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Association between short-term exposure to air pollution and COVID-19 infection: Evidence from China

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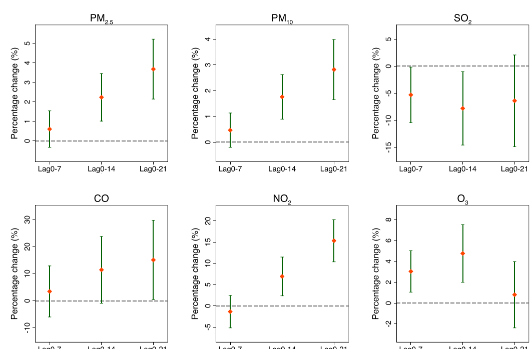
HIGHLIGHTS

- There was a significant relationship between air pollution and COVID-19 infection after controlling for confounding factors.
- Positive associations of $PM_{2.5}$, PM_{10}, CO, NO_2 and O_3 with COVID-19 confirmed cases were observed.
- However, SO_2 was negatively associated with the number of daily COVID-19 confirmed cases.

GRAPHICAL ABSTRACT



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ABSTRACT

The novel coronavirus pneumonia, namely COVID-19, has become a global public health problem. Previous studies have found that air pollution is a risk factor for respiratory infection by carrying microorganisms and affecting body's immunity. This study aimed to explore the relationship between ambient air pollutants and the infection caused by the novel coronavirus. Daily confirmed cases, air pollution concentration and meteorological variables in 120 cities were obtained from January 23, 2020 to February 29, 2020 in China. We applied a generalized additive model to investigate the associations of six air pollutants ($PM_{2.5}$, PM_{10}, SO_2, CO, NO_2 and O_3) with COVID-19 confirmed cases. We observed significantly positive associations of $PM_{2.5}$, PM_{10}, NO_2 and O_3 in the last two weeks with newly COVID-19 confirmed cases. A 10-μg/m^3 increase (lag0–14) in $PM_{2.5}$, PM_{10}, NO_2, and O_3 was associated with a 2.24% (95% CI: 1.02 to 3.46), 1.76% (95% CI: 0.89 to 2.63), 6.94% (95% CI: 2.38 to 11.51), and 4.76% (95% CI: 1.99 to 7.52) increase in the daily counts of confirmed cases, respectively. However, a 10-μg/m^3 increase (lag0–14) in SO_2 was associated with a 7.79% decrease (95% CI: −14.57 to −1.01) in COVID-19 confirmed cases. Our results indicate that there is a significant relationship between air pollution and COVID-19 infection, which could partially explain the effect of national lockdown and provide implications for the control and prevention of this novel disease.

1. Introduction

A novel coronavirus disease, namely COVID-19, was first detected in Wuhan city, China in December 2019 (Lu et al., 2020; Xu

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et al., 2020). In subsequent months, it spread rapidly to the rest of China, which has later become a global public health problem (Chen et al., 2020a; Gilbert et al., 2020; Sohrabi et al., 2020). COVID-19 is caused by the severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) (Dong et al., 2020; Sohrabi et al., 2020; Zhou et al., 2020). Generally, most SARS-CoV-2 infected patients have mild symptoms including fever, dry cough, and sore throat (Huang et al., 2020; Sohrabi et al., 2020). However, some patients could have severe and even fatal complications such as Acute Respiratory Distress Syndrome (ARDS) (Chen et al., 2020b; Sohrabi et al., 2020).

To control the spread of COVID-19, various studies have been conducted to explore important factors affecting the transmission of SARS-CoV-2. Several early studies have demonstrated that human-to-human contact could increase the risk of COVID-19 infection (Chan et al., 2020; Li et al., 2020; Wang et al., 2020). Besides, population mobility has a significant effect on the COVID-19 epidemic (Kraemer et al., 2020). In addition, a recent study has shown an association of ambient temperature with the infection of COVID-19 (Xie and Zhu 2020). However, the impact of short-term exposure to air pollution lacks careful consideration.

