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The Impact of COVID-19 Restrictions on Air Quality- Based on Seven Cities in China

by

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Abstract

Many researchers have studied the impact of the COVID-19 restrictions. However, in terms of the air quality impact, few studies have done so for specific cities. In this study, seven cities in China under the first stage of transmission prevention have been selected. The air quality standard indicators discussed are NO_2 (Nitrogen dioxide), $PM_{2.5}$ (fine particulate matter), and AQI (Air Quality Index). To find the causal inference, this study employed the fixed effect model and regression discontinuity in time design while using the high-frequency dataset around the policy date of each city. According to the policy-driven bandwidth for each city, the findings showed that NO_2 in every city decreased significantly. In contrast, 2 of 7 cities and 1 of 7 cities did not provide significant results in $PM_{2.5}$ and AQI respectively. The results are robust after various checks. This study confirmed the conclusions in the previous studies that the COVID-19 restrictions improved the ambient air quality.
Keywords: COVID-19, air quality, fixed effect model, regression discontinuity

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1 Introduction

In December 2019, there was a cluster of new pneumonia cases in Wuhan, China. Later on, it spread quickly within China and across the whole world. This pandemic negatively influenced every walk of life. Governments impose various combinations of restrictions to stop the spread of the disease. Research has studied effects of policies on (direct) health (confirmed cases and deaths, but also other indirect effects The effects of the coronavirus were unprecedented even for the air quality (Dang and Trinh, 2021). It is crucial to understand how prevention measures for the virus affect air quality. China is a good case for study because of its volume, size, and influence. Previous studies have shown that lockdown improves air quality at the national level (He, Pan, and Tanaka, 2020).

This paper used daily city-level data collected from Qingyue Open Environmental Data Center and Huiju Environment. The cities are Beijing, Tianjin, Shijiazhuang, Shanghai, Jinan, Zhengzhou, and Wuhan. They are municipalities or capital cities and are listed as important cities by the Chinese Ministry of Ecology and Environment[1] (MEE). The large dataset is allowed to construct different intervals for each city. The research periods are selected according to the response level which is a valuable indicator for policy stringency from provincial governments or municipalities. The information was from various local government notifications about epidemic prevention and the changing government response level. There were three periods for China to combat coronavirus. The restrictions in the first part were severe. In the first-level response, any restrictions can be possible such as school closures, banned gathering and non-essential business and production, and closed management of communities. Epidemic areas can be completely locked down, and potentially infected people were asked for mandatory quarantine. There was a strong first-stage in the China case. In each government notification about coronavirus prevention, people who do not obey or violate laws or rules will face punishment. **(**Appendix A**)**.

In this study, two aspects that I wanted to address in this paper. 1. Since some papers have shown that lockdown improved air quality globally (Dang and Trinh, 2021) and nationally (He, Pan, and Tanaka, 2020), would previous conclusions hold for city-level? 2. Through causal inference, how much improvement can be made on air quality for each city? Few studies did the city-specific analysis. Additionally, the air quality among important cities was also compared to find the causal effect separately.

[1] MEE. Monthly report on urban air quality. https://www.mee.gov.cn/hjzl/dqhj/cskqzlzkyb/

The approaches for the study the Fixed effect model and Regression Discontinuity in Time (RDiT) design to evaluate the indirect impact of the Chinese government's strict restriction policy initially intended to slow the disease's spread. These models provide support to the estimation since each city had fixed effects, and epidemic prevention was randomized. NO_2 and $PM_{2.5}$ are the primary indicators for air quality in this study. AQI was also performed to check the robustness of the study.

My intention is to find the relationship between air quality and restrictions at the city level and analyze each city separately. It would furthermore be interesting to add some comparisons among cities. The findings show that stringent policies could explain the air quality improvement. To conclude, this study showed how air quality changed over this special event and provided an analysis report for these metropolitan cities. Moreover It would be helpful for policymakers to draw experience when local governments try to establish new environmental policies. Lastly, I briefly discussed what policy designers could learn from the unexpected epidemic consequences for the air pollution governance and what strategies governments could do to live in a better environment.

2 Literature Review

Back to the beginning of the COVID-19, governments imposed severe restrictions to stop the spread of the disease due to the demanding situations in many counties. For example, Stay at home order, close schools, and non-essential business, and ban large gatherings. There have been massive papers associated with the effect of COVID-19 because researchers would like to know and explain this unknown virus. Many articles estimate the far-reaching impact on economics and evaluate different restriction measures and how the infection speed and rate changed after introducing the relative policy. For example, Friedson et al. (2020) used daily state-level data to see whether the case and death rates were decreased after shelter-in-place order (SIPO). California is the first state which imposed SIPO in the USA. In the research, the authors employed synthetic control methods to find the causal effect of an earlier SIPO. Results showed that SIPO reduced both confirmed coronavirus cases and deaths. In a review, Viner et al. (2020) talked about the effectiveness of school closures and summarized all the comparative research done previously about school closures. There was no sufficient available data to test the consequence of closing schools and no evidence that this policy can decrease the speed of infection since it is unclear how coronavirus spread from young generations. Also, interventions usually contain many measures. The closures of schools were not the only policy, which means it is tough to isolate the single effect from the overall effect caused by the various combination of restrictions. Kong and Prinz (2020) tried to isolate each non-pharmaceutical intervention from the whole to explain which intervention influenced the unemployment rate most during the lockdown period. Only restaurant and bars limitation and non-essential business closures explained a small part of the unemployment rate rise from the results. They discussed that there were other reasons which influenced the unemployment rate, such as consumer behaviors.

As the unprecedented and enduring pandemic continues spreading worldwide, some researchers shifted from the direct impact of policies to other interesting fields and thought about any indirect consequences people can learn lessons from. Some applied researchers found some indirect impacts of lockdown policies, especially in the environmental field. The primary purpose of restrictions for infectious disease is to slow transmission and save more lives. However, there were some positive and negative indirect impacts of coronavirus. For instance, Zambrano-Monserrate, Ruano, and Sanchez-Alcalde (2020) found that it positively affected the environment. Ambient air quality improved significantly in China, some parts of Europe. Beaches are cleaner than before because of fewer tourists. Environmental noise was reduced due to travel restrictions. In contrast, people had more opportunities to stay at home so that waste increased, which may cause severe pollution in the long run if people do not consider this problem correctly. The research paid attention to interpreting that some countries' air quality has been improved because of COVID-19 disease. Yunus et al. (2020) found that Vembanad lake experienced a decrease in the suspended particulate matter after lockdown, which means that lockdown also improved the lake quality. There were also some studies discussing China's air quality after the outbreak of disease. In a comprehensive study about China's air quality, He, Pan, and Tanaka (2020) evaluated the impacts of coronavirus restrictions on air quality. It allowed to understand that city lockdowns substantially impacted air quality improvement from an econometric perspective. It needed to be noted here that it included 95 cities as a treatment group and 324 cities as a control group through their definition of "lockdown" criteria. Another study in China's air quality (Zhao et al., 2021), similar to the last one, used Regression discontinuity design as the empirical model. Moreover, it is based upon the returning production date as the cutoff point and then addresses how production activity switches on and off to affect air quality. It also discussed the topic from a national level. Similarly, in a study using RD design, Dang and Trinh (2021) did a study from the world level and took 164 countries as samples. To estimate the reasonable coefficient, it relies on stringency data from a program in Oxford university to get the threshold as the treatment starting date.

3 Background Information

Coronavirus has been a constant threat to people. Usually, it can jump from animals to humans, causing people to have respiratory symptoms similar to a common cold. However, some more lethal varieties have a high transmission and mortality rate. For example, Middle East respiratory symptoms (MERS) caused 882 associated deaths, and 2566 cases were reported at the end of 2020. The case-fatality rate was high, at 37.1%, according to the report from Saudi Arabia (World Health Organization, 2020a). Besides, SARS (severe acute respiratory symptoms) was also a significant event in public health. This disease began in Guangdong province, South China, and quickly spread to other regions. SARS was indeed under control in the middle of 2003. However, many countries were hit by this virus, especially China, Canada, and Singapore. Schools were closed in China and Singapore because governments feared the further spread of the disease. In addition, the SARS pandemic harmed the tourist industry. The hotel use rate in Guangdong, Hong Kong, and Toronto dropped significantly[2].

On February 11, 2020, WTO (World Health Organization) named this unknown virus COVID-19 (CoronaVirus Disease 2019). According to the COVID-2019 dashboard developed by Johns Hopkins University (JHU)[3], by the end of April 20, 2021, more than 141 million cases have been confirmed, with more than 3 million deaths, making it one of the deadliest, contiguous, terrible pandemics in history. This new virus is super contagious, and there is no doubt that this virus has features on human-to-human transmission. Various common symptoms are reported, including fever, cough, loss of taste or smell, and so on. The viral transmission among humans in various ways, such as breathing, coughing, sneezing, or speaking and entering another person via their mouth, nose, or eyes, even droplets from an infected person. Since these potential symptoms would appear immediately after coronavirus exposure, the recommendation quarantine is 14 days, estimated upon the upper incubation period. WTO recommends that people keep social distance, wash hands and wear masks, and so on. There is indeed no direct treatment for this new virus, only support treatment. However, appropriate treatment methods and are still ongoing. Many countries have authorized the use of vaccines. Different countries are in different stages of coronavirus disease prevention. In the first half of 2021, while SARS-CoV-2, first identified in late 2019 and spread worldwide in the first season in 2020, still shows significant prevalence among many countries. While India, the US, European countries face terrible daily infection rates and death rates, Some countries such as China, Singapore have brought the epidemic under control. Now, they mainly focus

[2] SARS event (Baidu Baike, accessed 23 May, 2021). https://baike.baidu.com/item/SARS%E4%BA%8B%E4%BB%B6/7702261?fr=aladdin

[3] https://www.arcgis.com/apps/dashboards/bda7594740fd40299423467b48e9ecf6

on preventing disease and import cases that can circulate in the domestic severely. All countries are combated with the potential waves of the epidemic, with combinations of heterogeneous measures imposed by each government. Most countries still adopt previous practical recommendations, such as avoiding gathering, wearing masks in the public, and keeping social distancing (World Health Organization, 2020b; 2020c; 2021; Centers for Disease Control and Prevention, 2021).

China is the first country that imposed strict measures and initiated lockdown. As a result, remarkable achievements have been made in reducing the number of new cases after lockdown. More specifically, China first began city-level lockdown on January 23, 2020, in Wuhan, the epicenter of coronavirus. Later on, governments in other regions imposed similar restrictions but to a different extent in most of China. As for the seven cities in this study, Wuhan is a particular case because only Wuhan implemented some measures that the other six cities did not introduce. For example, the Wuhan government shut down the border. Wuhan's public transport was severely restricted, including public transit, trains, airports, and major highways. Residents were not allowed to leave Wuhan and travel within Wuhan[4].

Provincial governments in China implemented different levels of response when combating coronavirus. According to the National Emergency Plan for Natural Disaster Relief established by the State Council, four response levels[5] (Global Times, 2020) are designed to handle public health emergencies. The more serious public health problems are, the higher decision-making authorities are needed. After the provincial government initiates the first-level response to the public health emergencies, the provincial headquarters should organize and coordinate emergency response work within its administrative area following the decision and deployment of the State Council. The whole province or municipality should follow the guidance from State Council. If it is adjusted to a second-level response, the provincial government can deploy epidemic prevention and control work by itself; if the third-level response is adjusted, the city government will be responsible for overall planning. County or District can carry out the works in the fourth-level response. Those municipalities and provinces all activated first-level public health emergency response at the beginning of the coronavirus pandemic. Later on, they lowered to the second and the third as the successful control of coronavirus disease. It is important to note that the change of level-response does not mean the prevention measures will change immediately. Different response levels denote different strictness. When the province went into a lower response level, all restrictions were relaxed to some extent. For example, the closed management policy in each city changed as the corona situation got controlled. Shijiazhuang eased the closed management of communities before the provincial government announced the second response level. However,

[4] COVID-19 lockdown in China (Wikipedia, accessed 24 April, 2021a). https://en.wikipedia.org/wiki/COVID-19_lockdown_in_China#Closed_management_of_communities

[5] Global Times, 2020. What is the first level response? This article allows you to understand public health emergency first level response. https://baijiahao.baidu.com/s?id=1656598591948001969&wfr=spider&for=pc

other measures were still going[6]. The response-level mechanism denoted the stringency of restrictions, which helps deal with the heterogeneity of different local government policies. Under the same response level, governments adopted similar strategies. The prevention measures followed the guidance of response level. In the first-level response, the government can block epidemic areas when the conditions are met. For example, government can stop any crowd gathering activities. In addition, it is possible to suspend any works, business, school classes[7]. In contrast, under second and third-level responses, the government mainly focused on import cases and high-risk and medium-risk regions. People were allowed to travel and visit people. Productivity activities, business, school were gradually back to normal.

In the first level response, some places implemented closed community management, which means that each local government started to increase to the highest level of coronavirus prevention. In other words, people's lives were beginning to be affected by preventive measures. More specifically, closed community management means people who live in their community, village or unit cannot freely go outside and come back. People must wear masks and receive temperature tests when they want to enter or leave. Each community usually only left one entrance or exit for the community residence. The security guards or community workers will stand next to the only entrance and exit to ensure that people will follow the rules. When people want to enter the community, they must prove that they live here by showing the vouchers or valid credentials. Furthermore, people were prohibited from entering other communities. What is more, vehicles were regulated by similar regulations (Appendix A).

