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Did COVID-19 Improve Air Quality Near Hubei?*

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Abstract

Ambient pollution is a byproduct of economic activity. It has been widely reported that COVID-19 and associated lockdowns have generated large improvements in air quality worldwide, including to China's notoriously-poor air quality. We analyze China's official pollution monitor data and account for the large, recurrent improvement in air quality following Lunar New Year (LNY), which essentially coincided with lockdowns in 2020. With the important exception of NO_2, China's air quality improvements in 2020 are smaller than we should expect near the pandemic's epicenter: Hubei province. Compared with LNY improvements experienced in 2018 and 2019 in Hubei, we see smaller improvements in SO_2 while ozone concentrations increased in both relative and absolute terms (roughly doubling). Similar patterns are found for the six provinces neighboring Hubei. We conclude that whether COVID-19 actually decreased pollution in China depends on the pollutant and reference period considered.

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1 Background

Dramatic improvements in air quality have been attributed to COVID-19. NASA's satellite data show that NO_2 levels decreased precipitously in China in mid-February 2020 relative to early January (NASA, 2020). Data from US government-maintained pollution monitors in four Chinese cities show an average daily reduction of 15-17 $\mu g/m^3$ in $PM_{2.5}$ across Jan-Feb 2020 relative to the same period in the previous four years (Burke, 2020). On carbon dioxide emissions, the reduction in coal and crude oil use in 2020 suggests a reduction in CO_2 emissions of 25%, or about 100 million metric tons, compared to the same period in 2019 (Myllyvirta, 2020). These reductions have been widely discussed and disseminated in the popular press (Popovich, 2020; McMahon, 2020; Rathi and Hodges, 2020).

The broader context of these patterns is important to their interpretation. We highlight three aspects which together paint a more nuanced picture of the likely response of pollution to COVID-19 in China:

1. To the extent that air quality had been improving in China over time prior to the coronavirus outbreak (Greenstone and Schwarz, 2018), comparisons of 2020 pollution with previous years can overstate the role of COVID-19 in reducing pollution.
2. The COVID-19 outbreak in China occurred around the same time as Lunar New Year. Wuhan's lockdown began January 23, followed two days later by 2020's Lunar New Year (LNY). Lunar New Years have been found to reduce sharply pollution in the shorter-term in China and Taiwan (Tan et al., 2009; Jiang et al., 2015; Kong et al., 2015). Indeed, the pollution pattern is sufficiently pronounced that California's air quality improves around LNY due to reduced transboundary pollution from China (Ngo, Zhong, and Bao, 2018). Ignoring this recurrent annual drop likewise tends to overstate the pollution reduction attributed to COVID-19.
3. Most NO_x pollution tends to be produced by the transport sector, which markedly reduced its activity during Chinese lockdowns. In contrast:
   (a) Sulfur Dioxide (SO_2) tends to be produced by the combustion of fossil fuels in power generation and heating furnaces. Thus, it may respond differently to the coronavirus outbreak. Like NO_x, SO_2 impairs human health (EPA), labor market outcomes (Hanna and Oliva, 2015), and is a "criteria air pollutant" according to the US Environmental Protection Agency (EPA), but has been analyzed less in discussions of COVID-19.
   (b) Ozone (O_3) is not emitted directly, but produced by the combination of NO_x and volatile organic compounds (VOCs) in the presence of heat and sunlight. Like SO_2, ground-level ozone impairs human health (Neidell, 2009; Lleras-Muney, 2010; Deschenes et al., 2017) and is a "criteria air pollutant" (EPA).
   (c) Carbon Monoxide (CO) is released during combustion. Vehicles and machinery that burn fossil fuels release CO, including home heating sources and cooking. Like SO_2 and ozone, CO is also an EPA"criteria air pollutant" that can harm health (Currie and Neidell, 2005; Currie et al.,

2009).

Points 1. and 2. above suggest a “difference in differences” analysis, which is conventional in economics. In this spirit, satellites also show drops in air pollution during the Chinese Lunar New Year in previous years, but the drop in NO_2 in 2020 is about 10-30% larger than what is observed during the same period in the past fifteen years over central and eastern China (NASA, 2020).