Previous studies have suggested that ambient air pollutants are risk factors for respiratory infection by carrying microorganisms to make pathogens more invasive to humans and affecting body's immunity to make people more susceptible to pathogens (Becker and Soukup, 1999; Cai et al., 2007; Horne et al., 2018; Xie et al., 2019; Xu et al., 2016). Since COVID-19 is a respiratory disease and SARS-CoV-2 could remain viable in aerosols for hours (van Doremalen et al., 2020), it is interesting to investigate the effect of air pollution on COVID-19 infection. To provide useful implications for the control and prevention of this novel coronavirus disease, we aimed to explore the relationship between concentrations of six air pollutants and daily confirmed COVID-19 cases in 120 cities in China.

2. Materials and methods

2.1. Study area

This study included 120 cities (4 municipalities and 116 prefecture-level cities) in the geographic regions of 83.4° to 131.6° east longitude and 20.0° to 51.4° north latitude (Fig. 1). According to the National Health Commission, 79,968 COVID-19 confirmed cases have been identified in the whole of China as of February 29, 2020. Our studied cities covered 70% of confirmed cases. We focused our analysis on these 120 cities because of the limitation of the meteorological data and the air pollution data we have obtained.

2.2. Data collection

Daily confirmed new cases for each city between January 23, 2020 and February 29, 2020 were obtained from the reports released by local health commissions on the official websites. We set January 23, 2020 (i.e., the date of lockdown in Wuhan) as the starting point of our study period to minimize the potential inclusion of imported cases from Wuhan.

Air pollution data were collected from an online platform (https://www.aqistudy.cn) monitoring and analyzing the air quality. Daily concentrations of six air pollutants were measured, including particles with diameters ≤2.5 μm ($PM_{2.5}$), particles with diameters ≤10 μm (PM_{10}), sulfur dioxide (SO_2), carbon monoxide (CO), nitrogen dioxide (NO_2), and ozone (O_3).

Meteorological data on daily mean temperature, relative humidity, air pressure, and wind speed during the study period were obtained from the National Meteorological Information Center (http://data.cma.cn).

2.3. Statistical analysis

The generalized additive model (GAM) is a useful method to examine the effects of meteorological factors and air pollution on health

