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Association between air quality, meteorological factors and COVID-19 infection case numbers

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ABSTRACT

The coronavirus disease (COVID-19) has become a global pandemic affecting many countries, including Singapore. Previous studies have investigated the relationship of air pollutant levels and meteorological factors with respiratory disease risk and hospital admission rates. However, associations between air pollutant concentrations and meteorological factors with COVID-19 infection have been equivocal. This study aimed to assess the association between core air pollutant concentrations, meteorological variables and daily confirmed COVID-19 case numbers in Singapore. Data on air pollutant levels (particulate matter [$PM_{2.5}$, PM_{10}], ozone [O_3], carbon monoxide [CO], nitrogen dioxide [NO_2], sulphur dioxide [SO_2], pollutant standards index [PSI]) and meteorological factors (rainfall, humidity, temperature) was obtained from the Singapore National Environment Agency (NEA) from January 23, 2020 to April 6, 2020. The daily reported COVID-19 case numbers were retrieved from the Singapore Ministry of Health (MOH). Generalized linear models with Poisson family distribution and log-link were used to estimate the model coefficients and 95% confidence intervals (CIs) for the association between air pollutant concentrations and meteorological factors (8-day and 15-day moving averages (MA)) with COVID-19 case numbers, adjusting for humidity, rainfall and day of week. We observed significantly positive associations between NO_2, PSI, $PM_{2.5}$ and temperature with COVID-19 case numbers. Every 1-unit increase (15-day MA) in PSI, 1 μg/m^3 increase (15-day MA) in $PM_{2.5}$, NO_2 and 0.1 °C increase in temperature were significantly associated with a 35.0% (95% CI: 29.7%–40.5%), 22.6% (95% CI: 12.0%–34.3%), 34.8% (95% CI: 29.3%–40.4%) and 28.6% (95% CI: 25.0%–32.4%) increase in the average daily number of COVID-19 cases respectively. On the contrary, PM_{10}, O_3, SO_2, CO, rainfall and humidity were significantly associated with lower average daily numbers of confirmed COVID-19 cases. Similar associations were observed for the 8-day MAs. Future studies could explore the long-term consequences of the air pollutants on COVID-19 infection and recovery.

1. Introduction

The coronavirus disease (COVID-19) outbreak first emerged in Wuhan city (Hubei, China) in December 2019 and has since become a global pandemic (Dong et al., 2020). Runny nose, cough, sore throat, difficulty breathing, loss of taste or smell, and fever are some of the common symptoms of COVID-19 infection. The incubation period is around 5–14 days (Lauer et al., 2020). The first reported case of COVID-19 in Singapore occurred on January 23, 2020. As of April 30, 2020, the number of confirmed cases had increased to 16,169. In that period, there were only a total of 6 fatalities due to COVID-19. Elderly people are more prone to developing complications due to COVID-19 (Wang et al., 2020). With the rising daily COVID-19 case counts in Singapore, and to prevent further spread of the disease in the community, the government implemented a series of strict measures called the 'circuit breaker', essentially a partial lockdown from April 7, 2020 to June 1, 2020. During this period, all schools and non-essential places of work were suspended, with only essential businesses continuing operation.

Air pollution is one of the leading causes of overall mortality globally and accounts for more than 3 million deaths annually (World Health Organization, 2016). Previous studies have investigated the association

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between air pollutants and other meteorological factors on hospital admission rates (Liu et al., 2020; Qi et al., 2020; Zhu et al., 2020). A recent study investigated the short term effects of air pollutants on the number of hospital admissions in Bangkok, and showed that the increased exposure to air pollutants such as NO_2 or CO was associated with increased hospital admissions (Phosri et al., 2019). Other studies have also investigated the effects of meteorological variables on respiratory diseases and found an inverse relationship between temperature and respiratory disease risk. For instance, lower temperature was associated with an increased risk of invasive pneumococcal disease (Ciruela et al., 2016). A recent study in Brazil reported that the largest number of respiratory related problems occurred during the winter, with temperature inversely associated with the number of hospitalizations (da Silva et al., 2019).