The first-level response date is not the time discontinuity date in this study because the 2020 spring holidays started on January 24. Authorities were designing the epidemic prevention policies when the status of response-level status changed. As a result, there was a gap between the response-level change and actual prevention implement. Also, people prefer to stay home much longer on this traditional holiday. According to the Lunar calendar, Spring festival or Chinese New Year, a traditional Chinese festival, falls in January or February. Generally, people can have a seven-day holiday during the Chinese New Year festival holiday. As a result, people tend to spend more time with family members at home. The State Council extended the 2020 spring festival holiday extra two days due to coronavirus, from January 24 to February 2. Additionally, most local governments declared that non-essential businesses should not allow workers to return to work until February 9, while the Hubei province announced no later than February 13. The circular on extending the 2020 Spring festival can be found in Appendix A.

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[6] Circular on further standardizing community and rural epidemic prevention and control measures. http://www.sjz.gov.cn/col/1577843045360/2020/03/23/1584928355219.html

[7] Phoenix News, 2020. First order response, what does it do to us? https://ishare.ifeng.com/c/s/7tYIa6uY3F5

When coronavirus disease was under control in China, satellite images reported by ESA(Europe Space Agency) showed the significant air quality difference between pre-lockdown and during-lockdown (McMahon, 2020a). According to these images, it is shown that NO_2 (Nitrogen dioxide) pollution decreased dramatically in the national capital region. NO_2 comes from power plants, industrial facilities, and vehicles. Interestingly, the latest satellite image in February 2021 showed a high concentration of NO_2, which indicates that air pollution returned to the pre-lockdown period (Figure 1).

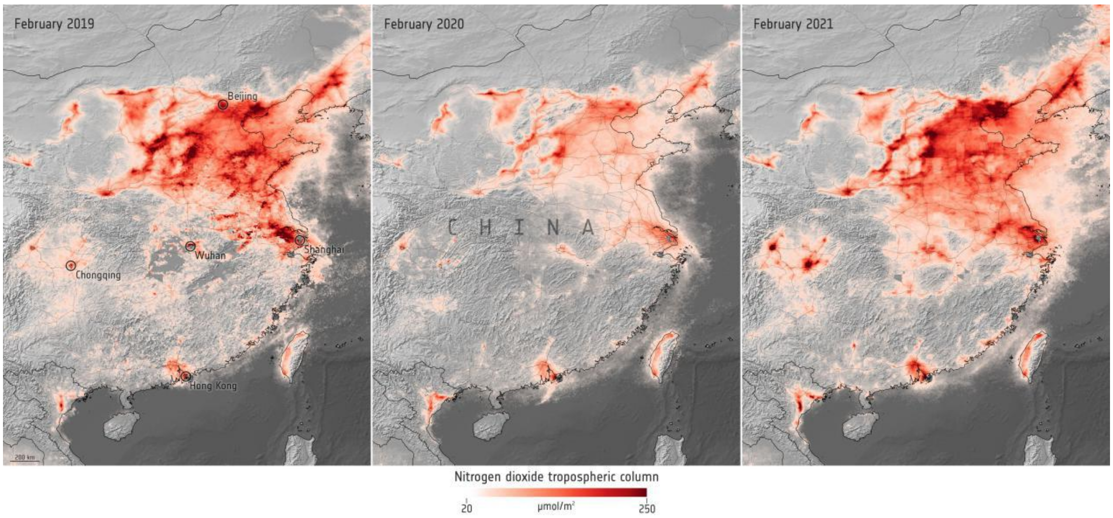


Figure 1. NO_2 Concentrations over China over China (The European Space Agency, 2021[8])

Xu et al. (2020) shows that air pollution is a big problem in China. Moreover, the scale and number of cities increased significantly during past years. Overpopulation consumes more energy goods, fossil fuels, and vehicles. Those all can cause air pollution, which also risks the public's health. In recent years China experienced a dramatic increase in fine particulate matter pollution, especially $PM_{2.5}$ pollution (atmospheric aerosol particles, with a diameter of 2.5 µm or less).

Poor air quality can cause terrible life health problems. It concluded that the poor air quality had caused substantial economic costs, including health costs. Many people suffer from respiratory ailments, heart disease since particulates are linked to these diseases (Matus et al., 2011). In a Jing-Jin-Ji study which is based on $PM_{2.5}$ and PM_{10} (coarse particulate matter, with a diameter of 10 µm or less), given the number from Fan, Lei, and Li (2019), the economic loss caused by health damage is substantial in this region. Moreover, people who suffer from diseases are likely to die early. As a result, there is a loss that people should have lived and worked longer under their life expectancy, which they are supposed to have. However, fatal premature diseases let infant and elder people be vulnerable to particulate matter. Burke (2020) estimated

8 http://www.esa.int/Applications/Observing_the_Earth/Copernicus/Sentinel-5P/Air_pollution_returning_to_pre-COVID_levels

that the temporary closures of factories and vehicles saved 77,000 lives in China during the COVID-19 pandemic lockdown period.

The Ministry of Ecology and Environment (MEE) publishes one national urban report for ambient air quality each month. In each report, it lists the Jing-Jin-Ji and its surrounding area (54 cites), Yangtze Delta (41 cites), and the Fenhe and Weihe plain (11 cites) as three "important" regions. Jing-Jin-Ji, the National Capital Region of China, contains Beijing city, Tianjin city, and Hebei province. The air pollution problems in Jing-jin-ji is serious. Also, each report summarizes the change in one month of those three regions specifically. Therefore, it is not difficult to see that MEE concentrates the environmental governance on these cities.

Figure 2. Map of Seven Cities

The research cities were Beijing, Tianjin, Shijiazhuang, Shanghai, Zhengzhou, Jinan, Wuhan (Figure 2). Beijing is the capital of the People's republic of China and is the most populous capital globally. Beijing is ideal for the study with its characteristics(center for culture, diplomacy and politics, business and economics, education, language, science and technology, and location[9]). Tianjin is a municipality and an economic center in the Bohai Rim region and an international comprehensive transportation hub. Tianjin has the fourth-largest urban population in China[10]. Shanghai is located in Southeast China, close to the Yangtze River. Shanghai is the

[9] Beijing (Wikipedia, accessed 24 April, 2021b). https://en.wikipedia.org/wiki/Beijing

[10] Tianjin (Wikipedia, accessed 24 April, 2021c). https://en.wikipedia.org/wiki/Tianjin

most populous urban area in China. Shang is famous for its influence on finance, research, technology, manufacturing, and transportation. The Port of Shanghai is the world's busiest container port[11]. Zhengzhou, Jinan, Wuhan, and Shijiazhuang are the capital cities of Henan province, Shandong province, Hubei province, and Hebei province. They have a larger urban area, a larger resident population, and a crucial role in politics, economy, transportation, and other aspects. There are several reasons why these cities are included and others are not:

- The chosen cities are all from these listed important regions except Wuhan, the epicenter of coronavirus. Wuhan does not belong to these three regions. The discussion of Wuhan is separated from other cities since Wuhan did announce a lockdown, and the restrictions were more severe than other places.

- Beijing, Tianjin, Shanghai are Direct-administered municipalities of China. Zhengzhou, Jinan, Wuhan, and Shijiazhuang are capital cities. Furthermore, Beijing, Tianjin, Zhengzhou, Jinan, and Shijiazhuang are in the Jing-jin-ji and its surrounding region, one of the notorious regions for poor air quality. For example, Hebei province highly relied on road transport while railways were not used sufficiently. Shanghai was added because Shanghai is in the Yangtze delta, the second important region.

- These cities, except Wuhan, did not officially declare a lockdown. However, similar severe restrictions such as closed management of communities were imposed during that period, and it is suitable for comparison when these cities were selected as the research group.

To summarize, these cities are listed as essential regions in the monthly government report, capital cities or municipalities, imposed strict controls, or the lockdown.

[11] Shanghai (Wikipedia, accessed 24 April, 2021d). https://en.wikipedia.org/wiki/Shanghai

4 Data

4.1 Air Quality Data

Daily city-level data was from Qingyue Open Environmental Data Center[12] (epmap.org). Qingyue was registered as a private non-enterprise in Shanghai. The business unit is Shanghai Minhang District Environmental Protection Bureau. The data declaration states that raw data collected by Qingyue is from MEE real-time release system since January 2016 and the daily average values of air quality indicators calculated from hourly data. For each city, the raw data contain Air Quality Index (AQI), primary daily pollution, publication time, air quality indicators on average, and including SO_2 (Sulfur dioxide). In addittion CO (Carbon monoxide), NO_2 (Nitrogen dioxide), O_3 (ozone), $PM_{2.5}$ (fine particulate matter), and PM_{10} (coarse particulate matter) is also included. SO_2, CO, NO_2, O_3 will harm people's health if the density of harmful gases in the air exceeds a specific value. $PM_{2.5}$ and PM_{10} can be suspended in the air for a longer time, and the higher concentration in the air, the more serious the air pollution. All these harmful components of air pollution can cause chemical and physical damage to the respiratory system.

NO_2 and $PM_{2.5}$ were selected for the primary analysis and AQI for further robustness check in this study. The reasons are as follows:

Nitrogen dioxide is an important indicator to monitor ambient air quality, as shown in ESA's relevant reports. Regarding the tropospheric density NO_2, Europe Space Agency has observed a substantial decrease after the coronavirus pandemic and a significant increase after lifting epidemic prevention policies in some regions of China. NO_2 in the air mainly comes from the combustion of fossil fuels and automobile exhausts. The population movement, production, and economic activities slowed down due to the coronavirus. High-density NO_2 can irritate organs and cause damage to people's respiratory systems. This toxic gas can contribute to chronic disease. For example, it can increase the probability of people suffering from severe respiratory diseases such as asthma, risky to the elderly (Environmental Protection Agency, 2021).

$PM_{2.5}$ is a suitable choice because it causes health problems and because research samples are most in the Jing-Jin-Ji and its surrounding region. Air quality studies based on this region mostly adopted particulate matter as the independent variable. Also, $PM_{2.5}$ is harmful to human health since its slight diameter characteristic allows it to enter the lung deeper, which causes change to the lung function (Xu, 2020).

[12] The Ministry of Ecology and Environment (MEE) of the People's Republic of China (http://106.37.208.233:20035/) provides an online platform for real-time data on air quality in cities across China. However, the old data are not accessible.

The air quality index[13] (AQI), calculated by the individual air quality index (IAQI), is a comprehensive measure of air quality. IAQI is calculated by the 24 hours or 1-hour average concentration limitation value of pollutants, including SO_2, NO_2, CO, O_3, $PM_{2.5}$, and PM_{10}. AQI represents the air quality and evaluates pollution from a general perspective. Therefore, using any sole indicator may not provide a comprehensive actual air situation. Furthermore, depending on the index value, AQI levels are classified into six categories according to the range of AQI, where different levels could bring different health effects. Therefore, the recommendations for public dealing with six air situations vary from level to level (Appendix B, Figure B1).

4.2 Meteorological Data

In this study, weather conditions are control variables. Meteorological data was acquired from Huiju Environment[14] (zc12369.com). It is an ecological environment big data platform built by the Langfang Smart Environment Ecological Industry Research Institute based on improving the ecological environment and facing users. Like air quality data format, daily city-level panel data includes the date, temperature (maximum, minimum, average), humidity, wind (speed, level, angle, direction), pressure, visibility, precipitation, and cloud cover. This study used average temperature, humidity, wind speed, air pressure, and precipitation for control variables. This is because these meteorological conditions affect air quality significantly (University Corporation for Atmospheric Research, 2020; Korber, 2019).

Province/municipality	First-level	Second-level	Third-level	City	Closed management	optimal bandwidth
Beijing	24-Jan	30-Apr	6-Jun	Beijing	10-Feb	79
Tianjin	24-Jan	30-Apr	6-Jun	Tianjin	7-Feb	82
Hebei province	24-Jan	30-Apr	6-Jun	Shijiazhuang	5-Feb	84
Shanghai	24-Jan	24-Mar	9-May	Shanghai	10-Feb	42
Shandong province	24-Jan	7-Mar	5-May	Jinan	5-Feb	30
Henan province	25-Jan	19-Mar	5-May	Zhengzhou	4-Feb	43

Figure 3. Timeline for Each City[15] (Appendix A)

[13] Air Quality Index is a globally acknowledged index while different countries have their own indices and standards.
https://web.archive.org/web/20180612162706/https://www.airnow.gov/index.cfm?action=airnow.international

[14] China's meteorological data service center (cma.cn) allows people to download hourly data from surface meteorological stations. These data are hourly observational values, including temperature, pressure, relative humidity, moisture pressure, wind, and precipitation. However, that data span is not suitable for the study because only recent seven-day data are available. They are not enough.

[15] Wuhan is not included in the Table because the bandwidth for Wuhan is between the official lockdown day and the ending day of the lockdown. The selection of optimal bandwidth has nothing to do with the date of closed management of communities and second level response.

Generally, the optimal bandwidth is days between the closed management date and the second-level response date. I have mentioned the relative background information and I will explain the bandwidth selection in next section. Therefore, the dataset for each city was between the closed management date and the second-level response date plus the symmetrical days before the closed management date of each city. For example, Beijing implemented closed management of communities on February 10 and lowered to second level response on April 30. Therefore, there are 79 days between the two dates which is the treatment period. The same data but before 79 days closed management was also included to add its corresponding control period. However, the days of each city are different from each other. I gathered policy information of each city through various government websites, official social media channels, and news reports. The timeline for each city see Figure 3[16].