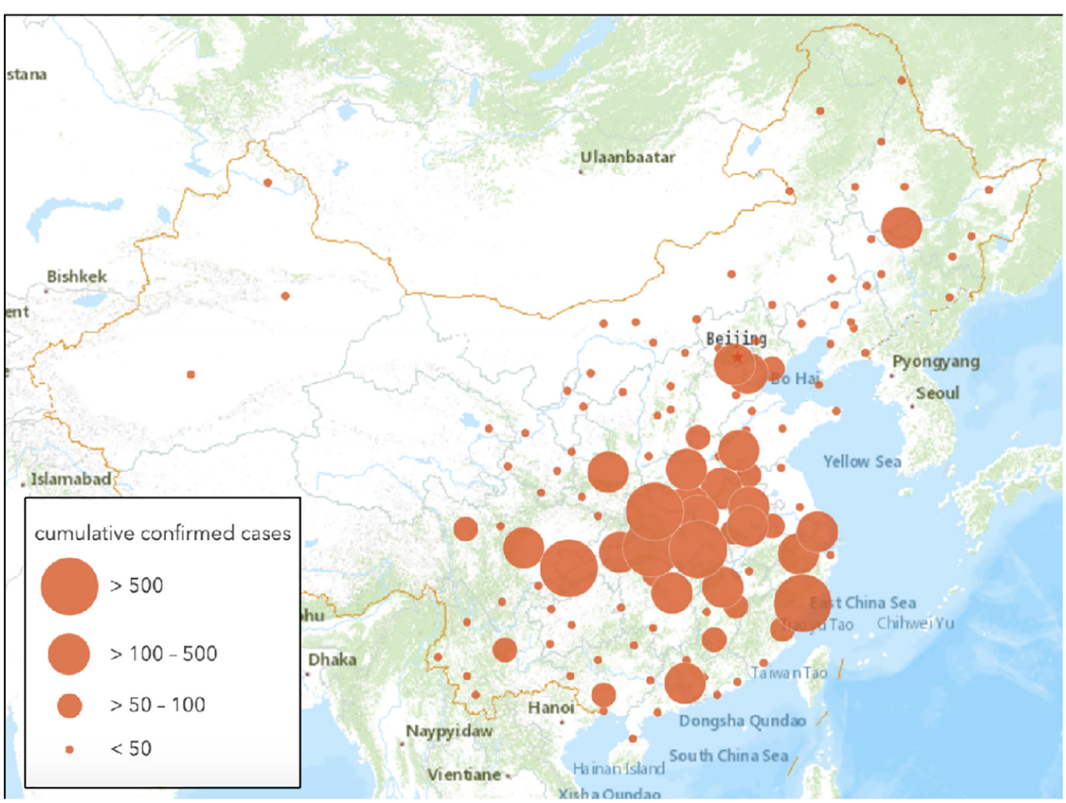

Fig. 1. Locations of 120 cities and cumulative COVID-19 confirmed cases in each city as of February 29, 2020.

Table 1
Descriptive statistics of daily confirmed new cases, concentration of air pollution, and meteorological variables across all cities and days.

	Mean (SD)	Min	Max
Daily confirmed cases	12.94 (228.96)	0	13,436
$PM_{2.5}$ (μg/m^3)	46.43 (38.55)	2	554
PM_{10} (μg/m^3)	62.97 (49.76)	4	632
SO_2 (μg/m^3)	12.23 (9.90)	2	87
CO (mg/m^3)	0.85 (0.47)	0.1	7.4
NO_2 (μg/m^3)	19.28 (11.87)	2	86
O_3 (μg/m^3)	78.22 (20.58)	11	152
Mean temperature (°C)	2.82 (10.11)	−33.8	26.5
Relative humidity (%)	67.25 (17.42)	17	100
Air pressure (hPa)	964.08 (76.15)	668.1	1039
Wind speed (m/s)	2.11 (1.19)	0	15.4

outcomes (Lin et al., 2018; Ma et al., 2020; Peng et al., 2006; Talmoudi et al., 2017; Yang et al., 2020). As demonstrated by previous studies, the effect of air pollution can last for several days (Lin et al., 2018; Myung et al., 2019; Xie et al., 2019; Yang et al., 2020). In addition, an incubation period of 1 to 14 days for COVID-19 was reported by the National Health Commission in China. So, it is a reasonable choice to apply a moving-average approach to capture the cumulative lag effect of ambient air pollution (Duan et al., 2019; Li et al., 2018; Yang et al., 2020). Thus, in this study, we used the GAM with a Gaussian distribution family to estimate the associations between the moving average concentrations of air pollutants (lag0–7, lag0–14, lag0–21) and daily COVID-19 confirmed cases (Hastie, 2017; Liu et al., 2020). Specifically, we examined the effects of six air pollutants in six separate models (i.e., single-pollutant models) to reduce the collinearity since some of these pollutants were highly correlated (Chen et al. 2018; Dastoorpoor et al., 2019; Phosri et al., 2019). The basic model was defined as follows:

$$\log(y_{it}) = a + Z_{il} + s(tem_{il}) + s(rhu_{il}) + s(prs_{il}) + s(win_{il}) + \log(y_{i,t-1}) + city_i + day_t + \varepsilon_{it}$$

Here, $log(y_{it})$ indicates the log-transformed COVID-19 counts reported on day t in city i (added 1 to avoid taking the logarithm of 0) (Liu et al., 2020; Xie and Zhu, 2020). a is the intercept. Z_{il} denotes the linear term of $(l + 1)$-day moving average concentration of air pollutant (lag0-l) in city i (Chen et al. 2018; Phosri et al., 2019). Meteorological factors during the same period were controlled for the possible confounding effect, including mean temperature (tem_{il}), relative humidity (rhu_{il}), air pressure (prs_{il}) and wind speed (win_{il}). $s(\cdot)$ is the smooth function (thin plate spline function with the maximum 3 degrees of freedom) of a certain meteorological factor (Liu et al., 2020; Wang et al., 2018; Xie and Zhu, 2020). $log(y_{i,\ t-1})$ indicates the log-transformed COVID-19 counts reported on day t-1 in city i to account for the potential serial correlation in our data (Liu et al., 2020). In addition, we included city fixed effects ($city_i$) to control for time-invariant city characteristics such as population size and density, and we also included day fixed effects (day_t) to control for unobserved factors affecting all cities in each day such as national lockdown (Amuakwa-Mensah et al., 2017; Lu and Lu, 2017).