Several studies have investigated the association between air pollutant concentrations and meteorological factors with the number of daily COVID-19 incident cases. However, the findings are conflicting. Most studies reported significant positive associations between PM_{10}, $PM_{2.5}$, NO_2 and O_3, but inverse associations between temperature and daily COVID-19 case counts (Liu et al., 2020; Marquès et al., 2021; Qi et al., 2020; Tobías and Molina, 2020). In contrast, a study conducted in Jakarta, Indonesia showed that temperature had a positive correlation with the daily number of COVID-19 cases (Tosepu et al., 2020). A recent study in Singapore reported that temperature, dew point, relative humidity, absolute humidity, and water vapor were positively correlated with COVID-19 cases (Pani et al., 2020). This study is the first study to assess the association between air pollutant levels and the number of daily COVID-19 cases in Singapore, controlling for other meteorological factors. Understanding the associations between air pollutant concentrations and climatic factors with COVID-19 infection may be helpful for resource planning in the primary care setting, and for crafting preventive interventions to limit or curb the spread of COVID-19 and other infectious diseases in the community, across every stage of a developing acute pandemic.

2. Materials and methods

2.1. Air pollution data

Air pollutant data for the period of January 23, 2020 to April 6, 2020 was obtained from the National Environment Agency (NEA) website (https://data.gov.sg/). From April 7, 2020, there was a spike in the reported number of COVID-19 cases in Singapore. The rise in the reported daily confirmed COVID-19 cases mainly stemmed from the increased testing of the migrant workers in dormitories, which contributed to a large proportion of confirmed cases in April. Air pollution levels were shown to be drastically lower during the COVID-19 lockdown periods in several cities (Anjum, 2020). Therefore, all data after April 7, 2020 was excluded in order to eliminate the effects from the circuit breaker as well as increased testing in dormitories.

The air pollutant data consisted of hourly nitrogen dioxide (NO_2), 24-h sulphur dioxide (SO_2), 8-h carbon monoxide (CO), 8-h ozone (O_3), hourly pollutant standards index (PSI), hourly particulate matter with a diameter of 2.5 μm or less ($PM_{2.5}$) and hourly particulate matter with a diameter of 10 μm or less (PM_{10}). The daily averages of the air pollutants were computed and used for the analysis.

The PSI calculation includes the six main air pollutants, CO, NO_2, O_3, $PM_{2.5}$, PM_{10} and SO_2. The calculation for the sub-index of each air pollutant involves transforming the concentrations to a scale from 0 to 500 (NEA, 2014). The overall value of the PSI is then derived from the maximum sub-index of the six air pollutants (NEA, 2014).

2.2. Meteorological factors

Temperature (°C) and total daily rainfall (mm) were obtained from the NEA website for the period of January 23, 2020 to April 6, 2020 (http://www.weather.gov.sg). Data on humidity (%), measured four times daily, was obtained from Time and Date AS (**Aksjeselskap**) (https://www.timeanddate.com/weather/singapore). The daily averages of the meteorological factors were computed and used for the analysis.

2.3. COVID-19 cases

The daily confirmed number of COVID-19 cases was obtained from the Ministry of Health, Singapore (https://covidsitrep.moh.gov.sg/). The first confirmed case of COVID-19 in Singapore was reported on January 23, 2020 and the data was collected up until April 6, 2020, one day before the start of the circuit breaker. The daily confirmed cases were reported at the end of each day, therefore there were no delays in terms of reporting. There were a total of 1375 COVID-19 cases and 6 fatalities during the period from January 23, 2020 to April 6, 2020.

2.4. Statistical analysis

Descriptive analysis was used to explore the distribution of the air pollutants. The Spearman rank correlation test was used to investigate the bivariate relationship between the air pollutants, meteorological variables, and the daily confirmed number of COVID-19 cases. Due to the incubation period of COVID-19 that lasts for up to 14 days, a moving average (MA) was applied to capture potential lag effects of the air pollutants (Liu et al., 2020; Qi et al., 2020; Zhu et al., 2020). Thus, 8 day and 15 day MAs of the air pollutants and meteorological factors were used in the analyses. A generalized linear model (GLM) with a Poisson family distribution and log-link function was used to estimate the association between the MA air pollutant concentrations and the log-transformed daily confirmed number of COVID-19 cases, adjusting for humidity (continuous), rainfall (continuous), and the day of week (categorical). Variables that were selected to be included in the final model were based on the chi-square test. Temperature was not included in the model as the temperature range during the study period was very narrow, as compared to rainfall and humidity. Each model contains one air pollutant to avoid collinearity due to their high correlations (Table A1).

