

COVID-19, City Lockdown, and Air Pollution: Evidence from China

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The rapid spread of COVID-19 is a global public health challenge. To prevent the escalation of its transmission, China locked down one-third of its cities and strictly restricted human mobility and economic activities. Using timely and comprehensive air quality data in China, we show that these counter-COVID-19 measures led to remarkable improvement in air quality. Within weeks, the Air Quality Index and PM_{2.5} concentrations were brought down by 25%. The effects are larger in colder, richer, and more industrialized cities. We estimate that such improvement would avert 24,000 to 36,000 premature deaths from air pollution on a monthly basis.

Keywords: COVID-19, coronavirus, PM_{2.5}, lockdown, health

JEL: Q53, Q52, I18, I15

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1. Introduction

The exponential spread of the COVID-19 pandemic is a global public health crisis. In December 2019, an unknown disease, later named as COVID-19, was identified in Wuhan (Lu et al., 2020; Zhu et al., 2020), and within three months, the disease had affected more than 100 countries (WHO, 2020). The explosion of the COVID-19 cases around the world has made it a global pandemic and brings about devastating consequences (Wang et al., 2020). To contain the virus, many countries adopted dramatic measures to reduce human interaction, including enforcing strict quarantine, prohibiting large-scale private and public gatherings, restricting private and public transportations, encouraging social-distancing, imposing a curfew, and even locking down an entire city.

While the costs of enforcing these preventative measures are undoubtedly enormous, there are also speculations that these measures could unintentionally bring about substantial social benefits. Among them, some argue that locking down cities could have significantly improved environmental quality, which would be beneficial to ordinary people and partially offset the costs of these counter-COVID-19 measures. For example, satellite images caught a sharp drop in air pollution in several counties that have taken aggressive measures on the transmission of the virus.²

In this study, we carry on a rigorous investigation into this issue and estimate how locking down cities affect air quality in China. We focus on China for two reasons. First, China was

² For example, the satellite images show dramatic declines in NO₂ in U.S., China, and Europe: US: <https://edition.cnn.com/2020/03/23/health/us-pollution-satellite-coronavirus-scen-trnd/index.html>; China: <https://www.earthobservatory.nasa.gov/images/146362/airborne-nitrogen-dioxide-plummets-over-china>; Europe: <https://www.eea.europa.eu/highlights/air-pollution-goes-down-as>. Relatedly, a news article on Forbes provided some rough estimates on the potential benefits caused by city lockdown in China: <https://www.forbes.com/sites/jeffmcmahon/2020/03/16/coronavirus-lockdown-may-have-saved-77000-lives-in-china-just-from-pollution-reduction>.

hit hard by the COVID-19 outbreak, and the Chinese government launched draconian countermeasures to prevent the escalation of the infections (Chen et al., 2020; Kucharski et al., 2020). Nearly one-third of Chinese cities were locked down in a top-down manner, and various types of economic activities were strictly prohibited. In these cities, individuals were requested to stay at home, unnecessary commercial operations, private and public gatherings were suspended, transportations were largely banned (both within a city and across cities), mandatory temperature checking could be found in most public facilities. Second, China also suffers greatly from severe air pollution problems, with some estimates suggesting that air pollution is associated with an annual loss of nearly 25 million healthy life years (Kassebaum et al., 2014). If city lockdown indeed significantly improved the air quality in China, the implied health benefits would be an order of magnitude larger than in countries with lower initial pollution levels.

Since the risk of disease transmission differed substantially across different locations and different periods, the timing of lockdown also varied. We thus estimate a set of difference-in-differences (DiD) models to quantify the impact of city lockdown on air pollution. Using air quality data from more than 1,600 monitoring stations in China, we find that city lockdown indeed improved the air quality: compared to cities without formal lockdown policies, the weekly Air Quality Index (AQI) and $PM_{2.5}$ concentration in the locked-down cities declined respectively by 19.4 points (18%) and $13.9 \mu g/m^3$ (17%).³ To further address the concern that cities without formal lockdown policies might also be affected by the diseases preventative measures (e.g., all cities extended the Chinese Spring Festival holiday, required social distancing and urged people to stay at home), we estimate another set of DiD

³ The Air Quality Index (AQI) is a comprehensive measure of air pollution in China and also widely used around the world. The index is constructed by $PM_{2.5}$, PM_{10} , SO_2 , CO , O_3 , and NO_2 concentrations.

models, comparing the changes in air pollution levels in these (no-lockdown) cities before and after the Spring Festival relative to the previous year, and find that in these cities the AQI and PM_{2.5} decreased by 8.8 points (7%), and 8.4 µg/m³ (8%). The overall improvement in both AQI and PM_{2.5} by the counter COVID-19 measures is estimated to be around 25% in locked-down cities and 7~8% in other cities.

The effect of lockdown differs considerably across different types of cities. We find that the richer, more industrialized, and colder cities experienced larger reductions in air pollution levels. For example, city lockdown is estimated to reduce on the AQI by more than 30 points in cities with more manufacturing output, which is three times larger than its impact on cities with lower manufacturing output.

The remarkable improvement in air quality has three important implications. First, it could potentially bring about massive health benefits. A back-of-envelope calculation shows that the improved air quality induced the counter-COVID-19 measures could avert 24,000 to 36,000 premature deaths on a monthly basis. As air pollution also affects morbidity, productivity, and people's defensive expenditure (e.g., air filters), the implied benefits could be even greater if such improvement could sustain (e.g., Deschênes et al., 2017; Barwick et al., 2018; Zhang et al., 2018; Ito and Zhang, 2020). Second, our findings show that traffic, industrial, and business activities are indeed important sources of air pollution. They provide a benchmark for future environmental regulations and highlight the necessity to control emissions from these sources when the business goes back to normal. Finally, while the air quality improvement during this period was unprecedented, the baseline air pollution level after city lockdown remained high. For example, the PM_{2.5} concentration in locked-down cities was still more than four times higher than what WHO considers safe (10 µg/m³ for the annual mean) (WHO, 2005), even though almost all the non-essential production and

business activities were suspended. This finding suggests that other sources of air pollution continue to contribute significantly: in particular, the coal-fired winter heating system could be the primary polluting source during our study period (Chen et al., 2013; Ebenstein et al., 2017). Our research highlights that without further reducing the reliance on coal, it will be a real challenge for the country to win its “war against pollution” (Greenstone and Schwartz, 2018; Greenstone et al., 2020).

2. Data and Methodology

2-1. Data

The core of our empirical analysis uses a comprehensive air quality data in China. The air quality data are collected from 1,600 monitoring stations covering all the prefectural cities in China. We aggregate the station level data to the city level and further combine them with weather variables, including temperature, precipitation, and snow. The air quality data are collected from the Ministry of Ecology and Environment, and the weather data are collected from the Global Historical Climatology Network from the National Oceanic and Atmospheric Administration.

We collect local governments’ lockdown policies city by city from news media and government announcements. The city-lockdown was implemented by the city government and had to be approved by the provincial government. As the disease prevalence varied greatly across different regions, the terms and requirements of city lockdown also differed across provinces and cities. In our analysis, we define city lockdown when the following three preventive measures were ALL enforced: 1) prohibition of the unnecessary commercial activities for people’s daily lives, 2) prohibition of any types of gathering by residents, 3) restrictions on private (vehicles) and public transportations. More details on these datasets

are described in Appendix 1.

Figure 1 presents the map on the location of locked-down cities.⁴ The map shows that in most cities near Wuhan city, the strict lockdown was enforced. However, there is a considerable variation in the lockdown status for cities that are far away from Wuhan. Following our definition, 95 out of 324 cities were locked-down during our study period. The timing of the lockdown is plotted in Appendix Figure A1. We see that that most of the lockdowns were enforced from January 23rd to February 11th.

Merging these datasets, we obtain city-by-week panel data in 324 Chinese cities from the period of January 1st to March 1st, which cover several weeks before and after the introduction of city lockdowns. We report the summary statistics of air pollution and weather variables during this period in Appendix Table A2. The average AQI is 74, with a standard deviation of 42. The PM_{2.5} concentration is 52 µg/m³, five times higher than the WHO standard (10 µg/m³ for annual mean, and 25 µg/m³ for a daily mean). Cities being locked-down were, on average, more polluted than the control cities. It is likely because Wuhan and its neighboring cities are generally more polluted than cities that are far away. We also see a sharp decline in AQI (roughly 34%) after the lockdown.