Two sensitivity analyses were conducted. First, since the number of confirmed cases in Wuhan city (the worst-hit region in China) was much larger than that in other cities, we excluded Wuhan from our data to test the robustness of our findings. Second, we applied two-pollutant models to examine whether the significant results from single-pollutant models were robust after controlling for other pollutants in the basic model (Chen et al. 2018; Phosri et al., 2019).

All analyses in this study were conducted using the "mgcv" package (version 1.8–28) in R statistical software (version 3.5.2). The statistical tests were two-sided, and $p < 0.05$ was considered statistically significant. Effect estimates were showed as percentage change (%) in daily COVID-19 confirmed cases per unit increase in pollutant concentration (i.e., 10 μg/m^3 increase in $PM_{2.5}$, PM_{10}, SO_2, NO_2, O_3 or 1 mg/m^3 increase in CO).

3. Results

3.1. Descriptive analysis

Table 1 shows the statistics for daily COVID-19 confirmed cases, concentration of air pollution, and meteorological variables. During the observation period, this study included over 58,000 cases with an average of 12.94. Average daily concentrations of $PM_{2.5}$, PM_{10}, SO_2, CO, NO_2 and O_3 were 46.43 μg/m^3, 62.97 μg/m^3, 12.23 μg/m^3, 0.85 mg/m^3, 19.28 μg/m^3 and 78.22 μg/m^3, respectively. The average of daily mean temperature, relative humidity, air pressure and wind speed were 2.82 °C, 67.25%, 964.08 hPa and 2.11 m/s, respectively.

Table 2 presents the spearman correlation coefficients between air pollutants and meteorological variables. Air pollutants had significant correlations with each other and all of them were correlated with mean temperature and relative humidity. SO_2, CO and O_3 were negatively correlated with air pressure, while $PM_{2.5}$ and NO_2 had positive correlations with air pressure. All of these air pollutants were significantly correlated with wind speed except for SO_2.

3.2. Relationship between air pollution and COVID-19 confirmed cases

Fig. 2 plots the moving average lag effects (lag0–7, lag0–14, lag0–21) of different air pollutants on daily confirmed cases of COVID-19 in single-pollutant models. We observed significantly positive associations of $PM_{2.5}$, PM_{10}, CO, NO_2 and O_3 with COVID-19 confirmed cases. For example, a 10-μg/m^3 increase (lag0–14) in $PM_{2.5}$, PM_{10}, NO_2, O_3 and 1-mg/m^3 increase in CO (lag0–21) was associated with a 2.24% (95% CI: 1.02 to 3.46), 1.76% (95% CI: 0.89 to 2.63), 6.94% (95% CI: 2.38 to 11.51), 4.76% (95% CI: 1.99 to 7.52) and 15.11% (95% CI: 0.44 to 29.77) increase in the daily counts of COVID-19 confirmed cases, respectively. However, SO_2 was negatively associated with COVID-19 confirmed cases at

Table 2
Spearman correlation coefficients between air pollutants and meteorological variables across all cities and days.

	$PM_{2.5}$	PM_{10}	SO_2	CO	NO_2	O_3	Mean temperature	Relative humidity	Air pressure	Wind speed
$PM_{2.5}$	1.00									
PM_{10}	0.91*	1.00								
SO_2	0.37*	0.45*	1.00							
CO	0.69*	0.62*	0.39*	1.00						
NO_2	0.64*	0.65*	0.52*	0.63*	1.00					
O_3	0.13*	0.19*	0.11*	−0.04*	0.08*	1.00				
Mean temperature	−0.13*	−0.17*	−0.52*	−0.09*	−0.18*	0.08*	1.00			
Relative humidity	0.08*	−0.08*	−0.41*	0.12*	−0.07*	−0.40*	0.34*	1.00		
Air pressure	0.07*	0.02	−0.21*	−0.04*	0.04*	−0.04*	0.15*	0.27*	1.00	
Wind speed	−0.21*	−0.13*	−0.03	−0.22*	−0.22*	0.04*	−0.07*	−0.13*	0.12*	1.00

* $p < 0.05$.