For more details about the dataset, see the data description (Table 1). Avt means average temperature. All weather indicators are daily average. The holiday variable denote "Spring festival holiday effects" and "downtime effects."

Table 1. Descriptive Statistics

Variable	Obs	Mean	Std. Dev.	Min	Max
avt	877	6.161	6.166	-8.5	23.2
humidity	877	59.188	21.503	6	99
wind speed	877	1.739	1.027	.1	6.3
air pressure	877	1018.376	8.73	992	1042
precipitation	877	1.049	3.607	0	31.9
AQI	877	91.489	53.328	20	315
NO_2	877	40.204	20.476	5	110
$PM_{2.5}$	877	60.836	46.962	3	265
holiday	877	.136	.343	0	1

16 The city column is not the second one after the column presenting provinces because the provincial government announces the response level, and the city government announces closed management.

5 Estimation Strategy

I used fixed effect model and Regression discontinuity design as the estimation strategies. Two ambient air quality studies (Dang and Trinh, 2021) and (He, Pan, and Tanaka, 2020) and provided good examples, and their ideas and model designs are essential for this study. Using fixed effect model can get rid of the influence of unobserved fixed factors. Each city likely has an inevitable trend of air quality in the given period without any exogenous reasons. This may include factors such as geographical location, fixed seasonal variation. However, I also want to see the change for each city. The Regression discontinuity in Time has been widely used to estimate the causality of a policy or a particular event in many economic works of literature where settings are traffic, air quality, car accidents, vehicle prices, energy use, fisheries (Hausman and Rapson, 2018).

5.1 Fixed Effect Model

It was assumed that there were two error terms in fixed effect model. One was fixed over time, the city fixed effect in this case, and the other was not fixed in the periods. The unobserved time-invariant factors for each city may cause bias for the estimation. Considering the dataset and fixed effects in each city, within-city effect was first established .

(1) $Y_{it} = \alpha_i + \rho D_{it} + \theta M_{it} + \beta H_{it} + \eta_i + \varepsilon_{it},$ where i and t denote the city and date.

In the equation (1), Y is the daily value of selected air quality indicators, including NO_2, $PM_{2.5}$, and AQI. α_i is the constant. η_i is the city fixed effect ,and ε_{it} is the error term, while the former does not vary over time, and the latter changes over time. D is a dummy variable and represents treatment days. D states whether people's everyday lives were affected. D will equal 1 for all days after threshold. The date when each government implemented closed management of communities is the treatment date. ρ is the coefficient that the study cares about, which means how much influence the policy on ambient air quality indicators. M denotes meteorological conditions, such as comprising humidity, wind speed, precipitation, and average temperature. θ is its parameter of interest. H is the holiday. Like the treatment variable D, holiday period H is coded as 1, otherwise coded as 0, and β stands for holiday effect and downtime effect.

5.2 Regression Discontinuity Design

The next estimation strategy proposed is Regression Discontinuity (RD). The panel data was split into time-series data to convey the results for each city. I undertook a sharp RD model to analyze the causal effect of restrictions on air quality. The forcing variable (the underlying continuous variable) is the day from the closed management of communities date. The idea of RD design is simple. It exploits precise knowledge about some arbitrary rules to determine treatment. If there is a discontinuity around the threshold in the outcomes, it provides a good experiment for the causal effect. Another advantage of using RD design is that one can use some graphical analysis to clearly understand the "jump" outcome around the cutoff point.

In this case, the difference from RD design is that the forcing variable is days from the date for each city implemented closed management. Hence, it is also called Regression Discontinuity in Time (RDiT). In the RDiT design, the rule is a particular policy date, and the method is to find different level of air quality indicators around the treatment date. Each city compared with itself around the threshold. Time before is the control group, while after that is the treatment group. If the air quality indicator occurred a significant "jump" around the same days from the policy date, this change indicates that the epidemic prevention restrictions impact air quality.

The COVID-19 pandemic shock was a natural experiment. This setting offers a counterfactual outcome that is allowed to evaluate the causal inference. Daily data is calculated from high-frequency data around the threshold over a specific time horizon in the time series data. Those observations around the threshold in this quasi-experimental framework explained that air quality differences are primarily due to policy shock (Hausman and Rapson, 2018). The equation (2) is as below:

(2) $Y_{it} = \alpha_i + f(x_{it}) + \rho D_{it} + \theta M_{it} + \beta H_{it} + \eta_{it}$, where i and t denote the city and date.

η is the error term. $f(x_{it})$ denotes the forcing variable's function (number of days from the lockdown dates). To perform better comparisons and robustness checks, three different functions of x_{it} were used. They are the linear model (x), the quadratic model (x^2), and the interaction model. Day variable (x) is days from the policy (closed management date) date, and day2 (x^2) is the square of the days. Postday and preday denote the post-policy days and pre-policy days, respectively. The policy date (threshold) is 0, and the pre-policy days are negative values, and the post-policy days are positive values. Other variables are in line with the fixed effect model.

Next, I defined the threshold date and optimal bandwidth based on the closed management date and second level response date.

5.3 Threshold

I used the date when each local government implemented "closed management" on a community basis. Here, the purpose is not to find the effect of closed management but consider this policy as an accurate marker of complete epidemic prevention because many severe restrictions accompany with closed management of communities. In the notices of each city government, they all introduced similar rules to the communities, vehicles, public places, and quarantine rules (Appendix A). Again, The interest of this study is the effect of the high-level restrictions on air quality.

All seven cities, except Wuhan, started severe control measures to slow the spread of disease in early February. Wuhan is a particular case in the study. The prevention measures were stricter than the other six cities. The lockdown time was roughly two months. For Wuhan, January 23, the lockdown date, was used as the threshold date. Since the restrictions were severe and lockdown time was long.

5.4 Bandwidth Selection

It is hard to compare restrictions among cities, and each province may adopt different strategies on different dates. According to the coronavirus situation, cities can relax some restrictions by themselves. Therefore, the national emergency response mechanism in public health developed by the State Council of the People's Republic of China was employed to determine the optimal bandwidth.

First, I used the idea set 100 days before and following the policy date (Dang and Trinh, 2021) and adjusted the optimal bandwidth for each city because air quality cannot change immediately because of the policy shock, and it takes time. Even though cities might lift restrictions during the first level response period and some might not, as long as cities do not introduce new-around robust measures or withdraw all restrictions, it would not bias estimations. Beijing, Tianjin, Hebei province lowered into a second-level response on April 30, while Shanghai, Shandong province, and Henan province announced on March 24, 7, 19. The optical bandwidth for each city is between the closed management date and the second-level starting date. The days for each city see (Figure 3). Wuhan indeed announced an official lockdown on January 23 and ended officially on April 8. So the optimal bandwidth for Wuhan is the gap between these two policy dates, 75 days.

In the RD design, researchers usually pay attention to test the density of the forcing variable in case people manipulate around the threshold (Hausman and Rapson, 2018). Since the RDiT design is based on the days from the threshold date, I did not test the continuity of the density of the forcing variable. Instead, I demonstrated some checking methods recommended by Hausman and Rapson (2018) to prove the results. Three different function forms of days(f(x)) were used in the RDiT design. For further robustness checks, AQI was considered as one of the indicators and repeated the estimation methods. Also, similar graph was produced as before but used one of the abiotic variables, daily average temperature. It is necessary to make sure that the control variable did not "jump" around the threshold. If the temperature changed dramatically, this could pose a threat to the results. Lastly, placebo test was conducted, which studied the same cases but from 2018 to 2019.

6 Results

As previously mentioned that COVID-19 pandemic allowed the Chinese government to take restrictions to stop the spread of disease transmission. To present the indirect impact of the policy on air quality, I have described the details about data selections and the intuition of estimation strategies. Firstly, the Fixed effect results are presented followed by the RDiT results.

6.1 Fixed Effect Model Results

The results are divided into two parts. Wuhan is a particular case due to the treatment heterogeneity. First, I merged all cities' time series data except Wuhan, which means that fixed effect model was about the analysis of Beijing, Shanghai, Tianjin, Shijiazhuang, Jinan, Zhengzhou. This is because the restrictions in Wuhan are more severe than in other cities. Second, Wuhan was included to observe how the result varied. Preferred results were regressions with controls, as it can help to reduce bias. In the results tables, column 1 represented the NO_2 difference, and column 2 described the improvement of $PM_{2.5}$. Control variables are the spring holiday and downtime effect, and meteorological conditions, including average temperature, humidity, wind speed, precipitation, air pressure.

Table 2. Fixed Effect Model, without Wuhan

	(1)	(2)
VARIABLES	NO_2_24h	$PM_{2.5}$_24h
treat	-21.53***	-22.34**
	(1.290)	(8.049)
avt	0.138	-0.177
	(0.0983)	(0.920)
humidity	0.153**	1.386***
	(0.0398)	(0.158)
wind speed	-7.658***	-6.045**
	(0.412)	(1.633)
air pressure	-0.595***	-1.600**
	(0.136)	(0.514)
precipitation	-0.625***	-3.497***
	(0.0903)	(0.442)

holiday	-24.13***	5.835
	(1.741)	(5.059)
Constant	665.5***	1,640**
	(140.1)	(529.8)
Observations	726	726
R-squared	0.678	0.513
Number of citycode	6	6

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 3. Fixed Effect Model, including Wuhan

	(1)	(2)
VARIABLES	NO_2_24h	$PM_{2.5}$_24h
treat	-23.50***	-22.90***
	(2.157)	(5.904)
avt	0.282	-0.0308
	(0.173)	(0.797)
humidity	0.131**	1.338***
	(0.0479)	(0.154)
wind speed	-7.648***	-5.117**
	(0.317)	(1.601)
air pressure	-0.514**	-1.320**
	(0.152)	(0.531)
precipitation	-0.542***	-2.612***
	(0.0847)	(0.550)
holiday	-21.34***	7.020
	(3.319)	(4.084)
Constant	582.4***	1,348**
	(154.9)	(545.6)
Observations	877	877
R-squared	0.642	0.476
Number of citycode	7	7

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Overall, the results showed that there was a positive relationship between restrictions and ambient air quality after the government increased the prevention measures. The air pollutant indicators, NO_2 and $PM_{2.5}$, are lower than before the policy day. Results in Table 2 and Table 3 show statistically significant at 1 percent level for NO_2 and $PM_{2.5}$. More specifically, in Table 2, decreases in the concentration of NO_2 and $PM_{2.5}$ were 21.53 ug/m^3 and 22.34 ug/m^3, respectively. Table 3 showed similar results. When including the only lockdown city, Wuhan, the influence of restrictions on air quality is more at -23.50 ug/m³ and -22.90 ug/m³, respectively.What is more, these two pollutants declined at a similar level in the post-treatment period.

From the results of control variables, adding covariates in the analysis is necessary since some weather conditions in both columns 1 and 2 and holidays in the first column reported significant results. Specifically, the parameters for wind speed, air pressure, and precipitation are significant and negative, indicating that the fluctuations of these indicator levels can influence the air environment. Humidity negatively influences the air quality. During the spring holiday, people spend more time at home, and they would like to set off fireworks, which may explained the decreased NO_2 and increased $PM_{2.5}$.

6.2 RDiT Results

Following the classification of research groups and models, Beijing, Shanghai, Shijiazhuang, Jinan, Zhengzhou, Tianjin, and Wuhan were evaluated respectively. I first showed the graphs plotted the difference on each side of the threshold for the air quality indicator according to 5-day bin construction. Figure 4 and Figure 5 plotted the association between the concentration of NO_2 or $PM_{2.5}$ and days from the threshold day. The days are grouped into 5-day bins, and the outcome indicators are calculated as the averages of pollutants. In addition, the linear fit lines were plotted according to the points on either side of the policy starting day, giving a clear visual presentation of the treatment effect.

Second, The tables (4-10) calculated by the RDiT equation for each city all have 6 columns and are added weather conditions and spring holiday and downtime effects as controls. NO_2, one of the air pollutants, is listed from column 1 to column 3, while $PM_{2.5}$ is the second air quality indicator for the primary analysis, starting from column 4 to column 6. Column 1, with the days control, described NO_2 change between pre-policy day and after-policy day. Column 2 presented a quadratic days function. Column 3 interacted treatment with days with controls. Same rules were applied when it comes to $PM_{2.5}$ as the outcome variable. Columns 4, 5, and 6 are for $PM_{2.5}$. I prefer to use those with control variables. The full tables see Table B1-B10 (Appendix B). Interaction model is the preferred model[17]. In the main analysis, results were presented with controls.

6.2.1 Graphical Analysis

[17] The interaction model interacts treatment status with days. It is common to allow forcing variable functions to differ on each side of the thresholds because air quality may show different relationships with days before and after the threshold date.