2-2. Empirical Strategy

We use two sets of DiD models to identify the impact of counter-COVID-19 on air pollution. First, in our baseline regression, we estimate the relative change in air pollution levels between the treated and control cities using the following model:

$$Y_{it} = 1[\text{city lockdown}]_{it} * \beta + X_{it} * \alpha + \mu_i + \pi_t + \varepsilon_{it} \quad (1)$$

where Y_{it} represents the level of air pollution in city i in month-by-week t , $1[\text{city lockdown}]_{it}$ denotes whether lockdown is enforced in city i in month-by-week t ,

⁴ Appendix Table A1 lists the lockdown status of all the Chinese prefectural cities.

and it takes one if the city is locked down and zero otherwise. X_{it} are the control variables, including temperature, temperature squared, precipitation, and snow depth. μ_i indicate city-fixed effects and π_t indicate month-by-week fixed effects. As both city and week fixed effects are included in the regression, the coefficient β estimates the difference in air pollution between the treated (locked-down) cities and the control cities before and after the enforcement of the lockdown policy. We expect the coefficient β to be negative, as the industrial and business activities were restricted in the locked-down cities, and thus their air pollution levels should significantly decrease.

The underlying assumption for the DiD estimator is that treated and control cities have parallel trends in the outcome before city lockdown. To test this assumption, we conduct a parallel-trend test following Jacobson et al. (1993):

$$Y_{it} = \sum_{m=k, m \neq -1}^M 1[\text{city lockdown}]_{it,k} * \beta^k + X_{it} * \alpha + \mu_i + \pi_t + \varepsilon_{it} \quad (2)$$

where $1[\text{city lockdown}]_{it,k}$ are a set of dummy variables indicating the treatment status at different periods. The dummy for $m = -1$ is omitted in Equation (2) so that the post-lockdown effects are relative to the period immediately before the launch of the policy. The parameter of interest β^k estimates the effect of city lockdown m weeks after the implementation. We include leads of the treatment dummy in the equation, testing whether the treatment affects the air pollution levels before the launch of the policy. Intuitively, the coefficient β^k measures the difference in air quality between cities under lockdown and otherwise in period k relative to the difference one year before the lockdown. We expect lockdown would improve air quality with β^k being negative when $k \geq 0$. If the parallel-trend assumption holds, β^k would be close to zero when $k \leq -2$.

Note that it is possible that even in a city that did not have a formal lockdown policy,

people's daily lives could still be affected by the counter-virus measures. In fact, in all Chinese cities, the Spring Festival holiday was extended, people were advised to stay at home when possible, enforce social distancing, and keep good hygiene. We, thus, examine this possibility by comparing the air pollution changes between 2019 and 2020 for the same period (January 1st to March 1st) within the control group. As the explosion of the COVID-19 cases coincided with China's Spring Festival (SF), we investigate whether the trend of air quality in 2020 differs from the trend in 2019 after the Festival, by fitting the following model:

$$Y_{itj} = 1[SF * 1(year \geq 2020)]_{itj} * \beta + X_{itj} * \alpha + \mu_i + \pi_t + \varepsilon_{itj} \quad (3)$$

where i denotes city, t is month-by-week, and j represents year. $1[SF * 1(year \geq 2020)]_{itj}$ is our variable of interest, and it takes one if it is after the Chinese Spring Festival in the year 2020, and takes zero otherwise. The estimated coefficient β would be zero if the coronavirus and countermeasures do not affect control cities. Similar to the Model (1) X_{itj} are the control variables, μ_i is city fixed effects and π_t indicates month-by-week fixed effects.

The identifying assumption for Model (3) is similar to Model (1). We require the trends in air quality before the Spring Festival in 2019 to be similar to the trends in air quality in the corresponding period in 2020 (i.e., the parallel-trend assumption). We can test this assumption analogously using Model (2). In all the regressions, we cluster the standard errors at the city level.

3. Results

3-1. Main Results

We start by presenting the patterns in the raw air quality data. In Panel A of Figure 2, we plot the AQI between the treatment and control cities over the study time in 2020 with a

solid blue line representing the treatment group and red dash line representing the control group. This figure shows the first margin: to what extent city lockdown affected air pollution between the treated and control cities. The figure shows the treatment group had worse air pollution levels (higher AQI) than the control group before the Chinese Spring Festival. However, the difference significantly decreased after more cities were locked down, suggesting the lockdown could improve air quality.

In Panel B of Figure 2, we look at the second margin: to what extent the control cities were also affected by the counter-virus measures. We see the AQI levels were almost equivalent before the Spring Festival in 2019 and 2020, implying the parallel trend assumption is likely to hold. In 2020, shortly after the festival, we observe that the air pollution levels became slightly lower, relative to the 2019 Post-Festival season. This result indicates that air quality in the control cities could be marginally improved, despite that they were not formally locked down.

Table 1 summarizes the regression results from estimating Equations (1) and (3). Column (1) to (4) shows the results on the first margin from Equation (1): the effects of the city lockdown on air quality. Here, we focus on AQI and $PM_{2.5}$ concentrations, as these are designated as the primary targets in reducing air pollution.⁵ We find that the coefficient of lockdown is large and statistically significant at 1% in all the regression. City lockdown decreased the AQI by 19.4 points (18%) and $PM_{2.5}$ by $13.9 \mu g/m^3$ (17%) when including weather controls and a set of fixed effects (in column (2) and (4)). These estimates are remarkably robust to the including of weather variables, indicating that the changes in air pollution caused by city lockdown are not correlated with weather conditions.

In Column (5) to (8), we test the second margin: whether the air quality in the control

⁵ The results for other pollutants are reported in Appendix Table A3.

cities was affected by the disease preventive measures (most of such actions were implemented around the Spring Festival period) relative to 2019 air quality. We find that air quality also improved, but the effects are smaller than the first margin. The results show that AQI decreases by 8.8 points (7%), and $PM_{2.5}$ by 8.4 (8%) after controlling for weather variables.

Combining these two sets of results, we could estimate the total effects of city-lockdown on air quality relative to the identical season in the previous year. We find that lockdown improves air quality substantially: it reduces AQI and $PM_{2.5}$ by around 25% in the locked-down cities and 7~8% in the control cities.

Figure 3 reports the parallel-trend tests using the event-study approach.⁶ In Panel A, we estimate the Equation (2) and plot the estimated coefficients and their 95% confidence intervals. We find that the estimated coefficients for the lead terms ($k \leq -2$) are all statistically insignificant, implying that there is no systematic difference in the trends between treatment and control groups before the city lockdown. We also see that the trends break after the city lockdown, i.e., the lag terms ($k \geq 0$) became negative and statistically significant. The AQI dropped by 20~30 points within two weeks after lockdown and remained statistically significant in subsequent periods. In Panel B, we test the parallel trend assumption for cities in the control group using data in 2019 and 2020. We find that their trends in air quality before the Chinese Spring Festival were also similar, suggesting that the air quality in 2019 could be a reasonable counterfactual for air quality in 2020 in the controlled cities. The estimated coefficients after the festival show a meaningful reduction in air pollution, with the AQI being reduced by 5 to 10 points. Appendix Figure A2 repeats the same exercise using log AQI, $PM_{2.5}$, and log $PM_{2.5}$ as the outcomes, and we observe very similar patterns.

⁶ The corresponding regression results are reported in Appendix Table A4 and Table A5.

In Appendix Table A6, we further check the robustness of the results in several ways. In Panel A, we exclude cities in Hubei provinces, where the COVID-19 epidemic originated, and re-estimate Table 1. We find that all the findings remain similar, suggesting that our main results are not driven by a few cities that were most affected by the virus. In Panel B, we repeat this exercise using daily-level data and again reach a similar conclusion.

3-2. Heterogeneity

In Figure 4, we investigate the heterogeneous impacts of city lockdown. We plot the estimated coefficients and their 95% confident intervals from fitting Equation (1) using different subsamples. We use the mean values to separate the “high” group from the “low” group for each pair of heterogeneity analyses. For example, if a city's GDP is higher than the mean GDP, it falls into a “high” GDP group.