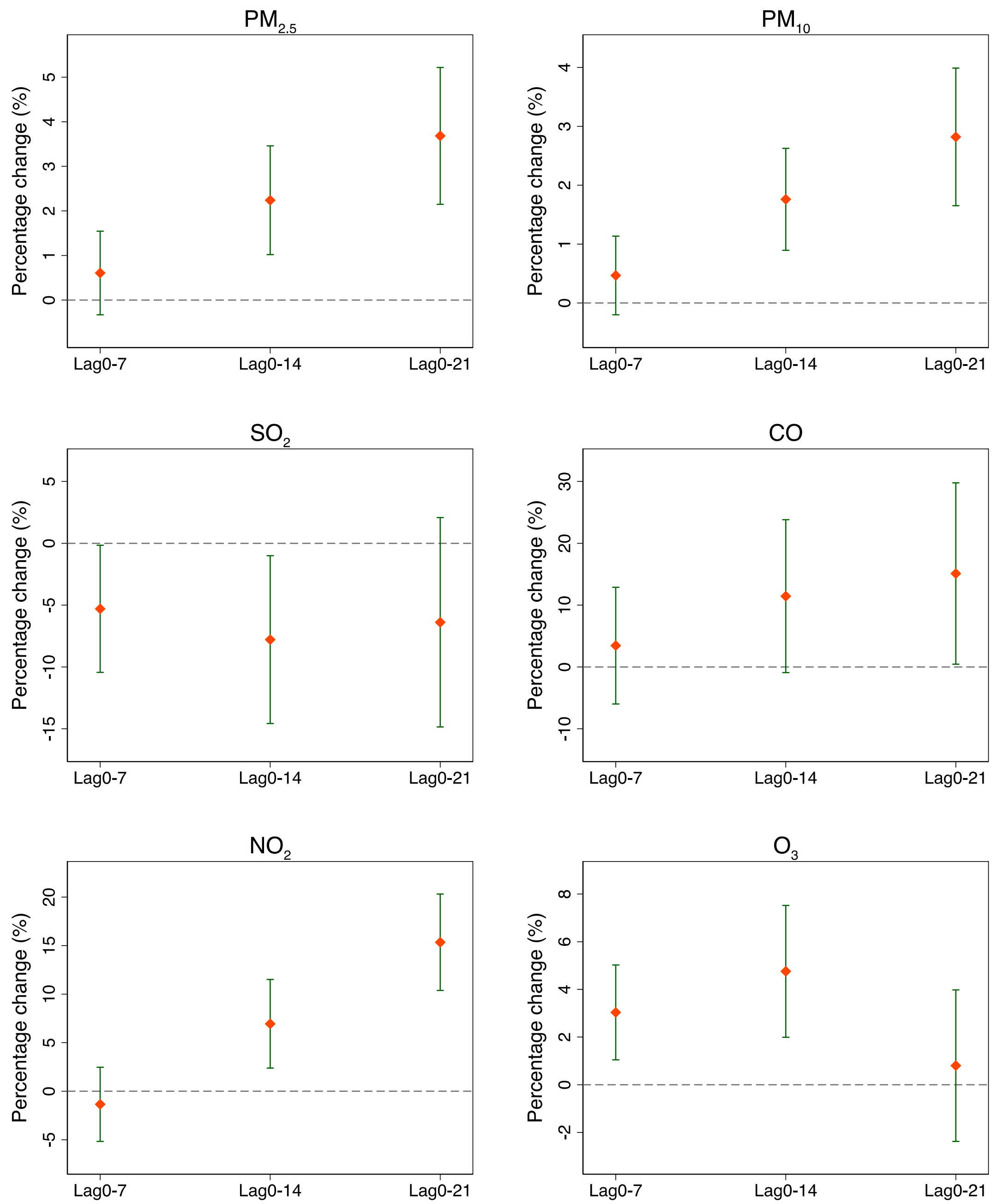

Fig. 2. Percentage change (%) and 95% CI of daily COVID-19 confirmed cases associated with a unit increase in pollutant concentration using single-pollutant models. Units are 10 μg/m^3 increase in $PM_{2.5}$, PM_{10}, SO_2, NO_2, O_3 and 1 mg/m^3 in CO.

lag0–7 (percentage change = −5.30%, 95% CI: −10.44 to −0.16) and lag0–14 (percentage change = −7.79%, 95% CI: −14.57 to −1.01).