2 Empirical Specification

Here, we build on the difference-in-differences (DD) thought experiment above (NASA, 2020) to estimate a regression model that accounts for both: a) annual differences in air quality and; b) the expected drop in pollution immediately following Lunar New Year. As noted above, failure to account for both can inflate estimates of the air quality benefits of COVID-19. In addition to the DD, we remove average differences across pollution monitors and thereby average pollution differences across provinces, along with the pronounced pollution differences by day of the week. Finally, we recast the data in an “event study” analysis which normalizes time around the Lunar New Year event (*cf.* dropping calendar dates which have a different position vis à vis Lunar New Year in different years(NASA, 2020)). We estimate the following regression equation:

$$y_{it} = \alpha_0 + \beta_1 \mathrm{Post_t} + \beta_2 \mathrm{Y2020_t} + \beta_3 \mathrm{Post_t} * \mathrm{Y2020_t} + \gamma_i + \tau_t + X_{it} + u_{it} \quad (1)$$

where y_{it} denotes pollution measures at monitor i in date t. Our independent variables include a binary variable $Post_t$ that is 1 after New Year’s day and 0 otherwise, a binary variable $Y2020_t$ that is 1 for year 2020 and 0 otherwise, and their interaction term $Post_t * Y2020_t$. The coefficient β_1 measures the change in pollution before versus after New Year’s day in year 2018-19. β_2 measures the annual change in average pollution in 2020 versus that in 2018-19. The coefficient of chief interest, β_3, measures the difference in pollution changes before versus after New Year’s day between year 2020 and year 2018-19. We also control for τ_t that includes a year 2018 dummy and day of week fixed effects, γ_i pollution monitor fixed effects, and X_{it} weather controls.

We present these results separately for Hubei, the province at the center of the outbreak. We estimate a second set of DD regressions in Hubei’s neighbors (dropping Hubei), and a third for the provinces that do not border Hubei.

Finally, we compare provinces according to their proximity to Hubei, year, and Lunar New Year in a triple-difference analysis. We describe further the triple difference specification and our data sources in the Supplementary Material Section 1.

3 Results

While some of the information reported about COVID-19 may be subject to doubt, Hubei was clearly the epicenter of COVID-19 in China. Hubei had over 1,000

COVID-19 cases per million, while neighboring provinces had 15 and non-neighbors just 8 (Table 1).[1,2] Similar differences are seen for COVID-19 mortality rates in Table 1. If COVID-19 decreased economic activity and therefore pollution, then we would expect larger decreases in pollution in and around the Pandemic's epicenter.

Table 1: Infection Rate on February 21, 2020

Province	Confirmed cases	Deaths	Cases per million people	Deaths per million people
Hubei	63,454	2,250	1,072.4	38.03
Neighbors	5,023	37	14.5	0.107
Non-neighbors	7,810	58	7.9	0.058

NO_2 aside, we find China's largest improvements in air quality did not occur in Hubei. Nor did they occur in Hubei's six neighboring provinces. Instead, the 24 provinces that do not border Hubei show the largest improvements in air quality. Figure 1 plots average SO_2 and O_3 concentrations before and after the Lunar New Year in 2020 and 2019 for three different locations: Hubei, neighboring provinces, and non-neighboring provinces. For SO_2 concentrations, all three locations experienced decreases after LNY in 2019. In 2020, however, Hubei and neighboring provinces have little reduction in SO_2 concentrations after LNY. Only in non-neighboring provinces, SO_2 concentrations show decreases in 2020. For O_3, the increases in concentrations after LNY in 2020 are more pronounced compared to those in 2019, particularly in Hubei. We illustrate the DD model by adding trend lines – predicted values from a simplified DD model – to the raw SO_2 and O_3 data in Supplementary Material Figure S1 .[3]

Figure 1 also shows higher pre-LNY SO_2 concentrations in 2019. This underscores the importance of also accounting for the annual decline in pollution when relating pollution changes to COVID-19 in 2020.