We find that the effect of lockdown varies significantly across different types of cities. Panel A shows that impact is much more significant in colder cities or ones located in the North. The estimated reduction in the AQI is around 20~30 points for those cities and is 0~10 points in warmer or Southern cities. The difference could be driven by the fact that colder cities consumed more coals for heating, and lockdown reduces such consumption in offices, plants, and schools, which eventually led to a greater improvement in air quality. In Panel B, we see the effect is greater in cities with larger GDP, population, and higher income (measured by per capita GDP). This is consistent with the fact that energy consumption is higher in more agglomerated economies, where a lot of economic activities take place. Finally, Panels C and D show that in the cities that rely more on industrial activities (measured by the manufacturing output, the volume of traffic, the number of firms, and the emissions of different types of pollutants), the effect is more substantial. We repeat our heterogeneity analysis to $PM_{2.5}$ and similarly illustrate the results in Appendix Figure A3. Appendix Table

A7 presents the full set of results on AQI and PM_{2.5}.

To summarize, the impact of city lockdown on air quality is more considerable in colder, larger, richer, and more industrialized cities. This finding implies that coal consumption, industrial activities, and transportation all contribute substantially to air pollution in China.

4. Potential Benefits from Improved Air Quality

A large strand of literature has investigated how air pollution affects population health. Here, we provide some back-of-the-envelope calculations on the potential benefits caused by the air quality improvement caused by China's efforts to contain the virus, based on estimates in the existing literature.

We borrow estimates from studies that meet the following two criteria. First, we focus on quasi-experimental studies that investigate how exogenous changes in air quality affects health outcomes. As the air pollution variation could be confounded by factors that also affect population health, the estimates from these studies are generally recognized as being more credible than those based on associational models (e.g., Graff Zivin and Neidell, 2013; Dominici et al., 2014). Second, we focus on the most recent research in China. Since the effects of air pollution on mortality could depend on the baseline pollution levels, income, and the institutional quality, studies using data from the early years may be less relevant to our research context (Arceo et al., 2014; Cheung et al., 2020).

We search for the literature and identify two studies that meet both criteria: He et al. (2020) use seasonal agricultural straw burnings as the instrumental variable for PM_{2.5}, and estimate how PM_{2.5} affects mortality; Fan et al. (2020) examine how turning-on the coal-fired winter heating system affects weekly mortality.⁷ These studies estimate 10 µg/m³ increase in

⁷ A few other studies also use quasi-experimental approaches to estimate the impacts of air pollution on

PM_{2.5} would lead to a 2.2%~3.25% increase in mortality, which is largely consistent with a recent quasi-experimental study in the U.S. (Deryugina et al., 2020).⁸

The results are summarized in Table 2. Recall that the counter-COVID-19 measures reduced PM_{2.5} in the control cities by 8.40 µg/m³, and the city lockdown further decreased PM_{2.5} in the treated cities by 13.9 µg/m³ (total 22.3 µg/m³). Assuming these counter-virus measures, on average last for 4 weeks/1 months (which is the case for most cities, except cities in Hubei), the total number of averted premature deaths would be around 24,000 to 36,000. These numbers are significantly larger than the total number of deaths caused by COVID-19 in China (less than 3,300 as of March 28, 2020) (WHO, 2020) and illustrate the enormous social costs associated with air pollution.

5. Conclusion

Using a timely and comprehensive dataset, we investigate the effect of city lockdown on air quality in China, which could bring about massive social benefits and partially offset the costs of the COVID-19 epidemic. We find such drastic preventive measures have a significant impact on air quality. We estimated that after its implementation, air quality declined by around 25% (28.2 points for AQI, and 22.3 µg/m³ for PM_{2.5}) relative to the same season in 2019. We also showed that, even in the control cities, where lockdown was not fully implemented, air quality improved (AQI decreased by 8.8 points (7%) and PM_{2.5} by 8.4 µg/m³ (8%)). These effects are much larger in more industrialized, richer, and colder cities.

The remarkable improvement in air quality could lead to substantial health benefits.

mortality in China, including Chen et al. (2013), He et al. (2016), and Ebenstein et al. (2017). However, these studies are less relevant to our research contest as they use data at least a decade ago and focus on coarse measures of air pollution, such as total suspended particles (TSP) or PM₁₀.

⁸ We summarize the related studies in the Appendix Table A8. We see that quasi-experimental studies find the larger effects on mortality than associational studies.

Based on the previous estimates on the relationship between air pollution and mortality, we show that averted premature deaths per month could be around 24,000 to 36,000, which is an order of magnitude larger than the number of deaths caused directly by COVID-19 in China (WHO, 2020). As air pollution also has significant impacts on morbidity, productivity, and defensive investment, our estimates should be interpreted as the lower-bound of the benefits that can be derived from the air quality improvement.⁹

We conclude by pointing out some caveats of this study. First, we only consider the short-term effects of city lockdown. As cities may recover their production after the lockdown, the short-term improvement in air quality could be offset in the longer term. Second, we examine the effect of city shutdown on outdoor air quality and do not account for indoor air quality in our benefit calculation. More people likely spend their time indoor after the lockdown. If indoor air quality is worse than outdoor air quality (e.g., some areas rely heavily on inefficient coal-fired stoves for heating), the beneficial effects from better outdoor air quality could be reduced. Finally, our calculation of the averted number of deaths is not based on actual mortality data, which are not yet available to the researchers. If COVID-19 or city-lockdown affects mortality through other channels, the overall mortality costs could be higher or lower, depending on how different channels are affected. For example, medical resources in many cities run short immediately after the disease outbreak, thus patients could die because they were unable to receive timely and proper treatment (Xie et al., 2020). The counter-virus measures also negatively affected the economy and employment, which are detrimental to population health. In such cases, the excess deaths caused could be larger. In comparison, COVID-19 may have raised individuals' awareness

⁹ For example, the morbidity cost of air pollution is found to be around two-thirds of mortality costs in China (Barwick et al., 2018),

of their health conditions and made people practice good hygiene. This could significantly reduce deaths from other diseases, particularly influenza.¹⁰ While estimating the overall mortality cost of COVID-19 and city lockdown is beyond the scope of our paper, future research on these issues is warranted to understand the full implications of the COVID-19 pandemic.

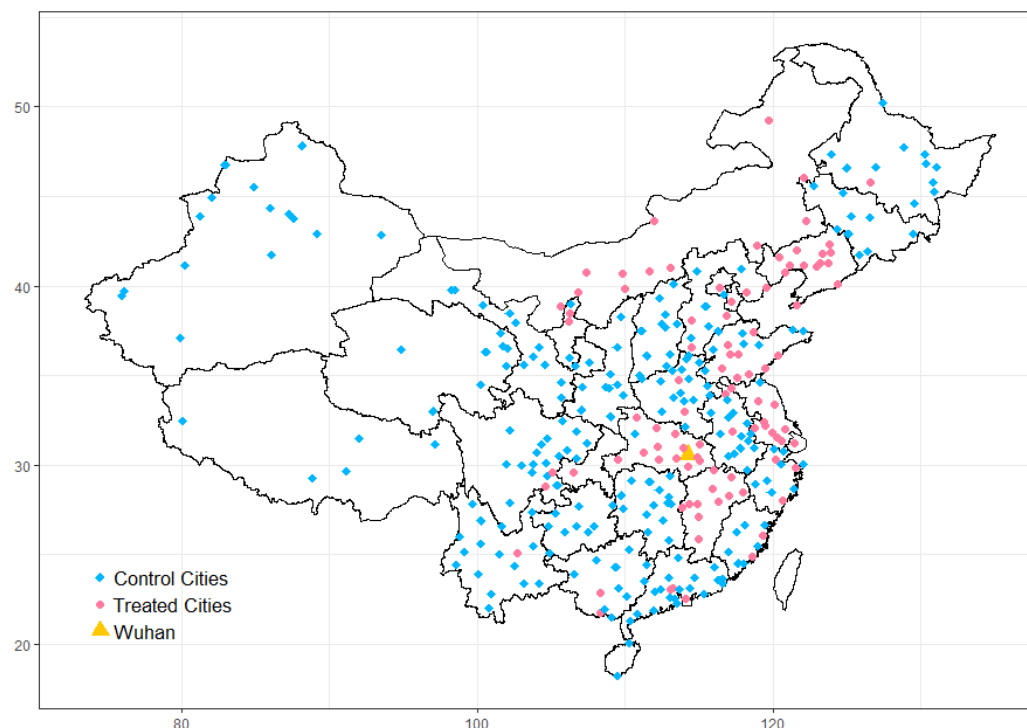
¹⁰ For example, in Hong Kong, the number of deaths caused by influenza and the number of cases of influenza-like illness reduced by more than 50% in, as compared to previous years: <https://www.ft.com/content/ad7ae6b4-5eab-11ea-b0ab-339c2307bcd4>; in Japan, the influenza-like illness cases in the first week of February were only about 30% compared to the same week a year ago: <https://www.japantimes.co.jp/news/2020/02/21/national/influenza-wave-dramatically-wanes-japan-amid-spread-coronavirus/#.Xn9VHqgzaUl>.

