Festival: fireworks, secondary aerosol, and holiday effects. Atmos. Chem. Phys. 15, 6023–6034.

Jing, Y., Yi-qiao, X., Yan-ning, Y., Ming, A., An-huai, Y., Lian-hong, Z., 2010. Clinical analysis of firework-related ocular injuries during Spring Festival 2009. Graefes Arch. Clin. Exp. Ophthalmol. 248, 333–338. https://doi.org/10.1007/s00417-009-1292-2.

Jing, H., Li, Y.F., Zhao, J., Li, B., Sun, J., Chen, R., Gao, Y., Chen, C., 2014. Wide-range particle characterization and elemental concentration in Beijing aerosol during the 2013 Spring Festival. Environ. Pollut. 192, 204–211. https://doi.org/10.1016/j.envpol.2014.06.003.

John, D., Philip, S.S., Mittal, R., John, S.S., Paul, P., 2015. Spectrum of ocular firework injuries in children: a 5-year retrospective study during a festive season in Southern India. Indian J. Ophthalmol. 63, 843–846. https://doi.org/10.4103/0301-4738.171966.

Joshi, M., Khan, A., Anand, S., Sapra, B.K., 2016. Size evolution of ultrafine particles: differential signatures of normal and episodic events. Environ. Pollut. 208, 354–360. https://doi.org/10.1016/j.envpol.2015.10.001.

Kan, H.D., London, S.J., Chen, G.H., Zhang, Y.H., Song, G.X., Zhao, N.Q., et al., 2007. Differentiating the effects of fine and coarse particles on daily mortality in Shanghai, China. Environ. Int. 33, 376–384. https://doi.org/10.1016/j.envint.2006.12.001.

Kong, S., Li, X., Li, L., Yin, Y., Chen, K., Yuan, L., et al., 2015a. Variation of polycyclic aromatic hydrocarbons in atmospheric $PM_{2.5}$ during winter haze period around 2014 Chinese Spring Festival at Nanjing: insights of source changes, air mass direction and firework particle injection. Sci. Total Environ. 520, 59–72. https://doi.org/10.1016/j.scitotenv.2015.03.001.

Kong, S., Li, L., Li, X.X., Yin, Y., Chen, K., Liu, D.T., et al., 2015b. The impacts of firework burning at the Chinese Spring Festival on air quality: insights of tracers, source evolution and aging processes. Atmos. Chem. Phys. 15, 2167–2184. https://doi.org/10.5194/acp-15-2167-2015.

Kumar, M., Singh, R.K., Murari, V., Singh, A.K., Singh, R.S., Banerjee, T., 2016. Fireworks induced particle pollution: a spatio-temporal analysis. Atmos. Res. 180, 78–91. https://doi.org/10.1016/j.atmosres.2016.05.014.

Lai, Y.H., Brimblecombe, P., 2017. Regulatory effects on particulate pollution in the early hours of Chinese New Year, 2015. Environ. Monit. Assess. 189, 14. https://doi.org/10.1007/s10661-017-6167-0.

Li, W., Shi, Z., Yan, C., Yang, L., Dong, C., Wang, W., 2013. Individual metal-bearing particles in a regional haze caused by firecracker and firework emissions. Sci. Total Environ. 443, 464–469. https://doi.org/10.1016/j.scitotenv.2012.10.109.

Li, J., Xu, T., Lu, X., Chen, H., Nizkorodov, S.A., Chen, J., Yang, X., Mo, Z., Chen, Z., Liu, H., Mao, J., Liang, G., 2017. Online single particle measurement of fireworks pollution during Chinese New Year in Nanning. J. Environ. Sci. 53, 184–195. https://doi.org/10.1016/j.jes.2016.04.021.

Lim, S.S., Vos, T., Flaxman, A.D., Danaei, G., Shibuya, K., Adair-Rohani, H., et al., 2012. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. Lancet 380, 2224–2260. https://doi.org/10.1016/S0140-6736(12)61766-8.

Lin, C.C., 2016. A review of the impact of fireworks on particulate matter in ambient air. J. Air Waste Manage. Assoc. 66, 1171–1182. https://doi.org/10.1080/10962247.2016.1219280.

Liu, H., Tian, Y.H., Xiang, X., Juan, J., Song, J., Cao, Y.Y., et al., 2018. Ambient particulate matter concentrations and hospital admissions in 26 of China's largest cities: a case-crossover study. Epidemiology 29, 649–657. https://doi.org/10.1097/ede.0000000000000869.

Moore, J.X., McGwin Jr., G., Griffin, R.L., 2014. The epidemiology of firework-related injuries in the United States: 2000–2010. Injury 45, 1704–1709. https://doi.org/10.1016/j.injury.2014.06.024.