$$\log(Y) = \alpha + \beta_1 \times X_i + \beta_2 \times \text{Humidity} + \beta_3 \times \text{Rainfall} + \beta_4 \times \text{day of week}$$

X_i represents each air pollutant used in the analysis. Effect estimates are reported in terms of percentage changes (%) in daily confirmed COVID-19 cases resulting from a unit increase in air pollutant concentrations or meteorological factors (i.e., 1 unit increase in PSI, 1% increase in humidity, 1 mm increase in daily rainfall, 1 μg/m^3 increase in PM_{10}, NO_2, O3, SO_2 or 0.01 mg/m^3 increase in CO). We obtained the percentage changes (%) by exponentiating the effect estimates, subtracting them by 1 and then multiplying them by 100. A negative binomial regression model was also used for comparison as part of a sensitivity analysis of the results.

All analyses in this study were performed using the R statistical software (version 3.6). False discovery rates (FDR) were calculated using the Benjamini-Hochberg method to account for multiple comparisons. All statistical analyses were evaluated using two-sided tests at the 0.05 level of significance.

3. Results

Table 1 presents the mean, standard deviation, median, interquartile range, minimum and maximum values of the air pollutants and the meteorological factors for the period from January 23, 2020 to April 6, 2020.

The correlation between the air pollutants and meteorological factors ranged from −0.68 to 0.82 (Table A.1). PSI and average $PM_{2.5}$ had

Table 1
Descriptive statistics of air pollutants and meteorological factors from January 23, 2020 to April 6, 2020.

Climatic variables	Mean (SD)	Median (IQR)	Minimum	Maximum
$PM_{2.5}$, μg/m^3	11.0 (2.37)	10.9 (2.54)	5.61	19.2
PM_{10}, μg/m^3	24.7 (4.11)	24.4 (4.98)	14.9	35.3
O_3, μg/m^3	29.5 (7.43)	28.8 (10.3)	13.2	44.9
NO_2, μg/m^3	15.6 (5.01)	15.0 (5.89)	8.48	33.4
CO, mg/m^3	0.49 (0.052)	0.49 (0.057)	0.38	0.62
SO_2, μg/m^3	3.71 (0.77)	3.50 (0.76)	2.80	7.24
PSI	44.0 (6.56)	44.5 (6.93)	24.7	58.1
Temperature, °C	28.2 (0.70)	28.3 (0.67)	26.3	29.5
Rainfall, mm	11.9 (19.9)	3.02 (10.2)	0	102
Humidity, %	76.5 (4.24)	75.8 (6.25)	68.3	87.3

Abbreviations: IQR: Interquartile Range, SD: Standard Deviation; NO_2: nitrogen dioxide, SO_2: sulphur dioxide, CO: carbon monoxide, O_3: ozone, PSI: pollutant standards index, $PM_{2.5}$: particulate matter with a diameter of 2.5 μm or less, PM_{10}: particulate matter with a diameter of 10 μm or less.

the highest correlation coefficient of 0.82, followed by daily rainfall and temperature with a correlation of −0.68 (p-value = $p < 0.001$) (Table A.1). $PM_{2.5}$ ($r = 0.34$; $p = 0.0032$), NO_2 ($r = 0.54$; $p < 0.001$), PSI ($r = 0.35$; $p = 0.0020$) and temperature ($r = 0.45$; $p < 0.001$) were significantly positively correlated with daily confirmed number of COVID-19 cases (Table 2). In contrast, O_3 ($r = -0.33$; $p < 0.0043$) was significantly negatively correlated with daily confirmed number of COVID-19 cases. Rainfall was significantly correlated with daily confirmed number of COVID-19 cases, but its spearman correlation coefficient of −0.23 indicates a weak correlation. PM_{10}, CO, SO_2 and humidity were not significantly correlated with the daily confirmed number of COVID-19 cases.