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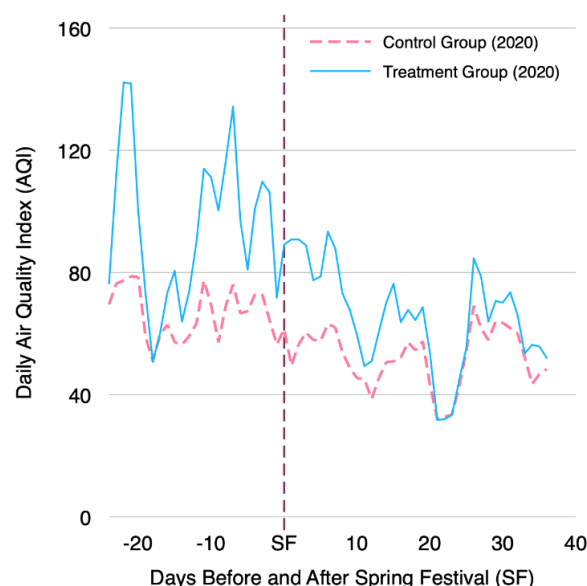
Figure 1. The Map of the Locked-down Cities



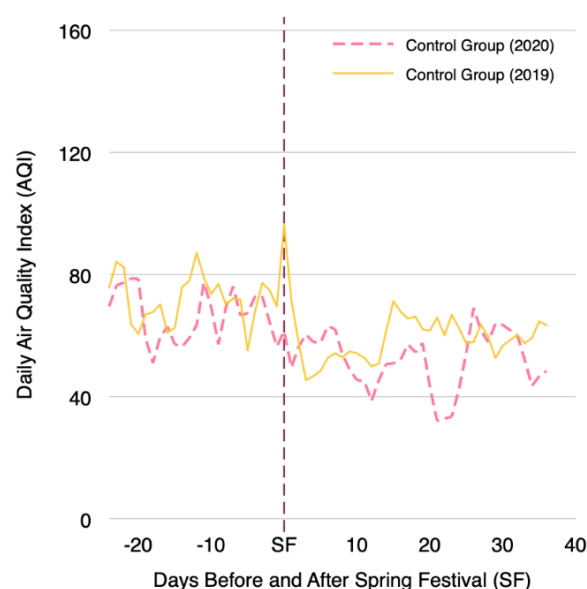
Notes: This map shows which cities were locked-down during the COVID-19 pandemic. The blue diamond represents locked-down cities. Overall, 95 out of 324 cities were locked down. The orange triangle indicates Wuhan city, where COVID-19 is first identified in China.

Figure 2. Trend of Air Quality in Treatment and Control Group

Panel A: Trend of AQI in the Treatment and Control Group in 2020

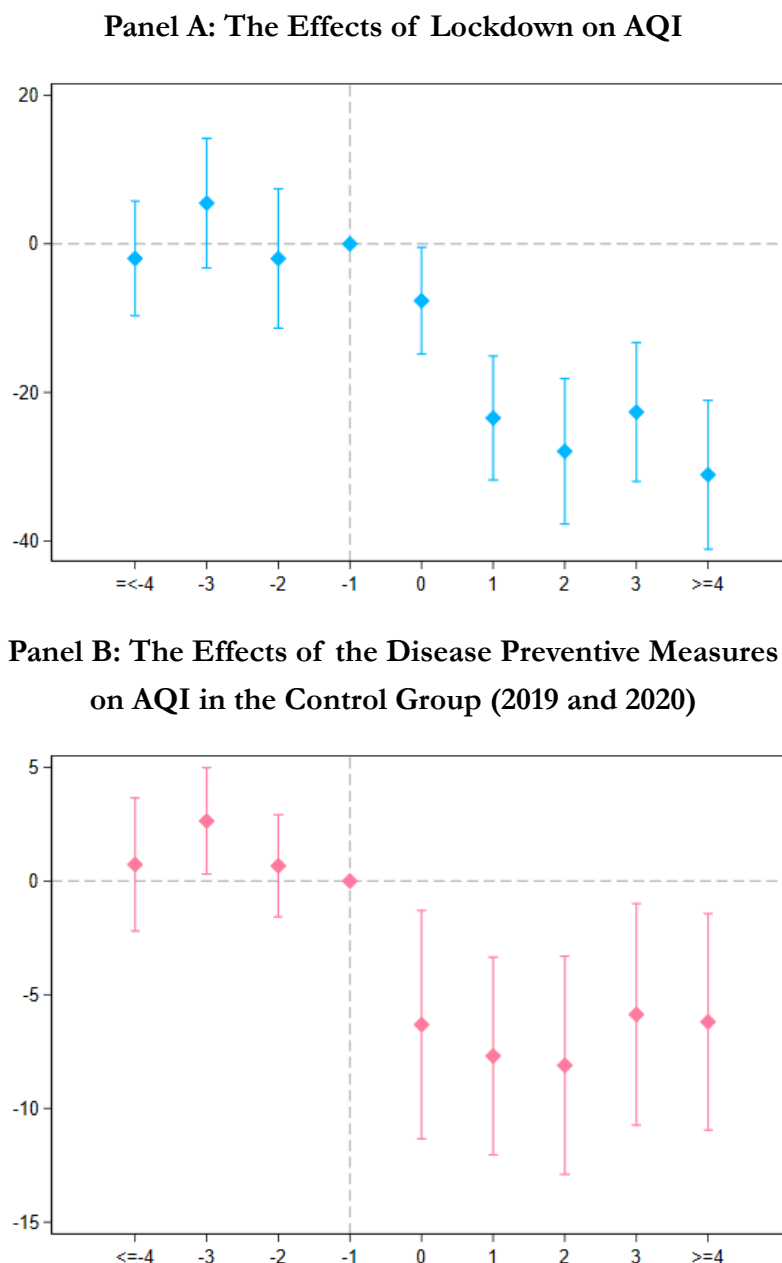


Panel B: Trend of AQI in the Control Group in 2019 and 2020



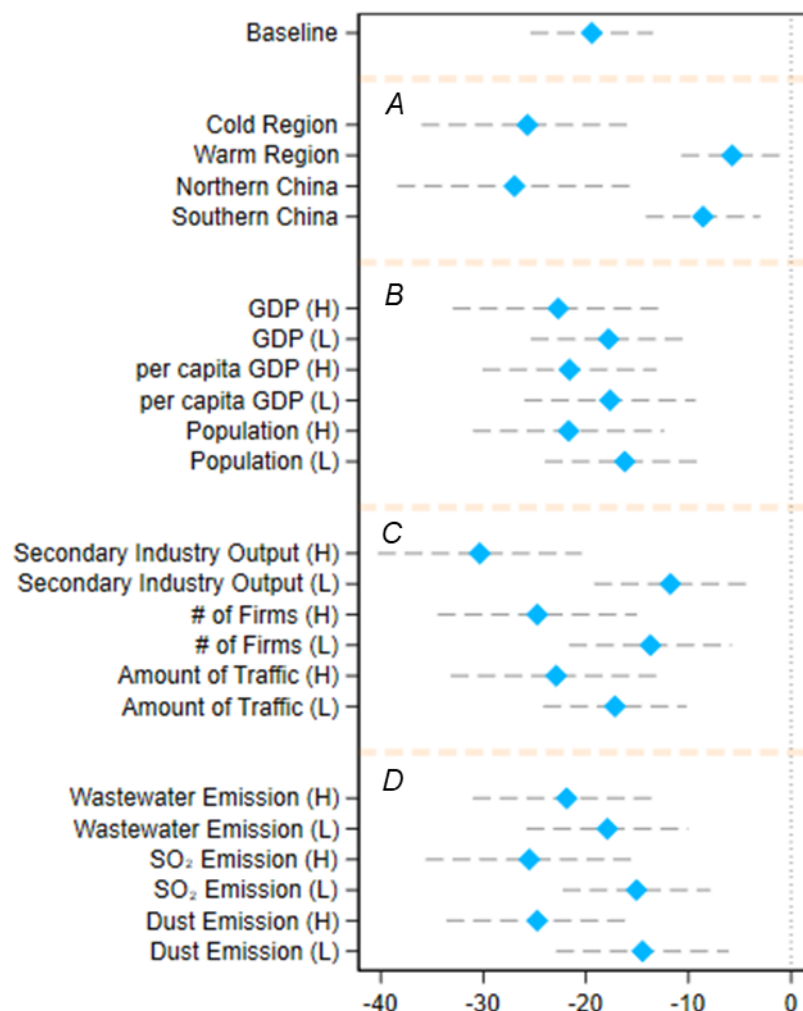
Notes: These figures show the trends in the Air Quality Index (AQI) in different groups of cities. In Panel A, we plot the AQI in the treatment and the control group in 2020. In Panel B, we plot the AQI in the control group in 2019 and 2020. The vertical dash purple line represents the timing of the Chinese Spring Festival.