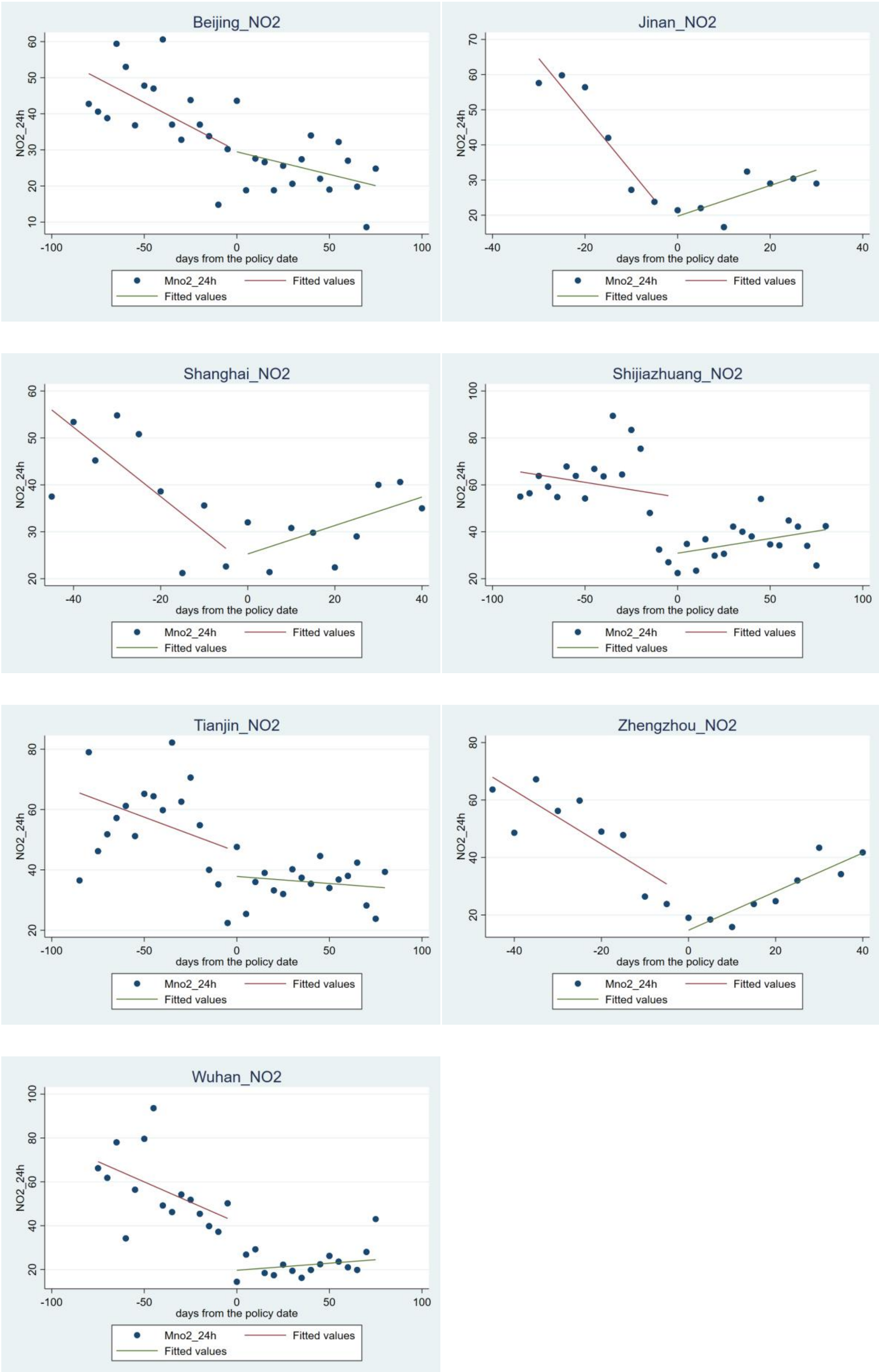
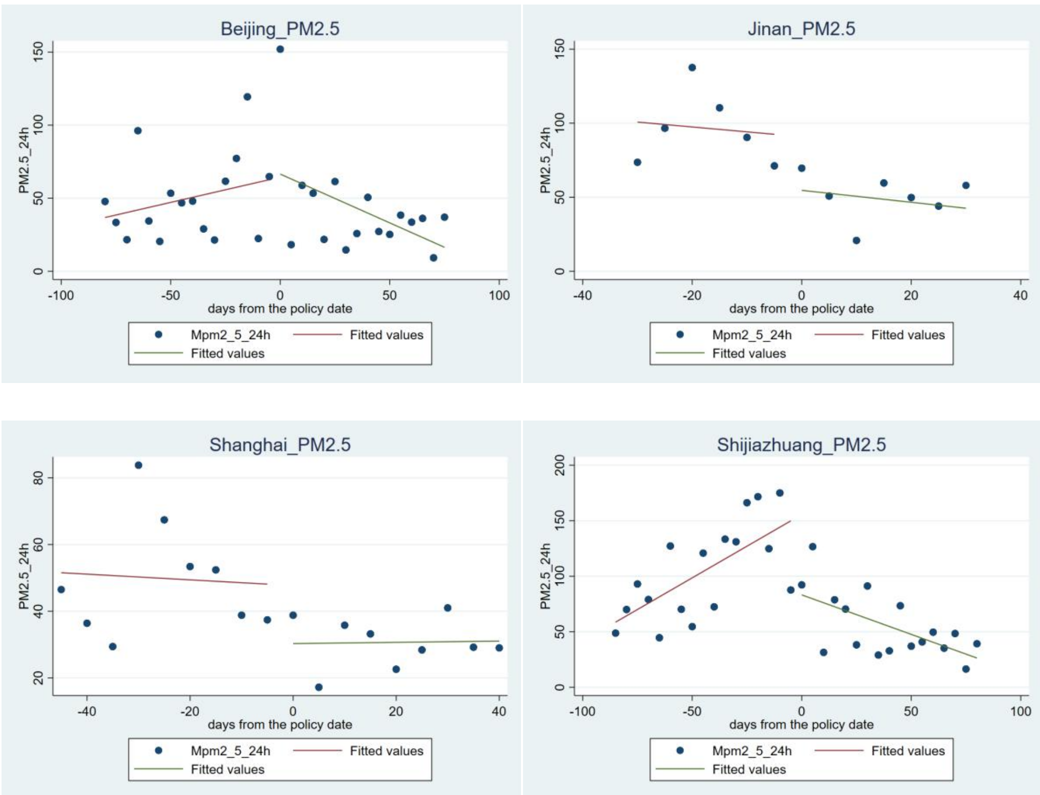


Figure 4. NO2 Concentrations in Each City at Five-day Bin Size.

In Figure 4, except Beijing, it shows discernible discontinuities around the threshold in the NO_2 density among these cites, while only Beijing did not show a significant discontinuity around the threshold. This finding supported the intuition of regression discontinuity and suggested that pandemic prevention improved the NO_2 level in Shanghai, Tianjin, Shijiazhuang, Wuhan, Zhengzhou, Jinan. The downward trend before policy day indicated that the NO_2 level decreased even before the treatment. This is easy to understand because the Spring festival and the downtime days were in the pre-threshold period where people's behaviors already influenced the air quality. Moreover, the NO_2 level had an increasing trend in most cities. As mentioned in the background information, this was mainly because the restrictions were eased as the decrease in the number of daily positive cases in the half stage of the first-level response.

The $PM_{2.5}$ graphs (Figure 5) depict a similar shape to the NO_2 figures. All cities except Beijing clearly showed sharp negative jumps in the $PM_{2.5}$. These discontinuities translated to a reduction in the $PM_{2.5}$ daily level of each city after the treatment.



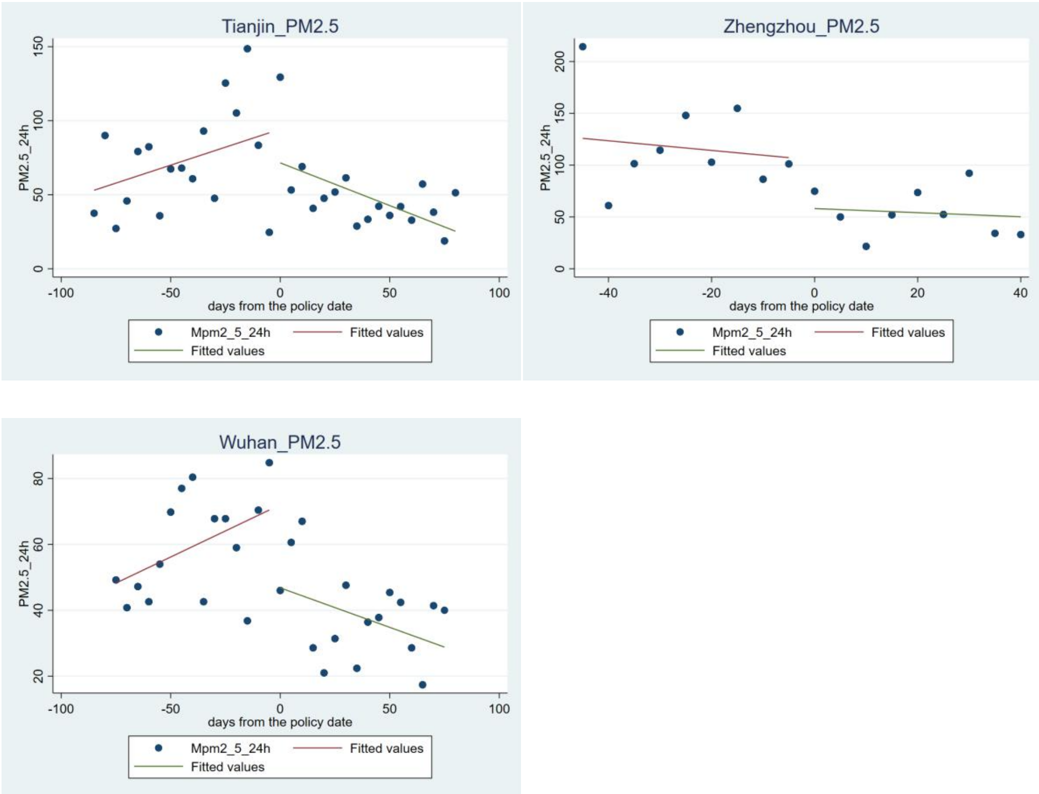


Figure 5. PM2.5 Concentrations in Each City at Five-day Bin Size.

6.2.2 Regression Results

Beijing

I first turned to the improvement of NO_2. It was found that there was a significant decrease in NO_2 when using 79 days as bandwidth. All three NO_2 results with controls (Table 4) showed statistically significant at least 5%, from around -16 ug/m^3 to -10 ug/m^3, while only one of the results without control groups (column 3, Table B1) showed significance. Surprisingly, those estimation coefficients for $PM_{2.5}$ reported insignificant for the COVID-19 prevention policy. On the other hand, five of six estimates are positive, meaning that the $PM_{2.5}$ might increase during this period (Table B1).

Tianjin

In Table B2, all coefficients for treatment variables are negative, which means that both estimates of NO_2 and $PM_{2.5}$ showed that air quality improved in the 165 days. More specifically, four results for NO_2 were reported at a 1 percent level or less, indicating a decrease in the city-level concentration of NO_2 compared with pre-policy days. In addition, although $PM_{2.5}$ saw a fall, only one of six regression estimates (column 9, Table B2) showed a significant number without controlling covariates.

Shanghai

NO_2 and $PM_{2.5}$ were positively improved. From the results in Table B3 where 10 of 12 coefficients are significant. Specifically, two examples were taken using interaction models with controls, which are column 3 and column 6 (Table 6). Restrictions caused by epidemic prevention led to 26.24 ug/m³ and 71.01 ug/m³ dramatic decreases in the two pollutant indicators.

Shijiazhuang

Table B4 shows that eleven estimates presented at 1 percent level and one coefficient less than 5 percent using 84 days as optimal bandwidth. These coefficients are significant and negative, indicating that prevention restrictions improved the concentration of NO_2 and $PM_{2.5}$ dramatically. After the threshold day, Column 3 and column 6 ((Table 7) present that the NO_2 level declined 27.48 ug/m³, and $PM_{2.5}$ fell 55.51 ug/m³ using the interaction model with controls.,

Jinan

Jinan has the shortest period of bandwidth (30 days) in this study. In terms of NO_2 estimates (Table B5), 4 of 6 results showed significant at least 1 percent level. As for $PM_{2.5}$ results, the results of the six equations are significant. Above all, all coefficients are negative. In Jinan, ambient air quality improved through the change of NO_2 and $PM_{2.5}$ around the threshold. There was a considerable drop in the $PM_{2.5}$ indicator particularly. From Table 8, the average coefficient of the linear model (column 4), quadratic model (column 5), and interaction model (column 6) with controls is -49.95 ug/m³.

Zhengzhou

Table B6 shows that the results for both NO_2 and $PM_{2.5}$ are negative and significant. All coefficients with controls showed a great significance, and the p-value is less than 0.01. Zhengzhou saw a drop in the air quality indicators. It suggested a strong positive impact on Zhengzhou's air quality under 43 days of first-level response restrictions.

Wuhan

Unsurprisingly, Table B7 shows that the air quality in Wuhan improved substantially because of the 75 days lockdown. More specifically, all parameters of the treatment variables are significant, and the p-value is less than 0.01 in every equation. Using the interaction model again (column 3 and column 6, Table 10), the decreases of NO_2 and $PM_{2.5}$ are 28.39 ug/m³ and 47.53 ug/m³ after the lockdown.