Moreno, T., Querol, X., Alastuey, A., Cruz Minguillón, M., Pey, J., Rodriguez, S., Vicente Miró, J., Felis, C., Gibbons, W., 2007. Recreational atmospheric pollution episodes: inhalable metalliferous particles from firework displays. Atmos. Environ. 41, 913–922. https://doi.org/10.1016/j.atmosenv.2006.09.019.

Morgan, G., Lincoln, D., Sheppeard, V., Jalaludn, B., Beard, J.F., Simpson, R., et al., 2003. The effects of low level air pollution on daily mortality and hospital admissions in Sydney, Australia, 1994 to 2000. Epidemiology 14, S111–S112. https://doi.org/10.1097/00001648-200309001-00269.

NHFPC, 2013, 2014, 2015, 2016, 2017. National Health and Family Planning Yearbook. Peking Union Medical College Press, Beijing.

Patel, R., Mukherjee, B., 2016. Crash and burn: ocular injuries due to fireworks. Semin. Ophthalmol. 31, 243–248. https://doi.org/10.3109/08820538.2014.962157.

Pope III, C.A., 2000. Invited commentary: particulate matter-mortality exposure-response relations and threshold. Am. J. Epidemiol. 152, 407–412. https://doi.org/10.1093/aje/152.5.407.

Ravindra, K., Mor, S., Kaushik, C.P., 2003. Short-term variation in air quality associated with firework events: a case study. J. Environ. Monit. 5, 260–264. https://doi.org/10.1039/b211943a.

Roca, J.B., de los Reyes, V.C., Racelis, S., Deveraturda, I., Sucaldito, M.N., Tayag, E., O'Reilly, M., 2015. Fireworks-related injury surveillance in the Philippines: trends in 2010–2014. West. Pac. Surveill. Response J. 6, 1–6. https://doi.org/10.5365/WPSAR.2015.6.1.014.

Sarkar, S., Khillare, P.S., Jyethi, D.S., Hasan, A., Parween, M., 2010. Chemical speciation of respirable suspended particulate matter during a major firework festival in India. J. Hazard. Mater. 184, 321–330. https://doi.org/10.1016/j.jhazmat.2010.08.039.

Seidel, D.J., Birnbaum, A.N., 2015. Effects of Independence Day fireworks on atmospheric concentrations of fine particulate matter in the United States. Atmos. Environ. 115, 192–198. https://doi.org/10.1016/j.atmosenv.2015.05.065.

Shi, G.L., Liu, G.R., Tian, Y.Z., Zhou, X.Y., Peng, X., Feng, Y.C., 2014. Chemical characteristic and toxicity assessment of particle associated PAHs for the short-term anthropogenic activity event: during the Chinese New Year's Festival in 2013. Sci. Total Environ. 482–483, 8–14. https://doi.org/10.1016/j.scitotenv.2014.02.107.

Song, W., Guo, H., Dai, H., 2008. A time-series study on the effects of $PM_{2.5}$ on daily mortality in Shanghai. Epidemiology 19, S167.

Tan, P.H., Chou, C., Liang, J.Y., Chou, C.C.K., Shiu, C.J., 2009. Air pollution "holiday effect" resulting from the Chinese New Year. Atmos. Environ. 43, 2114–2124. https://doi.org/10.1016/j.atmosenv.2009.01.037.

Tian, Y.Z., Wang, J., Peng, X., Shi, G.L., Feng, Y.C., 2014. Estimation of the direct and indirect impacts of fireworks on the physicochemical characteristics of atmospheric PM_{10} and $PM_{2.5}$. Atmos. Chem. Phys. 14, 9469–9479.

Tsai, H.H., Chien, L.H., Yuan, C.S., Lin, Y.C., Jen, Y.H., Ie, I.R., 2012. Influences of fireworks on chemical characteristics of atmospheric fine and coarse particles during Taiwan's Lantern Festival. Atmos. Environ. 62, 256–264. https://doi.org/10.1016/j.atmosenv.2012.08.012.

Vecchi, R., Bernardoni, V., Cricchio, D., D'Alessandro, A., Fermo, P., Lucarelli, F., Nava, S., Piazzalunga, A., Valli, G., 2008. The impact of fireworks on airborne particles. Atmos. Environ. 42, 1121–1132. https://doi.org/10.1016/j.atmosenv.2007.10.047.

Wang, Y., Zhuang, G., Xu, C., An, Z., 2007. The air pollution caused by the burning of fireworks during the lantern festival in Beijing. Atmos. Environ. 41, 417–431. https://doi.org/10.1016/j.atmosenv.2006.07.043.

Wang, C., Zhao, R., Du, W.L., Ning, F.G., Zhang, G.A., 2014a. Firework injuries at a major trauma and burn center: a five-year prospective study. Burns 40, 305–310. https://doi.org/10.1016/j.burns.2013.06.007.