Figure 3. The Effects of Lockdown Before and After its Implementation



Notes: These figures summarize the results of the parallel-trend tests. We include leads and lags of the start of the city lockdown dummy in the regressions. The dummy variable indicating one week before the city lockdown is omitted from the regressions. The estimated coefficients and their 95% confidence intervals are plotted. In Panel A, we compare the air pollution levels between the treated cities with the control cities, and in Panel B, we compare air pollution levels in the control cities between 2019 and 2020.

Figure 4. Heterogeneous Effects of Lockdown on the Air Quality Index



Notes: The X-axis shows the estimated coefficients and their 95% confidence intervals. Each row corresponds to separate regression using a corresponding subsample. We use the mean values to separate the “high” group from the “low” group for each pair of heterogeneity analyses. For example, if a city's GDP is higher than the mean GDP, it falls into a “high” GDP group. For temperature (colder or warmer group), we use data measured in the first week of our study period. North and South are divided along the Huai River. Other socio-economic data for the classification are measured in 2017. Each regression implements the Equation and controls for weather, city fixed effects, and month-by-week fixed effects. Standard errors are clustered at the city level.

Table 1. The Effects of Lockdown on Air Quality

	Treatment and Control Group in 2020				Control Group in 2019 and 2020			
	Levels		Log		Levels		Log	
	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
<i>Panel A. Air Quality Index (AQI)</i>								
Lockdown	-18.84*** (3.27)	-19.43*** (3.04)	-0.17*** (0.03)	-0.18*** (0.03)				
Spring Festival in 2020					-6.51** (2.53)	-8.77*** (2.40)	-0.04 (0.03)	-0.07*** (0.03)
R-Squared	0.695	0.723	0.769	0.793	0.647	0.655	0.701	0.711
<i>Panel B. PM_{2.5} ($\mu\text{g}/\text{m}^3$)</i>								
Lockdown	-13.47*** (2.65)	-13.94*** (2.36)	-0.15*** (0.03)	-0.17*** (0.03)				
Spring Festival in 2020					-7.58*** (2.06)	-8.40*** (2.07)	-0.06* (0.03)	-0.08** (0.03)
R-Squared	0.722	0.752	0.809	0.828	0.651	0.654	0.729	0.735
Weather Control		Y		Y		Y		Y
City FE	Y	Y	Y	Y	Y	Y	Y	Y
Month-by-Week FE	Y	Y	Y	Y	Y	Y	Y	Y
Obs.	2,916	2,916	2,916	2,916	4,158	4,158	4,158	4,158
No. of Cities	324	324	324	324	232	232	232	232

Notes: Weather controls include weekly mean temperature, its square, weekly mean precipitation, and weekly mean snow depth. Standard errors are clustered at the city level and reported below the coefficients. * significant at 10% ** significant at 5%. *** significant at 1%.

Table 2. Estimated Health Benefits from Improved Air Quality

	Elasticity (PM _{2.5} per 10 µg/m ³)	Actual Change in PM _{2.5} (per 10 µg/m ³)	Population Affected (per 1,000)	Base Monthly Mortality Rate (per 1000)	Estimated Monthly Deaths
	(1)	(2)	(3)	(4)	(5)
<i>Panel A. Elasticity from Fan et al. (2020)</i>					
Lockdown Cities	2.20%	2.234	545,820	0.59	15,939
Control Cities	2.20%	0.84	738,720	0.59	8,111
				total	24,050
<i>Panel B. Elasticity from He et al. (2020)</i>					
Lockdown Cities	3.25%	2.234	545,820	0.59	23,546
Control Cities	3.25%	0.84	738,720	0.59	11,983
				total	35,529

Notes: We estimate the overall monthly number of deaths in China by multiplying four variables represented in Column (1) to (4). In Column (1), the elasticity indicates to what extent a 10 µg/m³ change in PM_{2.5} concentration affects the mortality rate. Column (2) summarize estimated changes in PM_{2.5} in different types of cities based on Table 1. In Column (4), we obtain China's annual death rate from World Development Indicator and divide it by 12 to obtain the monthly death rate. As we do not have city-level mortality rate, in this calculation, we assume that the baseline mortality rate is the same across cities.

COVID-19, City Lock-down, and Air Pollution: Evidence from China

GUOJUN HE, YUHAN PAN, AND TAKANAO TANAKA

Online Appendix

Appendix 1: Data Appendix

Air Quality Data: The air quality data is a high-frequent dataset covering seven major sets of air pollutants. We obtain these data from the Ministry of Ecology and Environment. The original dataset includes hourly readings on Air Quality Index (AQI), PM_{2.5}, PM₁₀, SO₂, O₃, NO₂, and CO from 1605 air quality monitoring stations covering all the prefectural cities in China. Based on weights of the inverse of squared distance from the station and city population center, we collapse the dataset to 324 cities at a weekly level.

Weather Data: Weather data includes temperature, precipitation, and snow. These data are obtained from the Global Historical Climatology Network (GHCN) from the National Oceanic and Atmospheric Administration (NOAA). We collapse data to a weekly city-level dataset using the same methods as the air quality data.

Lockdown: We collect local governments' lockdown information city by city from news media and government announcements. Most of the cities' lockdown policies were directly issued by the city-level governments, while a few were promulgated by the provincial governments. To improve policy compliance, civil servants and volunteers were assigned to communities, firms, business centers, and traffic checkpoints. The local government also penalized offenders if the rules were violated. There are some variations in rules and degrees of the lockdown. For example, in some cities, individuals were not allowed to go out (food and daily necessities were delivered to them), while in other cities, they could go out if they did not have a fever. In this paper, we define lockdown when the following

three measures are all enforced: 1) prohibition of the unnecessary commercial activities for people's daily lives, 2) prohibition of any type of gathering by residents, 3) restrictions on private (vehicles) and public transportations. The primary dataset for lockdown is at a daily level. Thus, we aggregate this to a weekly level. Here, we define treatment = 1 if more than half of the days in the week were locked down. The timings of the cities' lockdown are presented in Appendix Table A1.

Socio-Economic Status: To explore the heterogeneity, we assemble the cities' socio-economic status from the 2017 China City Statistical Yearbook. It contains the city-level statistics such as GDP, population, amount of traffic, pollutant emission, and industrial output.

Appendix 2: Back-of-The-Envelope Calculations on Potential Health Benefits

We predict the reduced mortality from the improvement in air quality by calculating the following equation:

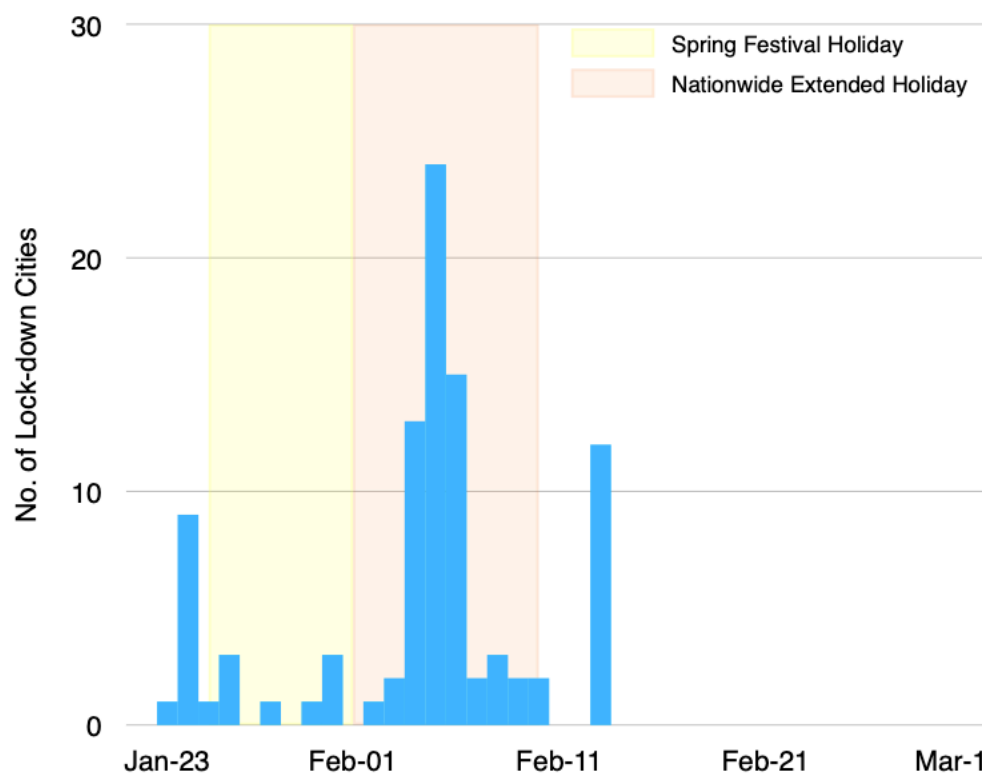
$$Mortality_{it} = \Delta \widehat{AQ}_{it} * Elasticity * Base MR_{it} * Population_{it} \quad (A1)$$

where $Mortality_{it}$ represents estimated saved deaths in city i in month t , $\Delta \widehat{AQ}_{it}$ indicates an estimated change in air quality from Equations (1) and (3) in city i in month t , where we assume the effect of lockdown on air quality is identical to each the treatment group and the control group. We borrow $Elasticity$ from existing literature, measuring the effect of air quality on mortality: this represents how much one unit change in air quality leads to a difference in deaths. $Base MR_{it}$ represents base mortality rate, and $Population_{it}$ denotes the population in the city i in week t . The computations are summarized in Table 7 in the main text.

Appendix Reference

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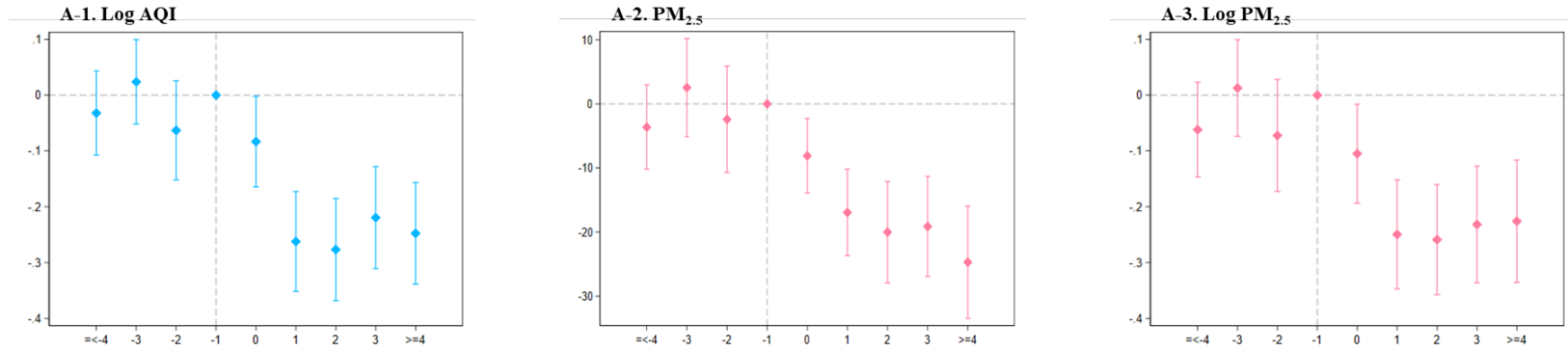
Figure A1. Timing of Lockdown



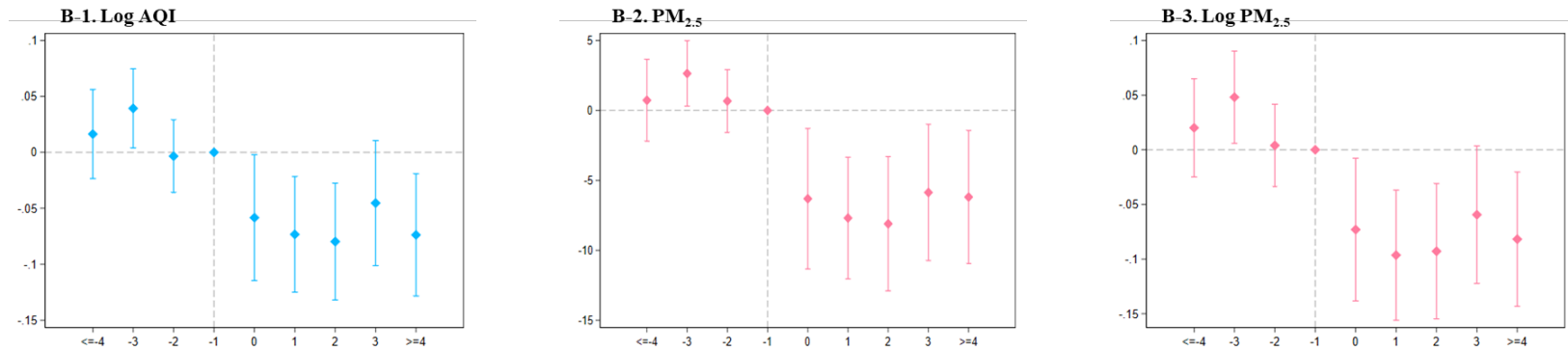
Notes: This graph shows the timing of the start of the city lockdown. The x-axis represents the date, and the Y-axis represents the number of locked-down cities. The yellow background represents the Chinese Spring Festival, and the red background represents the extended Spring Festival.

Figure A2. Event-Study Results on AQI and PM_{2.5}

Panel A. The Effects of Lockdown on Air Quality

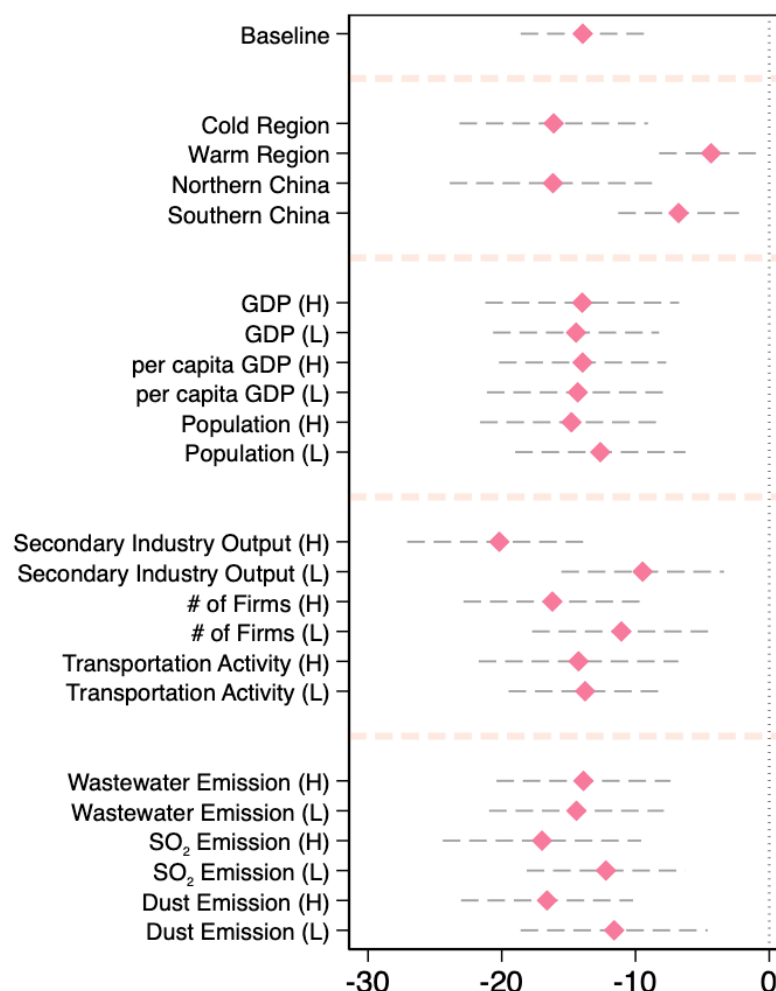


Panel B. The Effects of 2020 Spring Festival on Air Quality in the Control Group



Notes: These figures summarize the results of the parallel-trend tests. We include leads and lags of the start of the city lockdown dummy in the regressions. The dummy variable indicating one week before the city lockdown is omitted from the regressions. The estimated coefficients and their 95% confidence intervals are plotted. In Panel A, we compare the air pollution levels between the treated cities with the control cities, and in Panel B, we compare air pollution levels in the control cities between 2019 and 2020.