Table 4. Beijing

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	NO_2_24h	NO_2_24h	NO_2_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h

day	-0.0968**			-0.373**		
	(0.0471)			(0.152)		
treat	-14.10***	-15.69***	-10.23**	20.43	3.792	16.26
	(3.542)	(3.411)	(4.591)	(12.58)	(9.678)	(12.38)
avt	0.344	-0.314	-0.136	0.840	-0.595	1.358
	(0.247)	(0.311)	(0.350)	(0.657)	(0.922)	(1.022)
humidity	0.306***	0.310***	0.301***	1.589***	1.638***	1.595***
	(0.0690)	(0.0682)	(0.0676)	(0.212)	(0.214)	(0.213)
wind speed	-8.294***	-8.451***	-8.444***	-3.130	-3.230	-2.968
	(0.972)	(0.952)	(0.971)	(2.886)	(2.859)	(2.886)
precipitation	-0.580**	-0.606**	-0.582**	-3.183**	-3.240*	-3.180**
	(0.248)	(0.292)	(0.280)	(1.499)	(1.646)	(1.464)
air pressure	-0.562***	-0.672***	-0.686***	-1.594***	-1.659***	-1.460***
	(0.150)	(0.171)	(0.164)	(0.458)	(0.539)	(0.487)
holiday	-20.35***	-21.17***	-16.68***	29.65**	18.47	25.69*
	(2.787)	(2.513)	(3.672)	(12.70)	(12.03)	(14.06)
day2		0.00126*			0.00178	
		(0.000672)			(0.00148)	
preday			-0.191**			-0.271
			(0.0792)			(0.188)
postday			0.0248			-0.505*
			(0.0741)			(0.266)
Constant	615.2***	729.0***	737.7***	1,591***	1,668***	1,459***
	(154.9)	(175.0)	(167.4)	(468.2)	(551.6)	(496.6)
Observations	159	159	159	159	159	159
R-squared	0.770	0.769	0.775	0.629	0.612	0.630

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 5. Tianjin

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	NO_2_24h	NO_2_24h	NO_2_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h
day	-0.0342			0.172		
	(0.0500)			(0.169)		
treat	-17.74***	-22.60***	-19.51***	-22.36	-11.78	-21.30
	(3.978)	(4.020)	(5.030)	(14.15)	(10.59)	(16.53)
avt	0.264	0.544	0.601	-0.635	-0.319	-0.836
	(0.271)	(0.384)	(0.414)	(0.717)	(1.062)	(1.127)
humidity	0.133**	0.143**	0.125*	1.518***	1.469***	1.522***
	(0.0656)	(0.0645)	(0.0659)	(0.203)	(0.180)	(0.203)
wind speed	-8.388***	-8.254***	-8.278***	-8.490***	-8.496***	-8.555***
	(0.832)	(0.801)	(0.828)	(2.333)	(2.301)	(2.305)
precipitation	-1.535***	-1.505***	-1.455***	-5.969***	-5.793***	-6.018***

	(0.359)	(0.365)	(0.361)	(1.937)	(1.920)	(1.936)
air pressure	-0.664***	-0.534***	-0.579***	-1.928***	-2.021***	-1.979***
	(0.154)	(0.175)	(0.176)	(0.512)	(0.581)	(0.591)
holiday	-26.67***	-29.54***	-28.52***	-0.954	5.000	0.152
	(3.339)	(3.544)	(4.423)	(16.41)	(15.38)	(18.33)
day2		-0.000884			7.78e-06	
		(0.000823)			(0.00208)	
preday			0.0234			0.137
			(0.0882)			(0.268)
postday			-0.122			0.224
			(0.0894)			(0.245)
Constant	748.4***	618.2***	664.3***	1,992***	2,083***	2,042***
	(159.4)	(179.8)	(179.7)	(531.6)	(598.3)	(606.3)
Observations	165	165	165	165	165	165
R-squared	0.724	0.725	0.725	0.578	0.573	0.578

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 6. Shanghai

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	NO_2_24h	NO_2_24h	NO_2_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h
day	0.0605			0.115		
	(0.0892)			(0.269)		
treat	-25.98***	-23.34***	-26.24***	-32.00**	-42.63***	-71.01***
	(4.437)	(3.275)	(6.970)	(13.43)	(9.505)	(21.01)
avt	0.241	0.256	0.249	-2.254*	-0.738	-1.026
	(0.418)	(0.474)	(0.445)	(1.212)	(1.323)	(1.219)
humidity	-0.0828	-0.106	-0.0834	-0.108	-0.392**	-0.198
	(0.0821)	(0.0820)	(0.0820)	(0.203)	(0.180)	(0.188)
wind speed	-6.394***	-6.515***	-6.376***	-8.154**	-7.074**	-5.438*
	(0.919)	(0.944)	(0.936)	(3.203)	(3.101)	(3.081)
precipitation	-0.408**	-0.390**	-0.410**	-1.312***	-1.404***	-1.550***
	(0.182)	(0.177)	(0.186)	(0.440)	(0.426)	(0.479)
air pressure	-0.757***	-0.811***	-0.757***	-1.878**	-2.151***	-1.852**
	(0.216)	(0.219)	(0.217)	(0.763)	(0.680)	(0.727)
holiday	-22.34***	-21.03***	-22.54***	-15.53	-28.17***	-45.42***
	(3.057)	(2.922)	(4.965)	(10.73)	(9.717)	(16.44)
day2		2.10e-05			-0.0194***	
		(0.00220)			(0.00629)	
preday			0.0703			1.587**
			(0.201)			(0.645)
postday			0.0570			-0.415
			(0.0998)			(0.250)

Constant	846.7***	901.8***	846.7***	2,031**	2,336***	2,042***
	(224.0)	(228.0)	(225.3)	(792.4)	(709.6)	(755.6)
Observations	85	85	85	85	85	85
R-squared	0.729	0.728	0.729	0.340	0.406	0.409

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 7. Shijiazhuang

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	NO_2_24h	NO_2_24h	NO_2_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h
day	0.0144			0.140		
	(0.0462)			(0.146)		
treat	-26.55***	-27.99***	-27.48***	-32.87**	-46.86***	-55.51***
	(4.434)	(4.057)	(5.423)	(14.01)	(10.77)	(15.13)
avt	0.0301	0.390	0.210	-2.458***	1.046	1.914*
	(0.278)	(0.435)	(0.457)	(0.857)	(1.138)	(1.150)
humidity	0.139**	0.151**	0.145**	1.321***	1.437***	1.463***
	(0.0652)	(0.0657)	(0.0673)	(0.177)	(0.185)	(0.184)
wind speed	-7.880***	-8.001***	-7.966***	-3.298	-4.478	-5.399*
	(1.398)	(1.369)	(1.420)	(3.116)	(2.793)	(2.894)
precipitation	-0.118	-0.133	-0.113	-3.900	-4.041*	-3.773*
	(1.126)	(1.087)	(1.110)	(2.389)	(2.088)	(1.961)
air pressure	-0.874***	-0.776***	-0.823***	-2.647***	-1.690***	-1.413**
	(0.152)	(0.193)	(0.198)	(0.607)	(0.634)	(0.586)
holiday	-29.50***	-30.73***	-30.65***	21.33*	9.367	-6.623
	(3.489)	(4.029)	(4.936)	(12.56)	(12.56)	(14.62)
day2		-0.000744			-0.00724***	
		(0.000792)			(0.00189)	
preday			0.0445			0.873***
			(0.0895)			(0.241)
postday			-0.0256			-0.833***
			(0.0840)			(0.231)
Constant	956.7***	857.2***	906.2***	2,728***	1,759***	1,498**
	(156.7)	(196.1)	(200.9)	(620.8)	(648.4)	(596.4)
Controls	Yes	Yes	Yes	Yes	Yes	Yes
Observations	169	169	169	169	169	169
R-squared	0.687	0.689	0.687	0.631	0.656	0.670

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 8. Jinan

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	NO_2_24h	NO_2_24h	NO_2_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h

day	-0.242**			-0.284		
	(0.120)			(0.355)		
treat	-15.83***	-21.90***	-6.406*	-46.07***	-54.82***	-48.97***
	(4.528)	(2.967)	(3.727)	(11.84)	(6.822)	(16.06)
avt	0.880	1.246**	1.245***	5.242***	4.861***	5.130***
	(0.569)	(0.474)	(0.449)	(1.048)	(1.052)	(1.066)
humidity	0.168**	0.112	0.0464	1.072***	1.158***	1.109***
	(0.0792)	(0.0724)	(0.0649)	(0.232)	(0.250)	(0.257)
wind speed	-3.362**	-6.054***	-5.398***	-6.820*	-5.509	-6.194
	(1.640)	(1.524)	(1.645)	(3.986)	(4.255)	(4.251)
precipitation	-0.545	-0.457	-0.544	-4.710***	-4.684***	-4.710***
	(0.593)	(0.471)	(0.494)	(1.299)	(1.236)	(1.309)
air pressure	0.710*	0.732**	0.474	1.386	1.465	1.459
	(0.366)	(0.324)	(0.322)	(0.950)	(0.945)	(0.978)
holiday	-21.93***	-15.05***	-7.161*	-8.533	-15.94	-13.08
	(2.459)	(3.167)	(3.613)	(7.702)	(10.48)	(14.53)
day2		0.0197***			-0.0161	
		(0.00460)			(0.0149)	
preday			-1.386***			0.0687
			(0.257)			(0.987)
postday			0.419***			-0.487
			(0.155)			(0.491)
Constant	-672.4*	-692.7**	-448.5	-1,364	-1,437	-1,433
	(370.4)	(326.3)	(325.0)	(962.8)	(958.1)	(988.0)
Observations	61	61	61	61	61	61
R-squared	0.767	0.806	0.841	0.649	0.652	0.651

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 9. Zhengzhou

	(1)	(2)	(3)	(4)	(5)	(6)
VARIABLES	NO_2_24h	NO_2_24h	NO_2_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h
day	-0.106			-0.164		
	(0.140)			(0.426)		
treat	-20.62***	-16.67***	-14.30***	-66.57***	-65.35***	-62.51***
	(5.651)	(3.523)	(4.332)	(16.42)	(13.64)	(18.23)
avt	1.176	-0.0168	-0.106	6.858***	5.628**	6.033**
	(0.856)	(0.679)	(0.838)	(2.519)	(2.582)	(2.550)
humidity	0.178*	0.197*	0.165	2.258***	2.275***	2.249***
	(0.103)	(0.101)	(0.103)	(0.388)	(0.396)	(0.396)
wind speed	-4.704**	-6.029***	-5.907***	8.032	7.016	7.258
	(2.296)	(1.867)	(1.927)	(7.552)	(7.743)	(7.622)

precipitation	-0.307	-0.518	-0.522	-2.957	-3.170*	-3.096*
	(0.511)	(0.523)	(0.519)	(1.823)	(1.840)	(1.859)
air pressure	0.197	0.116	-0.0440	3.142**	3.053**	2.987*
	(0.468)	(0.379)	(0.391)	(1.487)	(1.516)	(1.512)
holiday	-21.99***	-14.20***	-8.281**	-13.03	-6.870	-4.215
	(3.269)	(2.932)	(3.420)	(10.89)	(11.08)	(14.32)
day2		0.0141***			0.0124	
		(0.00226)			(0.00969)	
preday			-0.779***			-0.596
			(0.175)			(0.728)
postday			0.687***			0.346
			(0.154)			(0.435)
Constant	-158.4	-80.67	74.29	-3,248**	-3,160**	-3,098*
	(479.4)	(388.7)	(402.2)	(1,533)	(1,563)	(1,557)
Observations	87	87	87	87	87	87
R-squared	0.615	0.715	0.720	0.618	0.627	0.623

Robust standard errors in parentheses
*** $p<0.01$, ** $p<0.05$, * $p<0.1$

Table 10. Wuhan

	(2)	(4)	(6)	(8)	(10)	(12)
VARIABLES	NO_2_24h	NO_2_24h	NO_2_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h
day	-0.133***			0.245**		
	(0.0475)			(0.114)		
treat	-28.16***	-39.13***	-28.39***	-48.46***	-30.76***	-47.53***
	(3.935)	(2.419)	(3.920)	(11.59)	(3.870)	(9.143)
avt	0.508	0.465	-0.104	0.536	2.287***	3.041***
	(0.388)	(0.456)	(0.482)	(0.752)	(0.785)	(0.801)
humidity	-0.442***	-0.419***	-0.451***	-0.274	-0.282	-0.238
	(0.119)	(0.122)	(0.119)	(0.300)	(0.286)	(0.281)
wind speed	-7.216***	-7.347***	-7.107***	2.513	2.343	2.066
	(1.465)	(1.504)	(1.452)	(2.527)	(2.239)	(2.231)
precipitation	0.0373	0.0312	-0.000890	-1.012**	-0.881***	-0.856***
	(0.220)	(0.224)	(0.210)	(0.393)	(0.315)	(0.327)
air pressure	-0.516*	-0.420	-0.723**	-0.0610	0.293	0.785
	(0.287)	(0.285)	(0.298)	(0.527)	(0.495)	(0.505)
holiday	2.660	9.325***	5.642**	28.90***	13.28**	16.70**
	(2.781)	(2.434)	(2.679)	(8.332)	(5.685)	(7.896)
day2		0.00121*			-0.00692***	
		(0.000685)			(0.00138)	
preday			-0.267***			0.794***
			(0.0916)			(0.140)
postday			0.0204			-0.383**

			(0.0623)			(0.148)
Constant	618.9**	521.9*	830.7***	148.4	-222.1	-718.2
	(299.5)	(298.5)	(311.3)	(555.3)	(521.6)	(530.8)
Observations	151	151	151	151	151	151
R-squared	0.737	0.731	0.744	0.332	0.404	0.436

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Overall, the epidemic prevention measures for COVID-2019 improved the air quality. The results are robust through the discontinuity graphs and different estimates calculated from different model settings. The results of NO_2 in both models showed a fall. All seven cities improved significantly in terms of the concentration of NO_2 even when controlling meteorological variables and holiday and downtime effects. Similarly, holidays and weather conditions in both models showed that they could influence the air quality. In the regression tables of Beijing and Tianjin, there are no clear answers since the results are insignificant both with and without control variables. Beijing, Tianjin, and Shijiazhuang had similar first-response level days. However, Shijiazhuang experienced a fall in the $PM_{2.5}$ level after introducing restrictions, while the restrictions did not impact the $PM_{2.5}$ level in Beijing and Tianjin. With nearly 38 days' bandwidth on average, Shanghai, Jinan, and Zhengzhou all reported remarkable decreases in NO_2 and $PM_{2.5}$. In the only lockdown case in the study, Wuhan, air quality also improved.