Using the GLM, we found significant positive associations between $PM_{2.5}$, PSI, NO_2 and temperature with daily confirmed number of COVID-19 cases after adjusting for humidity, rainfall and day of week (Table 3). For every 1 μg/m^3 increase (15-day MA) in $PM_{2.5}$ and NO_2, there was a 22.6% (95% CI: 12.0%–34.3%) and 34.8% (95% CI: 29.3%–40.4%) higher number of average daily confirmed COVID-19 cases. Similarly, every 1-unit increase (15-day MA) in PSI was associated with a 35.0% (95% CI: 29.7%–40.5%) increase in the average daily number of COVID-19 cases. On the other hand, we found significant negative associations between PM_{10}, O_3, SO_2, CO, rainfall and humidity with daily numbers of COVID-19 cases. For every 1 μg/m^3 increase (15-day MA) in PM_{10}, there was a −53.5% (95% CI: −56.3% to −50.5%) change in the average daily number of confirmed COVID-19 cases. Similarly, each 1 μg/m^3 increase (15-day MA) in O_3 and SO_2 was associated with a −30.3% (95% CI: −33.1% to −27.4%) and −83.5% (95% CI: −86.5% to −80.0%) change in the average number of daily confirmed COVID-19 cases respectively. Every 1% increase in humidity and 1 mm increase in daily rainfall was associated with −8.50% (95% CI: −9.54% to −7.45%) and −24.8% (95% CI: −32.0% to −16.9%) change in the average number of daily confirmed COVID-19 cases respectively. For CO, each 0.01 μg/m^3 increase (15-day MA) was associated with a −31.3% (95% CI: −33.5% to −29.1%) change in the average daily number of COVID-19 cases. The results from negative binomial regression models were mostly similar (Table A2).

Table 2
Spearman correlation coefficient between air pollutants and COVID-19 case numbers.

Climatic variables	Correlation coefficient	p-value
$PM_{2.5}$	0.34	**0.0032**
PM_{10}	−0.21	0.072
O_3	−0.33	**0.0043**
NO_2	0.54	**<0.001**
CO	−0.12	0.31
SO_2	−0.12	0.32
PSI	0.35	**0.0020**
Temperature	0.45	**<0.001**
Rainfall	−0.23	**0.049**
Humidity	−0.032	0.79

Abbreviations: NO_2: nitrogen dioxide, SO_2: sulphur dioxide, CO: carbon monoxide, O_3: ozone, PSI: pollutant standards index, $PM_{2.5}$: particulate matter with a diameter of 2.5 μm or less, PM_{10}: particulate matter with a diameter of 10 μm or less.

Table 3
Association between air pollutants, meteorological factors and COVID-19 case numbers.

Climatic variables	Estimate (%)[a]	95% CI (%)	p-value	FDR
8-day MA				
$PM_{2.5}$	0.059 (6.13)	0.0058 (0.59) to 0.11 (12.0)	**0.030**	**0.033**
NO_2	0.16 (17.5)	0.14 (14.5) to 0.19 (20.5)	**<0.001**	**<0.001**
PSI	0.11 (11.7)	0.089 (9.31) to 0.13 (14.1)	**<0.001**	**<0.001**
PM_{10}	−0.44 (−35.3)	−0.48 (−38.2) to −0.39 (−32.4)	**<0.001**	**<0.001**
O_3	−0.18 (−16.8)	−0.20 (−18.5) to −0.16 (−15.1)	**<0.001**	**<0.001**
SO_2	−1.18 (−69.3)	−1.32 (−73.4) to −1.04 (−64.6)	**<0.001**	**<0.001**
CO[c]	−0.28 (−24.7)	−0.31 (−26.5) to −0.26 (−22.9)	**<0.001**	**<0.001**
Temperature	0.13 (14.1)	0.12 (12.4) to 0.15 (15.8)	**<0.001**	**<0.001**
Rainfall[b]	−0.068 (−6.56)	−0.077 (−7.42) to −0.059 (−5.68)	**<0.001**	**<0.001**
Humidity[b]	−0.0063 (−0.63)	−0.041 (−4.04) to 0.029 (2.89)	0.72	0.72
15-day MA				
$PM_{2.5}$	0.20 (22.6)	0.11 (12.0) to 0.29 (34.3)	**<0.001**	**<0.001**
NO_2	0.30 (34.8)	0.26 (29.3) to 0.34 (40.4)	**<0.001**	**<0.001**
PSI	0.30 (35.0)	0.26 (29.7) to 0.34 (40.5)	**<0.001**	**<0.001**
PM_{10}	−0.76 (−53.5)	−0.83 (−56.3) to −0.70 (−50.5)	**<0.001**	**<0.001**
O_3	−0.36 (−30.3)	−0.40 (−33.1) to −0.32 (−27.4)	**<0.001**	**<0.001**
SO_2	−1.80 (−83.5)	−2.00 (−86.5) to −1.61 (−80.0)	**<0.001**	**<0.001**
CO[c]	−0.38 (−31.3)	−0.41 (−33.5) to −0.34 (−29.1)	**<0.001**	**<0.001**
Temperature	0.25 (28.6)	0.22 (25.0) to 0.28 (32.4)	**<0.001**	**<0.001**
Rainfall[b]	−0.089 (−8.50)	−0.10 (−9.54) to −0.077 (−7.45)	**<0.001**	**<0.001**
Humidity[b]	−0.29 (−24.8)	−0.39 (−32.0) to −0.19 (−16.9)	**<0.001**	**<0.001**