Wang, Z., Wang, Z.F., Zheng, H.T., 2014b. A new method to estimate the impacts of fireworks on airborne $PM_{2.5}$. Environ. Monit. China 30 (3), 31–36 (in Chinese).

Wang, H.L., Qiao, L.P., Lou, S.R., Zhou, M., Chen, J.M., Wang, Q., et al., 2015a. $PM_{2.5}$ pollution episode and its contributors from 2011 to 2013 in urban Shanghai, China. Atmos. Environ. 123, 298–305. https://doi.org/10.1016/j.atmosenv.2015.08.018.

Wang, J., Wang, S., Voorhees, A.S., Zhao, B., Jang, C., Jiang, J., et al., 2015b. Assessment of short-term $PM_{2.5}$-related mortality due to different emission sources in the Yangtze River Delta, China. Atmos. Environ. 123, 440–448. https://doi.org/10.1016/j.atmosenv.2015.05.060.

Watson, J.G., Chow, J.C., Houck, J.E., 2001. $PM_{2.5}$ chemical source profiles for vehicle exhaust, vegetative burning, geological material, and coal burning in Northwestern Colorado during 1995. Chemosphere 43, 1141–1151. https://doi.org/10.1016/S0045-6535(00)00171-5.

Wen, L., Chen, J., Yang, L., Wang, X., Caihong, X., Sui, X., et al., 2015. Enhanced formation of fine particulate nitrate at a rural site on the North China Plain in summer: the important roles of ammonia and ozone. Atmos. Environ. 101, 294–302. https://doi.org/10.1016/j.atmosenv.2014.11.037.

Xie, Y.B., Chen, J., Li, W., 2014. An assessment of $PM_{2.5}$ related health risks and impaired values of Beijing residents in a consecutive high-level exposure during heavy haze days. Environ. Sci. 35, 1–8 (in Chinese).

Xing, L., Fu, T.M., Cao, J.J., Lee, S.C., Wang, G.H., Ho, K.F., Cheng, M.C., You, C.F., Wang, T.J., 2013. Seasonal and spatial variability of the OM/OC mass ratios and high regional correlation between oxalic acid and zinc in Chinese urban organic aerosols. Atmos. Chem. Phys. 13, 4307–4318.

Xue, X.X., Chen, J.P., Sun, B.J., Zhou, B.S., Li, X.L., 2018. Temporal trends in respiratory mortality and short-term effects of air pollutants in Shenyang, China. Environ. Sci. Pollut. Res. 25, 11468–11479. https://doi.org/10.1007/s11356-018-1270-5.

Yang, L., Gao, X., Wang, X., Nie, W., Wang, J., Gao, R., Xu, P., Shou, Y., Zhang, Q., Wang, W., 2014. Impacts of firecracker burning on aerosol chemical characteristics and human health risk levels during the Chinese New Year Celebration in Jinan, China. Sci. Total Environ. 476, 57–64. https://doi.org/10.1016/j.scitotenv.2013.12.110.

Yao, L., Yang, L., Yuan, Q., Yan, C., Dong, C., Meng, C., Sui, X., Yang, F., Lu, Y., Wang, W., 2016. Sources apportionment of $PM_{2.5}$ in a background site in the North China Plain. Sci. Total Environ. 541, 590–598. https://doi.org/10.1016/j.scitotenv.2015.09.123.

China Statistical Yearbook, 2013, 2014, 2015, 2016, 2017. China Statistic Press, Beijing.

Yu, X., Shi, C., Ma, J., Zhu, B., Li, M., Wang, J., Yang, S., Kang, N., 2013. Aerosol optical properties during firework, biomass burning and dust episodes in Beijing. Atmos. Environ. 81, 475–484. https://doi.org/10.1016/j.atmosenv.2013.08.067.

Zhang, M., Wang, X., Chen, J., Cheng, T., Wang, T., Yang, X., Gong, Y., Geng, F., Chen, C., 2010. Physical characterization of aerosol particles during the Chinese New Year's firework events. Atmos. Environ. 44, 5191–5198. https://doi.org/10.1016/j.atmosenv.2010.08.048.

Zhang, Y.Y., Wei, J.M., Tang, A.H., Zheng, A.H., Shao, Z.X., Liu, X.J., 2017. Chemical characteristics of $PM_{2.5}$ during 2015 Spring Festival in Beijing, China. Aerosol Air Qual. Res. 17, 1169–1180. https://doi.org/10.4209/aaqr.2016.08.0338.

Zheng, Y., Che, H., Zhao, T., Zhao, H., Gui, K., Sun, T., An, L., Yu, J., Liu, C., Jiang, Y., Zhang, L., Wang, H., Wang, Y., Zhang, X., 2017. Aerosol optical properties observation and its relationship to meteorological conditions and emission during the Chinese National Day and Spring Festival holiday in Beijing. Atmos. Res. 197, 188–200. https://doi.org/10.1016/j.atmosres.2017.07.003.