6.2.3 Placebo Test

To find out the validity of the consequences of the shutdown period, I probed this study by using a placebo test here. More precisely, I assume that the restrictions happened at the beginning of 2019 instead of using the actual year 2020. I collected the daily meteorological data and daily air quality data from 2018 October 1 to May 31, 2019. Data was trimmed in the same way and then used the RDiT method to assess the causal effect of restrictions on ambient air quality. For example, the actual date for Beijing implementing the closed management of communities was February 10, 2020. In the placebo test, the fake threshold date becomes February 10, 2019. I wanted to check if the past treatment would influence the air quality as well. Suppose the results from the placebo test also plausibly showed statistical significance. In that case, the previous estimates are suspicious and it is highly likely that the air quality changed by other factors. If not, the results from the main analysis are robust. One adjustment for the model is that the holiday and downtime effect. The downtime effect was canceled and adjusted the holiday period. This is because the Spring festival will change each year according to the lunar calendar. People had seven days' holiday from February 4, 2019, to February 10, 2019.

The chosen model was the interaction model with controls. It was preferred as it separates the days on each side of the threshold and can avoid bias estimation. The coefficients of the treat variable indicated the estimated effect of fake epidemic prevention. For detailed results, see Table 11 and Table 12. Generally speaking, the estimated effects are different from the 2020 results. The specification of treatment effects in Beijing, Shanghai, Tianjin, Zhengzhou is minuscule and insignificant. Shijiazhuang and Wuhan reported significant results and decreased at 21.34 ug/m³ and 10.67 ug/m³ respectively in the NO_2 pollution compared with before treatment. However, the declines in Wuhan are much smaller than the decreases during the same period in 2020. For Shijiazhuang, the decreases in both years were significant. This may pose a threat to results validity. I checked the Shijiazhuang news around the fake treatment date, and found that the Hebei Provincial Government issued the "Implementation Plan for Promoting the Adjustment of Transportation Structure in Hebei Province" on February 21th which was close to the fake treatment threshold February 5. The "Plan" further focused on improving railway cargo transportation capacity. It stated that by 2020 coastal port ore and coke will be mainly transported by railway (Transport Department of Hebei Province, 2019). The change in the traffic structure, which can explain the disease in the NO_2.

The $PM_{2.5}$ placebo test results vary from city to city. In 2019, Jinan and Shanghai experienced considerable increases in the $PM_{2.5}$ pollution. The result in Shijiazhuang $PM_{2.5}$ was negative and significant at 1 percent level, while Beijing, Tianjin, and Wuhan did not provide significant results.

Overall, the results presented in the placebo test provide evidence that the fake restrictions in 2019 did not substantially improve the air environment across cities, which indicated that previous estimates in 2020 hold.

Table 11. Placebo Test: NO_2

	(1)	(2)	(3)	(4)	(5)	(6)	(7)
VARIABLES	NO2_24h	NO2_24h	NO2_24h	NO2_24h	NO2_24h	NO2_24h	NO2_24h
City	Beijing	Shanghai	Tianjin	Jinan	Shijiazhuang	Zhengzhou	Wuhan
treat	-2.806	6.343	-1.931	19.54	-21.34***	-7.923	-10.67***
	(3.861)	(7.713)	(4.575)	(13.85)	(6.467)	(10.17)	(3.903)
avt	0.718*	-1.282	0.357	4.811***	1.117*	1.208	1.882***
	(0.416)	(0.941)	(0.480)	(1.156)	(0.664)	(0.895)	(0.512)
humidity	0.242***	-0.354	0.0474	-0.0504	0.152	0.159	-0.542***
	(0.0864)	(0.235)	(0.0738)	(0.145)	(0.101)	(0.136)	(0.114)
wind speed	-11.31***	-11.04***	-9.876***	-16.06***	-14.58***	-16.34***	-12.13***
	(1.341)	(1.967)	(0.867)	(3.254)	(2.487)	(2.369)	(1.430)
precipitation	-0.746	-0.146	-1.389	-2.967	-1.001***	-1.076*	0.0146
	(0.734)	(0.277)	(1.058)	(3.371)	(0.319)	(0.582)	(0.234)
air pressure	-0.635***	-2.345***	-0.563*	1.885***	-0.455	0.137	-0.0595
	(0.218)	(0.552)	(0.297)	(0.593)	(0.427)	(0.530)	(0.305)
holiday	-19.96***	-22.66***	-31.67***	-12.83*	-30.04***	-17.55**	-5.341
	(4.949)	(6.768)	(3.763)	(6.888)	(5.812)	(7.472)	(4.203)
preday	-0.150**	-0.622***	-0.00513	-1.185***	0.368***	-0.365	0.284***

	(0.0673)	(0.234)	(0.0766)	(0.313)	(0.0963)	(0.232)	(0.0681)
postday	-0.388***	-0.192	-0.307***	-0.536	-0.534***	0.00147	-0.285***
	(0.0850)	(0.313)	(0.0887)	(0.672)	(0.128)	(0.371)	(0.103)
Constant	707.1***	2,504***	655.3**	-1,836***	561.2	-75.04	171.3
	(223.1)	(580.1)	(306.2)	(598.5)	(435.1)	(544.7)	(318.9)
Observations	159	85	165	61	169	87	151
R-squared	0.726	0.588	0.655	0.679	0.542	0.596	0.661

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table 12. Placebo Test: $PM_{2.5}$

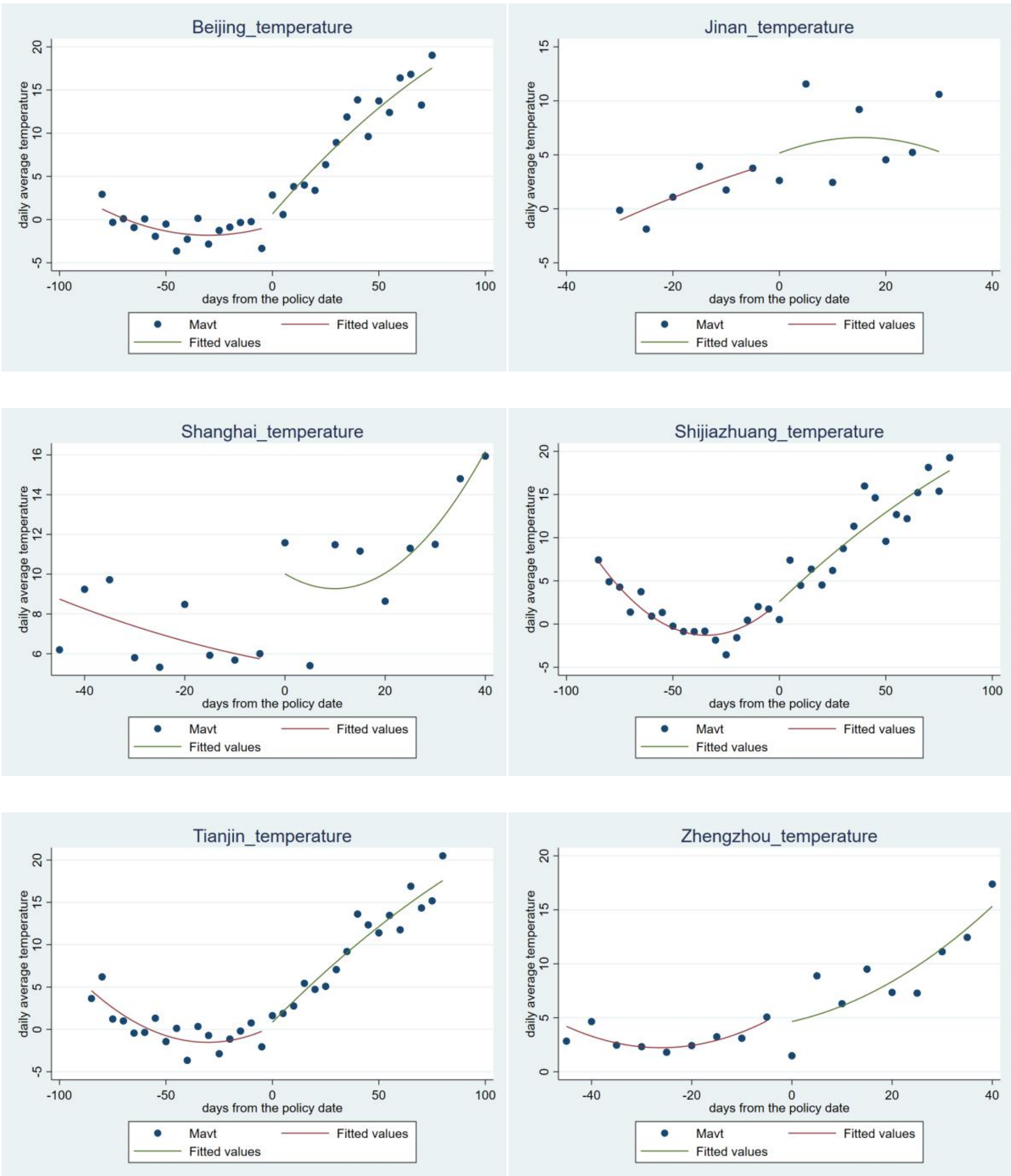
	(1)	(2)	(3)	(4)	(5)	(6)	(7)
VARIABLES	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h
City	Beijing	Shanghai	Tianjin	Jinan	Shijiazhuang	Zhengzhou	Wuhan
treat	-0.556	20.99*	-4.518	38.74*	-34.74*	35.50	-13.74
	(9.098)	(12.56)	(13.02)	(22.77)	(18.39)	(36.70)	(9.402)
avt	2.297***	-1.754	-0.295	11.69***	4.608***	8.613**	3.785***
	(0.821)	(1.487)	(1.444)	(2.391)	(1.620)	(3.427)	(1.234)
humidity	1.667***	-0.648*	1.626***	2.055***	2.394***	2.543***	-0.121
	(0.206)	(0.334)	(0.281)	(0.511)	(0.299)	(0.454)	(0.298)
wind speed	-3.263	-5.083	-5.721**	-20.29***	-15.15***	-16.66**	-6.709***
	(2.560)	(4.108)	(2.650)	(7.428)	(5.777)	(8.241)	(2.538)
precipitation	-4.961***	-1.599***	-8.784***	-29.85***	-4.040***	-0.314	-1.627***
	(1.790)	(0.489)	(3.368)	(7.181)	(1.094)	(2.611)	(0.594)
air pressure	-1.091**	-3.103***	-2.132**	2.725**	-0.248	2.090	0.828
	(0.490)	(0.909)	(0.856)	(1.248)	(1.009)	(1.775)	(0.652)
holiday	-7.988	-18.90	-32.33***	-1.745	-28.84*	-18.11	12.50
	(9.719)	(11.61)	(11.50)	(17.31)	(16.11)	(34.26)	(12.44)
preday	0.0446	-0.450	0.518**	-1.883**	1.293***	-0.866	0.921***
	(0.156)	(0.383)	(0.231)	(0.752)	(0.266)	(0.649)	(0.184)
postday	-1.075***	-0.965**	-0.944***	-2.935***	-2.220***	-3.076**	-1.285***
	(0.202)	(0.405)	(0.253)	(0.931)	(0.336)	(1.377)	(0.221)
Constant	1,128**	3,300***	2,230**	-2,758**	338.6	-2,156	-737.3
	(500.8)	(946.3)	(880.9)	(1,263)	(1,025)	(1,813)	(681.7)
Observations	159	85	165	61	169	87	151
R-squared	0.657	0.342	0.545	0.589	0.573	0.498	0.024

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

6.2.4 Further Robustness Checks

First, the discontinuity of daily average temperature was examined. (Figure 6). This is because air temperature influences air movement and temperature is a great indicator to judge cold weather or warm weather. The coding rules for graphs are the same as before. Here, the interval is still five days. Except for Shanghai, there were no jumps in the average temperature around the threshold for other cities. It is not strange that a significant but steady rise can be seen in the temperature of all cities because the season at that period shifted from winter to spring.

In the Table B8 (Appendix B), to get a more comprehensive result, the difference of AQI using the same RDiT design method was presented. The results again indicated that the air environment did improve.



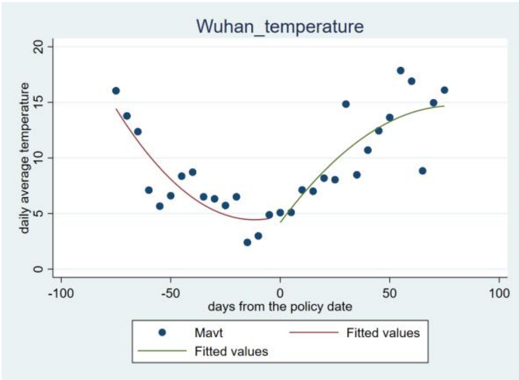


Figure 6. Days and Temperature at Five-day Bin Size

7 Conclusion

At the beginning of 2020, coronavirus started ravaging China, and later it became a worldwide outbreak. China took any possible measures to combat the disease. Almost all provinces implemented announced enter the first-level response. All activities, works and schools were affected to a great extent. When the Spring festival holiday ended, cities increased to strictest prevention to control the population movement. The non-essential business was prohibited, and people spent more time because of the closed management of communities. All the measures were aimed to reduce the COVID-19 case.