Abbreviations: CI: Confidence Interval, MA: Moving Average, NO_2: nitrogen dioxide, SO_2: sulphur dioxide, CO: carbon monoxide, O_3: ozone, PSI: pollutant standards index, $PM_{2.5}$: particulate matter with a diameter of 2.5 μm or less, PM_{10}: particulate matter with a diameter of 10 μm or less, FDR: False discovery rate using Benjamini & Hochberg.

[a] Models were adjusted for humidity, rainfall and day of week.

[b] Models were adjusted for humidity, rainfall and day of week unless the variable was the exposure of interest in the analysis.

[c] Estimates for CO are shown as a percentage change for a 0.01 mg/m^3 increase in CO.

4. Discussion

In this study, we found significant, positive associations between $PM_{2.5}$, PSI, and NO_2 with the daily number of confirmed COVID-19 cases. In addition, we found significant, negative associations between PM_{10}, O_3, SO_2, CO, daily rainfall and humidity with the daily number of confirmed COVID-19 cases.

This is consistent with results from previous studies conducted in

Italy and China, where NO_2 was found to be positively associated with daily COVID-19 cases (Frontera, 2020; Zhu et al., 2020). Prior to the COVID-19 pandemic, there were studies from China and Thailand that found positive associations between NO_2 and the morbidity due to rotavirus as well as the number of hospital admissions (Phosri et al., 2019; Yan et al., 2019). Furthermore, exposure to air pollutants has been previously reported to have an association with increased respiratory infections (Chen et al., 2007; Huff et al., 2019). Previous studies that investigated the effects of $PM_{2.5}$ have shown that it was positively associated with daily COVID-19 cases in China and the United States (Wu et al., 2020; Zhu et al., 2020). Potential mechanisms for this association include impaired immune and lung defence mechanisms in the respiratory mucosa and alterations in alveolar macrophage function in response to air pollutant exposures (Chauhan and Johnston, 2003; Huff et al., 2019).

There are some notable differences in our findings, compared to previous studies. It was previously shown that the NO_2, CO and SO_2 exposures were associated with a higher risk of respiratory disease infections (Chen et al., 2007). However, in our study, we found negative associations between CO and SO_2 with COVID-19 cases. In another study however, SO_2 was shown to have a negative association with daily COVID-19 cases, which was similar to our finding (Zhu et al., 2020). Our finding of a negative association between O_3 and the daily confirmed number of COVID-19 cases was conflicting with another previous study in China, where a positive association was reported (Zhu et al., 2020). In our study, PM_{10} was significantly negatively associated with daily confirmed number of COVID-19 cases. However, previous studies demonstrated a positive association between PM_{10} with daily hospitalization cases of respiratory diseases (Davila Cordova et al., 2020; Ferreira et al., 2016; Wu et al., 2020; Zhang et al., 2019). Higher concentrations of PM_{10} have been shown to prolong the spread of the virus in the atmosphere, as evidenced by a recent study conducted in Italy that provided evidence showing that the COVID-19 virus can be detected on outdoor particulate matter (Setti et al., 2020a). A similar paper in Italy had also discovered that in regions that had higher PM_{10} concentrations, the spread of the COVID-19 virus was faster (Setti et al., 2020b). Prior to the start of the circuit breaker on April 7, 2020, there have been several measures put in place progressively to reduce crowd sizes in public areas. These included allowing employees to work from home, and the closure of businesses and schools that had suspected cases or contact with confirmed cases. These preventive measures may have resulted in a reduction in the air pollutant levels due to restricted movement and lower traffic volume. This may partly explain the negative associations that we observed in the association between PM_{10} and daily COVID-19 cases.