Figure A3. Heterogeneous Impact Using PM_{2.5}



Notes: The X-axis shows the estimated coefficients and their 95% confidence intervals. Each row corresponds to separate regression using a corresponding subsample. We use the mean values to separate the “high” group from the “low” group for each pair of heterogeneity analyses. For example, if a city's GDP is higher than the mean GDP, it falls into a “high” GDP group. For temperature (colder or warmer group), we use data measured in the first week of our study period. North and South are divided along the Huai River. Other socio-economic data for the classification are measured in 2017.

Table A1. List of Locked-down City

Starting Date	Cities
23-Jan	Wuhan
24-Jan	Huangshi, Shiyan, Yichang, Ezhou, Jingmen, Xiaogan, Huanggang, Xianning, Enshi
25-Jan	Qinhuangdao
26-Jan	Xiangyang, Jingzhou, Xiantao
28-Jan	Tangshan
30-Jan	Dongying
31-Jan	Chongqing, Yinchuan, Wuzhong
2-Feb	Wenzhou
3-Feb	Wuxi, Jining
4-Feb	Harbin, Nanjing, Xuzhou, Changzhou, Nantong, Hangzhou, Ningbo, Fuzhou, Jingdezhen, Zaozhuang, Linyi, Zhengzhou, Zhumadian
5-Feb	Shenyang, Dalian, Anshun, Fushun, Benxi, Dandong, Jinzhou, Fuxin, Liaoyang, Panjin, Tieling, Chaoyang, Huludao, Yangzhou, Hefei, Quanzhou, Nanchang, Jinan, Qingdao, Taian, Rizhao, Laiwu, Nanning
6-Feb	Tianjin, Shijiazhuang, Suzhou, Pingxiang, Jiujiang, Xinyu, Yingtan, Ganzhou, Ji'an, Yichun, Fuzhou, Shangrao, Neijiang, Yibin, Xinyang
7-Feb	Suzhou, Guangzhou
8-Feb	Shenzhen, Foshan, Fangchenggang,
9-Feb	Cangzhou, HuaiBei
10-Feb	Beijing, Shanghai
13-Feb	Hohhot, Baotou, Wuhai, Chifeng, Tongliao, Ordos, Hulun Buir, Bayan Nur, Ulanqab, Xing'an League, Xilingol League, Alxa League

Notes: The lockdown information are from local government and various media news in 2020.

Table A2. Summary Statistics

	2020 (01. January ~ 01. March)			2019 (01. January ~ 01. March)		
	Treatment Group (Locked-down Cities)					
	All Cities	Before Treatment	After Treatment	Control Group	Treatment Group	Control Group
	(1)	(2)	(3)	(4)	(5)	(6)
<i>Panel A. Air Pollutant and Lockdown</i>						
Air Quality Index (AQI)	74.48 (42.41)	103.24 (47.94)	67.91 (26.75)	69.96 (41.41)	99.89 (41.58)	76.27 (38.35)
PM _{2.5} (μg/m ³)	51.70 (33.94)	76.88 (39.88)	46.89 (20.84)	47.56 (32.48)	70.90 (34.74)	49.61 (31.37)
Lockdown	0.14 (0.35)	0.00 (0.00)	1.00 (0.00)	0.00 (0.00)	/	/
<i>Panel B. Weather</i>						
Temperature (°C)	3.75 (8.20)	2.44 (6.19)	6.35 (5.40)	3.50 (8.89)	3.44 (5.23)	3.01 (7.52)
Precipitation (100mm)	24.00 (45.89)	19.62 (26.85)	18.68 (20.07)	25.96 (52.13)	39.65 (27.28)	47.10 (47.10)
Snow Depth (100mm)	60.13 (26.40)	59.78 (23.27)	58.30 (14.05)	60.57 (28.77)	61.10 (24.87)	65.70 (32.20)

Notes: Each column summarizes the mean values and standard deviations of each variable at a weekly level. More information about the dataset is described in Appendix 1.

Table A3. Main Specification Using Other Air Pollutants

	Treatment and Control Cities in 2020				
	CO	NO ₂	PM ₁₀	SO ₂	O ₃
	(mg/m ³)	(μg/m ³)	(μg/m ³)	(μg/m ³)	(μg/m ³)
	(1)	(2)	(3)	(4)	(5)
<i>Panel A. Levels</i>					
Lockdown	-0.07*** (0.03)	-4.70*** (0.63)	-22.22*** (3.18)	-1.25** (0.49)	3.10*** (0.76)
R-Squared	0.788	0.870	0.688	0.857	0.770
<i>Panel B. log</i>					
Lockdown	-0.03*** (0.01)	-0.13*** (0.02)	-0.22*** (0.03)	-0.09*** (0.02)	0.09*** (0.02)
R-Squared	0.814	0.907	0.811	0.907	0.753
Weather Control	Y	Y	Y	Y	Y
City FE	Y	Y	Y	Y	Y
Date FE	Y	Y	Y	Y	Y
Obs.	2,916	2,916	2,916	2,916	2,916
No. of Cities	324	324	324	324	324

Notes: Weather controls include weekly mean temperature, its square, weekly mean precipitation, and weekly mean snow depth. Standard errors are clustered at the city level and reported below the coefficients.

* significant at 10% ** significant at 5%. *** significant at 1%.

Table A4. Event Study: The Effects of Lockdown on Air Quality

	AQI		PM _{2.5} (μg/m ³)	
	levels	log	levels	log
	(1)	(2)	(3)	(4)
>=4 Weeks Before	-1.97 (3.92)	-0.03 (0.04)	-3.62 (3.35)	-0.06 (0.04)
3 Weeks Before	5.48 (4.43)	0.02 (0.04)	2.54 (3.89)	0.01 (0.04)
2 Weeks Before	-1.97 (4.77)	-0.06 (0.05)	-2.41 (4.23)	-0.07 (0.05)
Treatment Week	-7.65** (3.65)	-0.08** (0.04)	-8.10*** (2.95)	-0.11** (0.05)
1 Week Later	-23.45*** (4.24)	-0.26*** (0.05)	-16.94*** (3.43)	-0.25*** (0.05)
2 Weeks Later	-27.93*** (4.97)	-0.28*** (0.05)	-20.01*** (4.02)	-0.26*** (0.05)
3 Weeks Later	-22.65*** (4.75)	-0.22*** (0.05)	-19.13*** (3.97)	-0.23*** (0.05)
>=4 Weeks Later	-31.09*** (5.09)	-0.25*** (0.05)	-24.70*** (4.45)	-0.23*** (0.06)
Weather	Y	Y	Y	Y
City FE	Y	Y	Y	Y
Month-by-Week FE	Y	Y	Y	Y
Obs.	2,916	2,916	2,916	2,916
R-Squared	0.719	0.795	0.740	0.822
No. of Cities	324	324	324	324

Notes: Weather controls include weekly mean temperature, its square, weekly mean precipitation, and weekly mean snow depth. Standard errors are clustered at the city level and reported below the coefficients. * significant at 10% ** significant at 5%. *** significant at 1%

**Table A5. Event Study: The 2020 Spring Festival
on Air Quality in The Control Group**

	AQI		PM _{2.5} (μg/m ³)	
	levels	log	levels	log
	(1)	(2)	(3)	(4)
>=4 Weeks Before	0.65	0.02	0.73	0.02
	(1.95)	(0.02)	(1.48)	(0.02)
3 Weeks Before	2.46*	0.04**	2.64**	0.05**
	(1.48)	(0.02)	(1.19)	(0.02)
2 Weeks Before	0.31	-0.00	0.67	0.00
	(1.51)	(0.02)	(1.14)	(0.02)
Treatment Week	-6.21**	-0.06**	-6.32**	-0.07**
	(2.94)	(0.03)	(2.55)	(0.03)
1 Week Later	-8.18***	-0.07***	-7.70***	-0.10***
	(2.67)	(0.03)	(2.21)	(0.03)
2 Weeks Later	-8.65***	-0.08***	-8.10***	-0.09***
	(2.78)	(0.03)	(2.44)	(0.03)
3 Weeks Later	-5.70*	-0.05	-5.87**	-0.06*
	(2.96)	(0.03)	(2.47)	(0.03)
>=4 Weeks Later	-7.96***	-0.07***	-6.19**	-0.08***
	(3.01)	(0.03)	(2.42)	(0.03)
Weather	Y	Y	Y	Y
City FE	Y	Y	Y	Y
Month-by-Week FE	Y	Y	Y	Y
Obs.	4,158	4,158	4,158	4,158
R-Squared	0.653	0.712	0.652	0.735
No. of Cities	232	232	232	232