This study focused on the indirect impact of policies on ambient air quality. Previous studies proved that lockdown improved the air quality globally and nationally. Unlike previous studies, it performed the reduction in NO_2, $PM_{2.5}$, and AQI for the particular city with high-frequency data. The conclusions are that restrictions for preventing the virus indirectly improved the air environment for these seven cities selected according to the classification from government reports and the conclusions still hold for each city. It was proved that past conclusions still hold and are consistent with those previous studies even though the research level is shrunk from national to regional. Significantly, the density of NO_2 saw a significant reduction among these cities. The findings are robust after some robustness checks, such as the placebo test. Interestingly, the concentration of $PM_{2.5}$ did not show significant results in every city.

The findings allowed people to think more about environmental governance. People, of course, wanted the air quality to become better. However, those severe restrictions for slow the coronavirus disease cannot be duplicated. It is not realistic to sacrifice the tremendous economic benefits. There is a constant tradeoff between economic growth and environmental protection. People should not expect that any future shocks can always improve air quality. The limitation of the study is that there were no further discussions on contemporary air quality measures which Chinese government have implemented. Therefore, further studies can be done on how to take examples from COVID-19 restrictions for achieving environmental goals and current air environment policies should be included in the discussion. More specifically, during the lockdown period, the use of private vehicles and production activities were decreased. Although pandemic restrictions are combinations of many measures, we can adopt some measures and apply them in different ways. For example, the authorities can revolve around how to advocate reducing car use and adjusting measures that attract people to take more public transportations. In addition, MEE can think about how to guarantee factories meet the emission standards.

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Appendix A

Circular of the General Office of the Chinese State Council on extending the 2020 Spring Festival holiday. http://www.gov.cn/zhengce/content/2020-01/27/content_5472352.htm

The date of resumption of work in all regions in 2020. https://jingyan.baidu.com/article/a3761b2b6e581c5476f9aab8.html

Summary of emergency response levels in 31 provinces. https://www.sohu.com/a/393427935_120206175

Beijing has upgraded its public health emergency response level from level-2 to level-3. http://www.xinhuanet.com/politics/2020-06/05/c_1126080194.htm

The level of emergency response for epidemic prevention and control in Tianjin has been adjusted from Level 2 to Level 3. http://www.cnr.cn/tj/jrtj/20200606/t20200606_525118820.shtml

Hebei's emergency response level has been upgraded from two to three. https://baijiahao.baidu.com/s?id=1668647468852060678&wfr=spider&for=pc

Shanghai: from tomorrow, the level 2 response will be changed to level 3 response. https://baijiahao.baidu.com/s?id=1666088525926243861&wfr=spider&for=pc

Notice on further strengthening community (village) epidemic prevention and control work. http://www.beijing.gov.cn/zhengce/zhengcefagui/202002/t20200210_1627106.html

Closed management shall be implemented in residential communities throughout the city. http://www.tj.gov.cn/sy/tpxw/202005/t20200520_2505145.html

Circular on further strengthening community management during epidemic prevention and control. http://www.sjz.gov.cn/col/1577843045360/2020/02/06/1580951204326.html

"Closed management" has been implemented in most of Shanghai's 13,000 residential communities. https://baijiahao.baidu.com/s?id=1658118633906180732&wfr=spider&for=pc

Henan implemented half closed management or closed for many communities. Some communities in Zhengzhou closed at 8 PM.

https://baijiahao.baidu.com/s?id=1657571722183136373&wfr=spider&for=pc

The latest! All villages in Jinan are under 24-hour closed management. https://baijiahao.baidu.com/s?id=1657730818391827867&wfr=spider&for=pc

Announcement of the City Headquarters for the Prevention and Control of Pneumonia Epidemic Caused by New Coronavirus Infection (No. 1). https://mp.weixin.qq.com/s/SN3UrB8Y9YMbZUIX8Cc6vA

China to Lift Lockdown Over Virus Epicenter Wuhan on April 8. https://www.bloomberg.com/news/articles/2020-03-24/china-to-lift-lockdown-over-virus-epicenter-wuhan-on-april-8

Appendix B

AQI	Air Pollution Level	Air Pollution Category	Health Implications	Recommended Precautions
0–50	Level 1	Excellent(好极了)	No health implications.	Everyone can continue their outdoor activities normally.
51–100	Level 2	Good(良好)	Some pollutants may slightly affect very few hypersensitive individuals.	Only very few hypersensitive people should reduce outdoor activities.
101–150	Level 3	Lightly Polluted(輕度污染)	Healthy people may experience slight irritations and sensitive individuals will be slightly affected to a larger extent.	Children, seniors and individuals with respiratory or heart diseases should reduce sustained and high-intensity outdoor exercises.
151–200	Level 4	Moderately Polluted(中度污染)	Sensitive individuals will experience more serious conditions. The hearts and respiratory systems of healthy people may be affected.	Children, seniors and individuals with respiratory or heart diseases should avoid sustained and high-intensity outdoor exercises. General population should moderately reduce outdoor activities.
201–300	Level 5	Heavily Polluted(重度污染)	Healthy people will commonly show symptoms. People with respiratory or heart diseases will be significantly affected and will experience reduced endurance in activities.	Children, seniors and individuals with heart or lung diseases should stay indoors and avoid outdoor activities. General population should reduce outdoor activities.
>300	Level 6	Severely Polluted(嚴重)	Healthy people will experience reduced endurance in activities and may also show noticeably strong symptoms. Other illnesses may be triggered in healthy people. Elders and the sick should remain indoors and avoid exercise. Healthy individuals should avoid outdoor activities.	Children, seniors and the sick should stay indoors and avoid physical exertion. General population should avoid outdoor activities.

Figure B1. AQI and health implications (MEE, 2012[18])

[18] The original figure in Chinese is available on The Ministry of Ecology and Environment (MEE). http://www.mee.gov.cn/ywgz/fgbz/bz/bzwb/jcffbz/201203/W020120410332725219541.pdf. But I downloaded the figure in English from Wikipedia page (https://en.wikipedia.org/wiki/Air_quality_index#Mainland_China).

Table B1. Beijing

VARIABLES	(1) NO_2_24h	(2) NO_2_24h	(3) NO_2_24h	(4) NO_2_24h	(5) NO_2_24h	(6) NO_2_24h	(7) $PM_{2.5}$_24h	(8) $PM_{2.5}$_24h	(9) $PM_{2.5}$_24h	(10) $PM_{2.5}$_24h	(11) $PM_{2.5}$_24h	(12) $PM_{2.5}$_24h
day	-0.194***	-0.0968**					-0.169	-0.373**				
	(0.0546)	(0.0471)					(0.180)	(0.152)				
treat	-0.767	-14.10***	-16.20***	-15.69***	-0.616	-10.23**	5.011	20.43	-8.551	3.792	4.008	16.26
	(4.732)	(3.542)	(2.512)	(3.411)	(4.678)	(4.591)	(18.22)	(12.58)	(6.542)	(9.678)	(17.00)	(12.38)
avt		0.344		-0.314		-0.136		0.840		-0.595		1.358
		(0.247)		(0.311)		(0.350)		(0.657)		(0.922)		(1.022)
humidity		0.306***		0.310***		0.301***		1.589***		1.638***		1.595***
		(0.0690)		(0.0682)		(0.0676)		(0.212)		(0.214)		(0.213)
wind speed		-8.294***		-8.451***		-8.444***		-3.130		-3.230		-2.968
		(0.972)		(0.952)		(0.971)		(2.886)		(2.859)		(2.886)
precipitation		-0.580**		-0.606**		-0.582**		-3.183**		-3.240*		-3.180**
		(0.248)		(0.292)		(0.280)		(1.499)		(1.646)		(1.464)
air pressure		-0.562***		-0.672***		-0.686***		-1.594***		-1.659***		-1.460***
		(0.150)		(0.171)		(0.164)		(0.458)		(0.539)		(0.487)
holiday		-20.35***		-21.17***		-16.68***		29.65**		18.47		25.69*
		(2.787)		(2.513)		(3.672)		(12.70)		(12.03)		(14.06)
day2			0.000577	0.00126*					-0.00482**	0.00178		
			(0.000700)	(0.000672)					(0.00186)	(0.00148)		
preday					-0.271***	-0.191**					0.342	-0.271
					(0.0866)	(0.0792)					(0.232)	(0.188)
postday					-0.120*	0.0248					-0.661***	-0.505*
					(0.0678)	(0.0741)					(0.247)	(0.266)
Constant	33.22***	615.2***	39.76***	729.0***	30.14***	737.7***	43.13***	1,591***	60.11***	1,668***	63.57***	1,459***
	(2.618)	(154.9)	(2.376)	(175.0)	(3.390)	(167.4)	(9.091)	(468.2)	(6.310)	(551.6)	(10.83)	(496.6)
Observations	159	159	159	159	159	159	159	159	159	159	159	159
R-squared	0.274	0.770	0.214	0.769	0.283	0.775	0.018	0.629	0.057	0.612	0.093	0.630

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table B2. Tianjin

VARIABLES	(1) NO_2_24h	(2) NO_2_24h	(3) NO_2_24h	(4) NO_2_24h	(5) NO_2_24h	(6) NO_2_24h	(7) $PM_{2.5}$_24h	(8) $PM_{2.5}$_24h	(9) $PM_{2.5}$_24h	(10) $PM_{2.5}$_24h	(11) $PM_{2.5}$_24h	(12) $PM_{2.5}$_24h
day	-0.134**	-0.0342					-0.0486	0.172				
	(0.0617)	(0.0500)					(0.175)	(0.169)				
treat	-8.982	-17.74***	-19.99***	-22.60***	-8.804	-19.51***	-20.13	-22.36	-24.29***	-11.78	-21.20	-21.30
	(6.174)	(3.978)	(2.823)	(4.020)	(5.989)	(5.030)	(19.32)	(14.15)	(7.456)	(10.59)	(18.82)	(16.53)
avt		0.264		0.544		0.601		-0.635		-0.319		-0.836

		(0.271)		(0.384)		(0.414)		(0.717)		(1.062)		(1.127)
humidity		0.133**		0.143**		0.125*		1.518***		1.469***		1.522***
		(0.0656)		(0.0645)		(0.0659)		(0.203)		(0.180)		(0.203)
wind speed		-8.388***		-8.254***		-8.278***		-8.490***		-8.496***		-8.555***
		(0.832)		(0.801)		(0.828)		(2.333)		(2.301)		(2.305)
precipitation		-1.535***		-1.505***		-1.455***		-5.969***		-5.793***		-6.018***
		(0.359)		(0.365)		(0.361)		(1.937)		(1.920)		(1.936)
air pressure		-0.664***		-0.534***		-0.579***		-1.928***		-2.021***		-1.979***
		(0.154)		(0.175)		(0.176)		(0.512)		(0.581)		(0.591)
holiday		-26.67***		-29.54***		-28.52***		-0.954		5.000		0.152
		(3.339)		(3.544)		(4.423)		(16.41)		(15.38)		(18.33)
day2			0.000384	-0.000884					-0.00569***	7.78e-06		
			(0.000734)	(0.000823)					(0.00179)	(0.00208)		
preday					-0.224**	0.0234					0.495*	0.137
					(0.101)	(0.0882)					(0.292)	(0.268)
postday					-0.0459	-0.122					-0.573***	0.224
					(0.0689)	(0.0894)					(0.173)	(0.245)
Constant	50.46***	748.4***	55.12***	618.2***	46.69***	664.3***	71.12***	1,992***	86.12***	2,083***	93.68***	2,042***
	(3.647)	(159.4)	(3.095)	(179.8)	(4.894)	(179.7)	(11.47)	(531.6)	(8.938)	(598.3)	(16.25)	(606.3)
Observations	165	165	165	165	165	165	165	165	165	165	165	165
R-squared	0.261	0.724	0.239	0.725	0.272	0.725	0.059	0.578	0.111	0.573	0.123	0.578

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table B3. Shanghai

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
VARIABLES	NO_2_24h	NO_2_24h	NO_2_24h	NO_2_24h	NO_2_24h	NO_2_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h
day	-0.202*	0.0605					-0.0104	0.115				
	(0.110)	(0.0892)					(0.187)	(0.269)				
treat	-0.525	-25.98***	-8.936***	-23.34***	0.528	-26.24***	-18.62**	-32.00**	-19.09***	-42.63***	-18.60**	-71.01***
	(5.225)	(4.437)	(2.515)	(3.275)	(4.160)	(6.970)	(9.101)	(13.43)	(5.522)	(9.505)	(9.290)	(21.01)
avt		0.241		0.256		0.249		-2.254*		-0.738		-1.026
		(0.418)		(0.474)		(0.445)		(1.212)		(1.323)		(1.219)
humidity		-0.0828		-0.106		-0.0834		-0.108		-0.392**		-0.198
		(0.0821)		(0.0820)		(0.0820)		(0.203)		(0.180)		(0.188)
wind speed		-6.394***		-6.515***		-6.376***		-8.154**		-7.074**		-5.438*
		(0.919)		(0.944)		(0.936)		(3.203)		(3.101)		(3.081)
precipitation		-0.408**		-0.390**		-0.410**		-1.312***		-1.404***		-1.550***
		(0.182)		(0.177)		(0.186)		(0.440)		(0.426)		(0.479)
air pressure		-0.757***		-0.811***		-0.757***		-1.878**		-2.151***		-1.852**
		(0.216)		(0.219)		(0.217)		(0.763)		(0.680)		(0.727)

holiday		-22.34***		-21.03***		-22.54***		-15.53		-28.17***		-45.42***
		(3.057)		(2.922)		(4.965)		(10.73)		(9.717)		(16.44)
day2			0.0113***	2.10e-05					-0.00181	-0.0194***		
			(0.00227)	(0.00220)					(0.00420)	(0.00629)		
preday					-0.747***	0.0703					-0.0220	1.587**
					(0.137)	(0.201)					(0.335)	(0.645)
postday					0.306**	0.0570					0.000453	-0.415
					(0.117)	(0.0998)					(0.185)	(0.250)
Constant	35.81***	846.7***	33.24***	901.8***	24.08***	846.7***	49.49***	2,031**	50.82***	2,336***	49.24***	2,042***
	(3.363)	(224.0)	(2.568)	(228.0)	(3.286)	(225.3)	(5.941)	(792.4)	(5.591)	(709.6)	(8.030)	(755.6)
Observations	85	85	85	85	85	85	85	85	85	85	85	85
R-squared	0.144	0.729	0.311	0.728	0.369	0.729	0.128	0.340	0.130	0.406	0.128	0.409