Reducing air pollutant levels such as NO_2 may help in limiting the spread of COVID-19 infection. Further laboratory research should be performed to uncover the fundamental mechanisms between air pollutant concentrations and daily confirmed COVID-19 cases. From our understanding, this is the first study investigating the association between air pollutants, climatic factors and number of confirmed COVID-19 cases in a densely populated Asian city with a tropical climate, using a relatively large number of data points spanning over three months. A similar study was done in Singapore that investigated the correlation between the meteorological factors with the daily confirmed COVID-19 cases from January 23, 2020 and May 31, 2020 (Pani et al., 2020). That study investigated 9 different meteorological variables and their correlations with the daily confirmed number of COVID-19 cases, while our study looked at humidity, rainfall and temperature along with the air pollutant concentrations. However, it should be noted that this study has some limitations. Firstly, we only investigated the associations between the core air pollutant concentrations and number of COVID-19 cases for which data was available. Therefore, we were unable to test the associations of other air pollutants and sub-components of $PM_{2.5}$. Secondly, we did not have information on the demographics such as age, gender, ethnicity or other socio-economic factors of the COVID-19 cases and hence, we were unable to do further stratification by demographic factors. For the period from January 23, 2020 to April 6, 2020, there were a total of 6 fatalities from the COVID-19 virus. We were unable to expand the analysis to assess the association between chronic exposure to air pollutants and the mortality due to COVID-19 in Singapore. The rapid testing in the dormitories took place from April 7, 2020 during the partial lockdown (circuit breaker) imposed in Singapore. Therefore, we do not have the data on the total number of tests that occurred in Singapore and were not able to calculate the ratio of COVID-19 cases to tests. In addition, we did not have information on other potential confounders such as smoking status and traffic flow. Lastly, Singapore has a rather stable climate throughout the year, and has a smaller range of the meteorological levels and air pollutant concentrations, namely CO, SO_2 and temperature, as compared to other temperate countries. The temperature range was not wide enough to cover cool weather due to the tropical climate in Singapore, and as such, we were unable to investigate if low temperatures are associated with the number of COVID-19 cases in Singapore. This may have contributed to differences with the findings from other countries.

5. Conclusions

Our study found significant associations between some of the core air pollutants with the daily confirmed number of COVID-19 cases. Short-term exposures to higher concentrations of $PM_{2.5}$, PSI, and NO_2 were associated with higher case numbers of COVID-19 infection, while short-term exposures to higher concentrations of PM_{10}, O_3, SO_2, CO, rainfall and humidity were associated with lower case numbers of COVID-19 infection. Our findings may be helpful in resource planning and intervention policies to curb the spread of COVID-19 infection and other infectious diseases in the community. Future studies could explore the long-term effects of air pollution on COVID-19 infection and recovery, as well as potential effect modification by age and smoking status.

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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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Appendix

Table A1
Spearman correlation coefficient between air pollutants and weather variables

	PM_{10}	$PM_{2.5}$	PSI	CO	NO_2	SO_2	O_3	Rain	Hum	Temp
PM_{10}	1.00									
$PM_{2.5}$	**0.62***	1.00								
PSI	**0.68***	**0.82***	1.00							
CO	**0.25***	**0.25***	**0.32***	1.00						
NO_2	−0.18	0.18	0.22	**0.35***	1.00					
SO_2	**0.24***	0.20	0.23	0.11	0.05	1.00				
O_3	**0.52***	**0.40***	**0.31***	0.01	**−0.30***	0.18	1.00			
Rain	−0.07	−0.21	−0.23	**0.27***	0.22	**−0.26***	**−0.24***	1.00		
Hum	**−0.27***	**−0.26***	**−0.28***	**0.27***	**0.47***	−0.10	**−0.39***	**0.68***	1.00	
Temp	−0.03	**0.24***	**0.23***	**−0.26***	−0.01	**0.35***	0.09	**−0.68***	**−0.47***	1.00

*refers to $p < 0.05$.
Abbreviations: NO_2: nitrogen dioxide, SO_2: sulphur dioxide, CO: carbon monoxide, O_3: ozone, PSI: Pollutant Standards Index, $PM_{2.5}$: particulate matter with a diameter of 2.5 μm or less, PM_{10}: particulate matter with a diameter of 10 μm or less, Hum: Humidity, Rain: Rainfall, Temp: temperature.