3.3. Sensitivity analysis

In the first sensitivity analysis, the relationship between COVID-19 confirmed cases and air pollution was robust after excluding Wuhan from our data (Fig. 3). Fig. 4 shows the results of two-pollutant models. For $PM_{2.5}$ and PM_{10}, the effects on COVID-19 confirmed cases became insignificant only when controlling for NO_2. For SO_2, the association could not remain significant after adding NO_2 or O_3 into the model. For CO, its effect was robust only when SO_2 or O_3 was included in the model. For NO_2, the effect estimate did not alter much after the inclusion of SO_2, CO or O_3. The association of O_3 with daily confirmed cases of COVID-19 remained robust after adjustment for other air pollutants.

4. Discussion

In this paper, we used a generalized additive model to explore the relationship between ambient air pollutants and daily COVID-19 confirmed cases. We found significantly positive associations of $PM_{2.5}$, PM_{10}, CO, NO_2 and O_3 with COVID-19 confirmed cases, while SO_2 was negatively associated with the number of daily confirmed cases. These findings could provide evidence that air pollution is an important factor in COVID-19 infection.

As demonstrated by previous literature, air pollution is also closely related to respiratory infection caused by other microorganisms (Chauhan and Johnston, 2003; Ciencewicki and Jaspers, 2007; Mehta et al., 2013). So, we compared our main findings with previous studies to find similarities and differences. Horne et al. (2018) reported that short-term exposure to higher $PM_{2.5}$ was associated with more