Notes: Weather controls include weekly mean temperature, its square, weekly mean precipitation, and weekly mean snow depth. Standard errors are clustered at the city level and reported below the coefficients. * significant at 10% ** significant at 5%. *** significant at 1%

Table A6. Robustness Check Using Different Samples

	AQI	log (AQI)	PM _{2.5}	log (PM _{2.5})
	(1)	(2)	(3)	(4)
<i>Panel A. Drop Cities in Hubei Province</i>				
Lockdown	-21.69*** (3.3)	-0.20*** (0.03)	-15.83*** (2.56)	-0.19*** (0.03)
R-Squared	0.725	0.796	0.754	0.831
Obs.	2808	2808	2808	2808
Month-by-Week FE	Y	Y	Y	Y
<i>Panel B. Using Daily Data</i>				
Lockdown	-19.84*** (3.13)	-0.17*** (0.03)	-14.07*** (2.53)	-0.17*** (0.03)
R-Squared	0.515	0.601	0.541	0.641
Obs.	19764	19764	19764	19764
Date FE	Y	Y	Y	Y
Weather Control	Y	Y	Y	Y
City FE	Y	Y	Y	Y
No. of Cities	324	324	324	324

Notes: Weather controls include mean temperature, its square, precipitation, and snow depth. Standard errors are clustered at the city level and reported below the coefficients. * significant at 10% ** significant at 5%. *** significant at 1%.

Table A7. Heterogeneity Analysis

	AQI		PM _{2.5} (μg/m ³)	
	levels	log	levels	log
	(1)	(2)	(3)	(4)
<i>Panel A</i>				
Cold Region	-26.97*** (5.77)	-0.20*** (0.05)	-16.17*** (3.90)	-0.12*** (0.04)
Warm Region	-8.58*** (2.83)	-0.12*** (0.03)	-6.78*** (2.29)	-0.14*** (0.04)
Northern China	-25.71*** (5.23)	-0.20*** (0.04)	-16.11*** (3.57)	-0.13*** (0.04)
Southern China	-5.75** (2.50)	-0.10*** (0.03)	-4.34** (1.97)	-0.11*** (0.04)
<i>Panel B</i>				
GDP (high)	-22.70*** (5.19)	-0.22*** (0.05)	-13.98*** (3.66)	-0.19*** (0.05)
GDP (low)	-17.79*** (3.85)	-0.16*** (0.03)	-14.44*** (3.15)	-0.16*** (0.04)
per capita GDP (high)	-21.61*** (4.29)	-0.21*** (0.04)	-13.95*** (3.16)	-0.18*** (0.05)
per capita GDP (low)	-17.65*** (4.23)	-0.16*** (0.04)	-14.32*** (3.44)	-0.16*** (0.04)
Population (high)	-21.69*** (4.71)	-0.22*** (0.04)	-14.79*** (3.46)	-0.21*** (0.05)
Population (low)	-16.21*** (3.94)	-0.14*** (0.04)	-12.63*** (3.23)	-0.12*** (0.04)
Weather	Y	Y	Y	Y
City FE	Y	Y	Y	Y
Month-by-Week FE	Y	Y	Y	Y

Notes: Each cell represents a separate regression using the corresponding subsample. For example, a warm region uses cities whose temperature is above the mean. Weather controls include weekly mean temperature, its square, weekly mean precipitation, and weekly mean snow depth. Standard errors are clustered at the city level and reported below the coefficients. * significant at 10% ** significant at 5%. *** significant at 1%

Table A7 (Cont.). Heterogeneity Analysis

	AQI		PM _{2.5} (μg/m ³)	
	levels	log	levels	log
	(1)	(2)	(3)	(4)
<i>Panel C</i>				
Secondary Industry Output (high)	-30.35*** (5.02)	-0.27*** (0.04)	-20.18*** (3.48)	-0.24*** (0.05)
Secondary Industry Output (low)	-11.77*** (3.77)	-0.12*** (0.04)	-9.46*** (3.08)	-0.12*** (0.04)
No. of Firms (high)	-24.74*** (4.91)	-0.23*** (0.04)	-16.21*** (3.36)	-0.20*** (0.04)
No. of Firms (low)	-13.71*** (4.02)	-0.12*** (0.04)	-11.05*** (3.38)	-0.12*** (0.04)
Transportation Activity (high)	-22.90*** (5.19)	-0.24*** (0.05)	-14.26*** (3.77)	-0.22*** (0.05)
Transportation Activity (low)	-17.17*** (3.54)	-0.15*** (0.03)	-13.76*** (2.90)	-0.14*** (0.03)
<i>Panel D</i>				
Wastewater Emission (high)	-21.88*** (4.62)	-0.24*** (0.04)	-13.89*** (3.29)	-0.21*** (0.05)
Wastewater Emission (low)	-17.91*** (4.00)	-0.14*** (0.04)	-14.41*** (3.31)	-0.14*** (0.04)
SO ₂ Emission (high)	-25.52*** (5.11)	-0.25*** (0.05)	-16.99*** (3.75)	-0.22*** (0.05)
SO ₂ Emission (low)	-15.07*** (3.65)	-0.13*** (0.03)	-12.21*** (3.00)	-0.13*** (0.04)
Dust Emission (high)	-24.75*** (4.48)	-0.25*** (0.04)	-16.61*** (3.26)	-0.22*** (0.04)
Dust Emission (low)	-14.49*** (4.26)	-0.12*** (0.04)	-11.60*** (3.54)	-0.12*** (0.04)
Weather	Y	Y	Y	Y
City FE	Y	Y	Y	Y
Month-by-Week FE	Y	Y	Y	Y

Notes: Each cell represents a separate regression using the corresponding subsample. For example, a warm region uses cities whose temperature is above the mean. Weather controls include weekly mean temperature, its square, weekly mean precipitation, and weekly mean snow depth. Standard errors are clustered at the city level and reported below the coefficients. * significant at 10% ** significant at 5%. *** significant at 1%

Table A8. Summary of Related Literature on the Health Impacts of Air Pollution

Study	Country	Period	Method	Effects
<i>Panel A. Quasi-Experiment Study</i>				
Fan et al. (2020)	China	2014~ 2015	Regression Discontinuity	A 10 µg/m ³ increment in PM _{2.5} is associated with a 2.2% increase in mortality rate per 100,000 using the timing of the start of winter heating
He et al. (2020)	China	2013~ 2015	Instrumental Variable	A 10 µg/m ³ increment in PM _{2.5} is associated with a 3.25% increase in mortality rate per 100,000 using the air pollution from agricultural fire
Deryugina et al. (2020)	USA	1999~ 2013	Instrumental Variable	A 10 µg/m ³ increment in PM _{2.5} is associated with a 1.8% increase in three-day mortality rate per million people aged 65+ using the wind speed
<i>Panel B. Associational Study</i>				
Shang et al. (2013)	China	2004~ 2008	Meta-Analysis	A 10-µg/m ³ increase in PM _{2.5} concentrations is associated with a 0.38% increase in total mortality.
Zhou et al. (2015)	China	2013	Multi-City Time-Series	A 10-µg/m ³ increase in two-day average PM _{2.5} concentrations is associated with a 0.6-0.9% increase in all-cause mortality in rural China.
Franklin et al. (2008)	USA	2000~ 2005	Hierarchical Model	A 1.21% increase in all-cause mortality is associated with a 10-µg/m ³ increase in the previous day's PM _{2.5} concentrations.
Kloog et al. (2013)	USA	2000~ 2008	Time-Series	For every 10-µg/m ³ increase in PM _{2.5} exposure, PM-related mortality increases by 2.8%.
Atkinson et al. (2014)	World	-	Meta-Analysis	A 10-µg/m ³ increment in PM _{2.5} is associated with a 1.04% increase in the risk of death. The substantial regional variation observed around the globe.