Table A2
Association between air pollutants, meteorological factors and COVID-19 cases using Poisson and negative binomial regression.

	Poisson regression models				Negative binomial model			
Climatic variables	Estimate (%)[a]	95% CI (%)	p-value	FDR	Estimate (%)[a]	95% CI (%)	p-value	FDR
8-day MA								
$PM_{2.5}$	0.059 (6.13)	0.0058 (0.59) to 0.11 (12.0)	**0.030**	**0.033**	0.24 (26.6)	-0.025 (-2.51) to 0.50 (64.5)	0.077	0.085
NO_2	0.16 (17.5)	0.14 (14.5) to 0.19 (20.5)	**<0.001**	**<0.001**	0.34 (40.6)	0.24 (26.9) to 0.44 (55.9)	**<0.001**	**<0.001**
PSI	0.11 (11.7)	0.089 (9.31) to 0.13 (14.1)	**<0.001**	**<0.001**	0.21 (23.4)	0.12 (12.5) to 0.30 (35.3)	**<0.001**	**<0.001**
PM_{10}	-0.44 (-35.3)	-0.48 (-38.2) to -0.39 (-32.4)	**<0.001**	**<0.001**	-0.38 (-31.6)	-0.50 (-39.3) to -0.26 (-22.9)	**<0.001**	**<0.001**
O_3	-0.18 (-16.8)	-0.20 (-18.5) to -0.16 (-15.1)	**<0.001**	**<0.001**	-0.22 (-19.6)	-0.29 (-25.2) to -0.15 (-13.6)	**<0.001**	**<0.001**
SO_2	-1.18 (-69.3)	-1.32 (-73.4) to -1.04 (-64.6)	**<0.001**	**<0.001**	-1.11 (-67.1)	-1.67 (-81.2) to -0.55 (-42.4)	**<0.001**	**<0.001**
CO[c]	-0.28 (-24.7)	-0.31 (-26.5) to -0.26 (-22.9)	**<0.001**	**<0.001**	-0.23 (-20.5)	-0.30 (-25.8) to -0.16 (-15.8)	**<0.001**	**<0.001**
Temperature	0.13 (14.1)	0.12 (12.4) to 0.15 (15.8)	**<0.001**	**<0.001**	0.17 (18.5)	0.11 (11.8) to 0.23 (25.6)	**<0.001**	**<0.001**
Rainfall[b]	-0.068 (-6.56)	-0.077 (-7.42) to -0.059 (-5.68)	**<0.001**	**<0.001**	-0.072 (-7.00)	-0.10 (-9.64) to -0.044 (-4.27)	**<0.001**	**<0.001**
Humidity[b]	-0.0063 (-0.63)	-0.041 (-4.04) to 0.029 (2.89)	0.72	0.72	-0.0030 (-0.30)	-0.16 (-15.1) to 0.17 (18.5)	0.97	0.97

Abbreviations: CI: Confidence Interval, MA: Moving Average, NO_2: nitrogen dioxide, SO_2: sulphur dioxide, CO: carbon monoxide, O_3: ozone, PSI: Pollutant Standards Index, $PM_{2.5}$: particulate matter with a diameter of 2.5 micrometres or less, PM_{10}: particulate matter with a diameter of 10 micrometres or less, FDR: False discovery rate using Benjamini & Hochberg.
[a] Models were adjusted for humidity, rainfall and day of week.
[b] Models were adjusted for humidity, rainfall and day of week unless the adjustment was the exposure in the analysis.
[c] Estimates for CO are shown as a percentage change for a $0.01 mg/m^3$ increase in CO.

Authorship contribution statement

Jason Lorenzo Sam Leo: Data curation, Formal analysis, Methodology, Writing – original draft. Wilson Wai San Tam: Methodology, Writing – review & editing. Wei Jie Seow: Methodology, Supervision, Validation, Writing – review & editing.

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