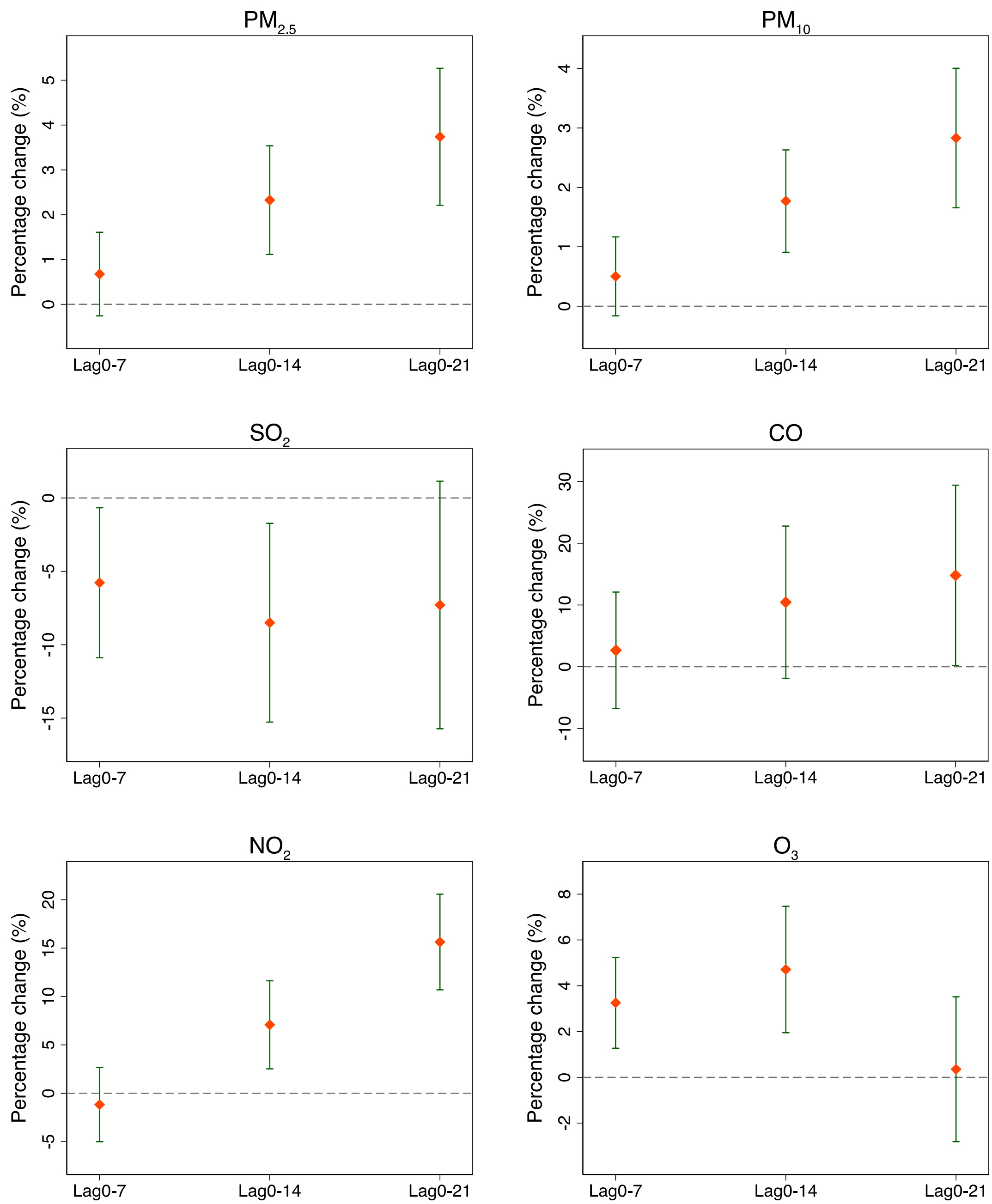

Fig. 3. Percentage change (%) and 95% CI of daily COVID-19 confirmed cases associated with a unit increase in pollutant concentration using single-pollutant models after excluding Wuhan. Units are 10 μg/m^3 increase in $PM_{2.5}$, PM_{10}, SO_2, NO_2, O_3 and 1 mg/m^3 in CO.

healthcare encounters for acute lower respiratory infection by a case-crossover design. Xie et al. (2019) also found a significant association of atmospheric particulate matter ($PM_{2.5}$ and PM_{10},) and hospitalizations for respiratory disease using a distributed lag nonlinear model. A time-series analysis conducted in Thailand observed that PM_{10}, SO_2, CO, NO_2 and O_3 were significantly related to increased risk of respiratory hospital admissions (Phosri et al., 2019). A literature review also showed that exposure to SO_2, CO and NO_2 was harmful to our health and increased the risk of respiratory disease (Chen et al., 2007). Overall, all of the six air pollutants could be risk factors in respiratory infection. However, our results are different from previous studies since we observed a negative relationship between SO_2 and COVID-19 confirmed cases. The virucidal property of SO_2 may be a possible reason (Berendt et al., 1971, 1972), and additional research is needed to determine the biological mechanisms behind this phenomenon.

Our study has some implications for the control and prevention of COVID-19. First, governments and the public should pay more attention to regions with high concentrations of $PM_{2.5}$, PM_{10}, CO, NO_2 and O_3, since these regions may suffer more serious COVID-19 epidemic. In other words, reducing air pollutants (not include SO_2) could be a useful way to control COVID-19 infection. Additionally, it is noteworthy that SO_2 has a negative association with COVID-19 confirmed cases, and further laboratory research needs to be conducted to elucidate the underlying mechanism.

Our study has several limitations. First, we only focused on the association between air pollutants and COVID-19 confirmed cases and not the causal effect of air pollution on COVID-19 infection. Second, our data did not include gender- or age-specific confirmed cases, so we could not conduct subgroup analyses. Third, our findings were not globally representative since cities of other countries