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table B4. Shijiazhuang

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
VARIABLES	NO_2_24h	NO_2_24h	NO_2_24h	NO_2_24h	NO_2_24h	NO_2_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h
day	0.00274	0.0144					0.200	0.140				
	(0.0617)	(0.0462)					(0.170)	(0.146)				
treat	-24.74***	-26.55***	-24.49***	-27.99***	-24.48***	-27.48***	-66.94***	-32.87**	-50.33***	-46.86***	-68.78***	-55.51***
	(6.556)	(4.434)	(2.696)	(4.057)	(6.151)	(5.423)	(18.54)	(14.01)	(6.980)	(10.77)	(16.77)	(15.13)
avt		0.0301		0.390		0.210		-2.458***		1.046		1.914*
		(0.278)		(0.435)		(0.457)		(0.857)		(1.138)		(1.150)
humidity		0.139**		0.151**		0.145**		1.321***		1.437***		1.463***
		(0.0652)		(0.0657)		(0.0673)		(0.177)		(0.185)		(0.184)
wind speed		-7.880***		-8.001***		-7.966***		-3.298		-4.478		-5.399*
		(1.398)		(1.369)		(1.420)		(3.116)		(2.793)		(2.894)
precipitation		-0.118		-0.133		-0.113		-3.900		-4.041*		-3.773*
		(1.126)		(1.087)		(1.110)		(2.389)		(2.088)		(1.961)
air pressure		-0.874***		-0.776***		-0.823***		-2.647***		-1.690***		-1.413**
		(0.152)		(0.193)		(0.198)		(0.607)		(0.634)		(0.586)
holiday		-29.50***		-30.73***		-30.65***		21.33*		9.367		-6.623
		(3.489)		(4.029)		(4.936)		(12.56)		(12.56)		(14.62)
day2			0.000627	-0.000744					-0.0101***	-0.00724***		
			(0.000672)	(0.000792)					(0.00155)	(0.00189)		
preday					-0.128	0.0445					1.135***	0.873***
					(0.105)	(0.0895)					(0.240)	(0.241)
postday					0.129**	-0.0256					-0.702***	-0.833***
					(0.0562)	(0.0840)					(0.176)	(0.231)
Constant	60.50***	956.7***	58.88***	857.2***	54.93***	906.2***	113.3***	2,728***	128.9***	1,759***	153.0***	1,498**

	(4.004)	(156.7)	(3.096)	(196.1)	(5.513)	(200.9)	(10.29)	(620.8)	(7.577)	(648.4)	(13.13)	(596.4)
Observations	169	169	169	169	169	169	169	169	169	169	169	169
R-squared	0.333	0.687	0.337	0.689	0.355	0.687	0.210	0.631	0.350	0.656	0.372	0.670

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table B5. Jinan

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
VARIABLES	NO_2_24h	NO_2_24h	NO_2_24h	NO_2_24h	NO_2_24h	NO_2_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h
day	-0.536***	-0.242**					-0.410	-0.284				
	(0.183)	(0.120)					(0.403)	(0.355)				
treat	-2.692	-15.83***	-18.75***	-21.90***	-0.651	-6.406*	-34.74**	-46.07***	-47.31***	-54.82***	-34.71**	-48.97***
	(6.487)	(4.528)	(2.672)	(2.967)	(3.161)	(3.727)	(14.02)	(11.84)	(7.651)	(6.822)	(14.30)	(16.06)
avt		0.880		1.246**		1.245***		5.242***		4.861***		5.130***
		(0.569)		(0.474)		(0.449)		(1.048)		(1.052)		(1.066)
humidity		0.168**		0.112		0.0464		1.072***		1.158***		1.109***
		(0.0792)		(0.0724)		(0.0649)		(0.232)		(0.250)		(0.257)
wind speed		-3.362**		-6.054***		-5.398***		-6.820*		-5.509		-6.194
		(1.640)		(1.524)		(1.645)		(3.986)		(4.255)		(4.251)
precipitation		-0.545		-0.457		-0.544		-4.710***		-4.684***		-4.710***
		(0.593)		(0.471)		(0.494)		(1.299)		(1.236)		(1.309)
air pressure		0.710*		0.732**		0.474		1.386		1.465		1.459
		(0.366)		(0.324)		(0.322)		(0.950)		(0.945)		(0.978)
holiday		-21.93***		-15.05***		-7.161*		-8.533		-15.94		-13.08
		(2.459)		(3.167)		(3.613)		(7.702)		(10.48)		(14.53)
day2			0.0293***	0.0197***					-0.00640	-0.0161		
			(0.00480)	(0.00460)					(0.0125)	(0.0149)		
preday					-1.607***	-1.386***					-0.425	0.0687
					(0.210)	(0.257)					(0.700)	(0.987)
postday					0.434***	0.419***					-0.397	-0.487
					(0.0796)	(0.155)					(0.445)	(0.491)
Constant	36.16***	-672.4*	35.25***	-692.7**	19.56***	-448.5	90.28***	-1,364	98.65***	-1,437	90.05***	-1,433
	(3.850)	(370.4)	(2.682)	(326.3)	(2.699)	(325.0)	(7.904)	(962.8)	(7.340)	(958.1)	(11.06)	(988.0)
Observations	61	61	61	61	61	61	61	61	61	61	61	61
R-squared	0.438	0.767	0.606	0.806	0.750	0.841	0.407	0.649	0.400	0.652	0.407	0.651

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table B6. Zhengzhou

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)

VARIABLES	NO_2_24h	NO_2_24h	NO_2_24h	NO_2_24h	NO_2_24h	NO_2_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h
day	-0.0946	-0.106					-0.263	-0.164				
	(0.145)	(0.140)					(0.406)	(0.426)				
treat	-16.56**	-20.62***	-20.44***	-16.67***	-14.97***	-14.30***	-50.46***	-66.57***	-61.88***	-65.35***	-50.35***	-62.51***
	(7.188)	(5.651)	(2.743)	(3.523)	(4.107)	(4.332)	(16.99)	(16.42)	(9.906)	(13.64)	(17.51)	(18.23)
avt		1.176		-0.0168		-0.106		6.858***		5.628**		6.033**
		(0.856)		(0.679)		(0.838)		(2.519)		(2.582)		(2.550)
humidity		0.178*		0.197*		0.165		2.258***		2.275***		2.249***
		(0.103)		(0.101)		(0.103)		(0.388)		(0.396)		(0.396)
wind speed		-4.704**		-6.029***		-5.907***		8.032		7.016		7.258
		(2.296)		(1.867)		(1.927)		(7.552)		(7.743)		(7.622)
precipitation		-0.307		-0.518		-0.522		-2.957		-3.170*		-3.096*
		(0.511)		(0.523)		(0.519)		(1.823)		(1.840)		(1.859)
air pressure		0.197		0.116		-0.0440		3.142**		3.053**		2.987*
		(0.468)		(0.379)		(0.391)		(1.487)		(1.516)		(1.512)
holiday		-21.99***		-14.20***		-8.281**		-13.03		-6.870		-4.215
		(3.269)		(2.932)		(3.420)		(10.89)		(11.08)		(14.32)
day2			0.0159***	0.0141***					0.000306	0.0124		
			(0.00229)	(0.00226)					(0.0102)	(0.00969)		
preday					-0.917***	-0.779***					-0.319	-0.596
					(0.173)	(0.175)					(0.770)	(0.728)
postday					0.673***	0.687***					-0.210	0.346
					(0.0947)	(0.154)					(0.329)	(0.435)
Constant	46.41***	-158.4	38.36***	-80.67	28.31***	74.29	110.3***	-3,248**	115.9***	-3,160**	109.1***	-3,098*
	(4.501)	(479.4)	(2.796)	(388.7)	(3.688)	(402.2)	(9.948)	(1,533)	(8.971)	(1,563)	(15.49)	(1,557)
Observations	87	87	87	87	87	87	87	87	87	87	87	87
R-squared	0.316	0.615	0.546	0.715	0.607	0.720	0.322	0.618	0.318	0.627	0.322	0.623

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table B7. Wuhan

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
VARIABLES	NO_2_24h	NO_2_24h	NO_2_24h	NO_2_24h	NO_2_24h	NO_2_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h	$PM_{2.5}$_24h
day	-0.148***	-0.133***					0.0315	0.245**				
	(0.0568)	(0.0475)					(0.0867)	(0.114)				
treat	-23.13***	-28.16***	-34.25***	-39.13***	-22.70***	-28.39***	-23.44***	-48.46***	-21.14***	-30.76***	-23.99***	-47.53***
	(4.252)	(3.935)	(2.486)	(2.419)	(3.788)	(3.920)	(8.258)	(11.59)	(3.544)	(3.870)	(7.751)	(9.143)
avt		0.508		0.465		-0.104		0.536		2.287***		3.041***
		(0.388)		(0.456)		(0.482)		(0.752)		(0.785)		(0.801)
humidity		-0.442***		-0.419***		-0.451***		-0.274		-0.282		-0.238

		(0.119)		(0.122)		(0.119)		(0.300)		(0.286)		(0.281)
wind speed		-7.216***		-7.347***		-7.107***		2.513		2.343		2.066
		(1.465)		(1.504)		(1.452)		(2.527)		(2.239)		(2.231)
precipitation		0.0373		0.0312		-0.000890		-1.012**		-0.881***		-0.856***
		(0.220)		(0.224)		(0.210)		(0.393)		(0.315)		(0.327)
air pressure		-0.516*		-0.420		-0.723**		-0.0610		0.293		0.785
		(0.287)		(0.285)		(0.298)		(0.527)		(0.495)		(0.505)
holiday		2.660		9.325***		5.642**		28.90***		13.28**		16.70**
		(2.781)		(2.434)		(2.679)		(8.332)		(5.685)		(7.896)
day2			0.00261***	0.00121*					-0.00330***	-0.00692***		
			(0.000671)	(0.000685)					(0.000986)	(0.00138)		
preday					-0.369***	-0.267***					0.311**	0.794***
					(0.0962)	(0.0916)					(0.129)	(0.140)
postday					0.0642	0.0204					-0.237**	-0.383**
					(0.0418)	(0.0623)					(0.0924)	(0.148)
Constant	50.62***	618.9**	51.26***	521.9*	42.23***	830.7***	60.55***	148.4	65.66***	-222.1	71.16***	-718.2
	(2.628)	(299.5)	(2.324)	(298.5)	(3.293)	(311.3)	(4.746)	(555.3)	(3.800)	(521.6)	(6.262)	(530.8)
Observations	151	151	151	151	151	151	151	151	151	151	151	151
R-squared	0.563	0.737	0.580	0.731	0.604	0.744	0.184	0.332	0.235	0.404	0.243	0.436

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1

Table B8. Robustness Check: Air Quality Index

AQI	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)
City	Beijing		Tianjin		Shanghai		Shijiazhuang		Jinan		Zhengzhou		Wuhan	
Linear model														
treat=1	2.525	15.8	-25.17	-31.88*	-19.66*	-40.06***	-79.40***	-48.35***	-39.81**	-53.98***	-61.51***	-80.55***	-28.75***	-59.74***
	-20.88	-15.67	-22.09	-17.66	-10.06	-13.79	-20.91	-16.63	-17	-14.94	-19.69	-19.75	-9.349	-13.63
Quadratic model														
treat=1	-2.986	7.167	-26.32***	-13.24	-18.96***	-49.87***	-53.62***	-59.03***	-55.31***	-65.60***	-68.96***	-76.92***	-29.49***	-41.81***
	-7.55	-11.54	-8.52	-13.07	-6.104	-9.87	-8.214	-13.31	-9.277	-8.462	-11.26	-16.23	-4.241	-4.307
Interaction model														
treat=1	1.85	18.67	-25.96	-26.13	-18.99*	-72.03***	-81.05***	-70.46***	-39.67**	-59.04***	-61.01***	-75.87***	-28.94***	-58.94***
	-20.2	-15.67	-21.98	-20.43	-9.874	-23.19	-19.71	-18.83	-17.36	-20.65	-20.16	-21.68	-9.265	-11.68
Controls	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	No	Yes
Observations	159	159	165	165	85	85	169	169	61	61	87	87	151	151

Robust standard errors in parentheses
*** p<0.01, ** p<0.05, * p<0.1