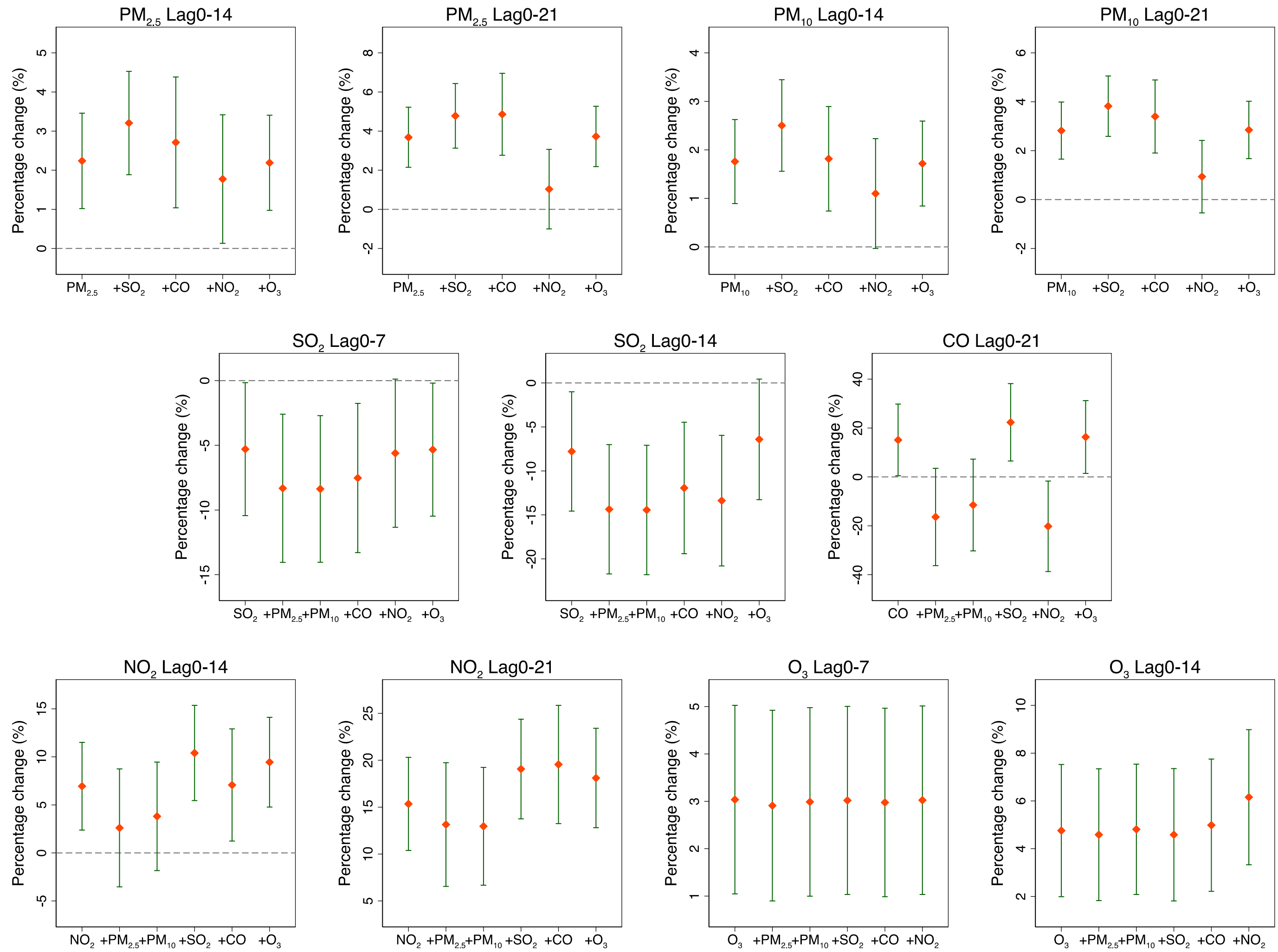

Fig. 4. Percentage change (%) and 95% CI of daily COVID-19 confirmed cases associated with a unit increase in pollutant concentration using single and two-pollutant models. Units are 10 μg/m^3 increase in $PM_{2.5}$, PM_{10}, SO_2, NO_2, O_3 and 1 mg/m^3 in CO.

were not included in this study. Future studies are needed to overcome these limitations.

5. Conclusion

Our study suggests that there is a statistically significant relationship between air pollution and COVID-19 infection. Short-term exposure to higher concentrations of $PM_{2.5}$, PM_{10}, CO, NO_2 and O_3 is associated with an increased risk of COVID-19 infection. However, short-term exposure to a higher concentration of SO_2 is related to the decreased risk of COVID-19 infection. Further laboratory studies are needed to explore the underlying mechanisms.

CRediT authorship contribution statement

Yongjian Zhu: Data curation, Writing - original draft, Visualization, Investigation. **Jingui Xie:** Conceptualization, Methodology, Supervision. **Fengming Huang:** Validation, Investigation. **Liqing Cao:** Validation, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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