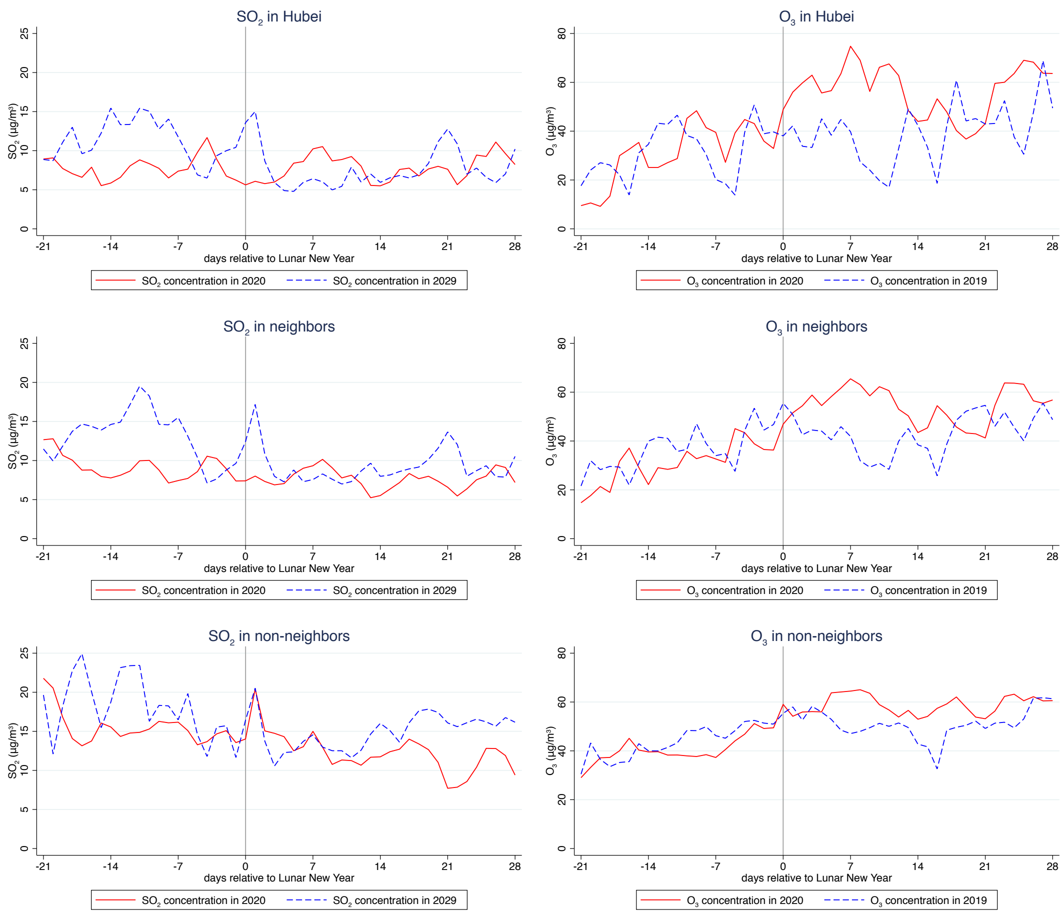
In Table 2, we show results from our difference-in-difference framework described in Section 2. In Panel A for all China, negative coefficients on `Post` for $\ln(NO_2)$, $\ln(SO_2)$, $\ln(PM_{2.5})$, and $\ln(CO)$ reflect decreases after the New Year day in 2018-19. The negative estimates of the interaction term `Post*Y2020` for $\ln(NO_2)$, $\ln(PM_{2.5})$, and $\ln(CO)$ suggest additional reductions in these three pollution measures in 2020, compared to those in 2018-19. For $\ln(SO_2)$, however, the positive estimate of

[1]We use accumulated cases and deaths on Feb 21 because this is the latest day of our study period, namely 28 days after LNY in 2020.

[2]That said, we take the reported number of confirmed COVID-19 cases and COVID-19 deaths with a large grain of salt: testing is incomplete, endogenous, etc. Aggregating up to broader geographic regions may reduce measurement error and moreover, Hubei's status as the provincial epicenter is unambiguous.

[3]These simplified DD estimates are consistent with our DD estimates that include the full set of control variables reported in Supplementary Material Table S2. This indicates that our basic results are robust to and relatively unaffected by: weather controls, day of week fixed effects, a 2018 year dummy, and fixed effects for each pollution monitor.

Figure 1: SO_2 and O_3 concentration by day before and after the Lunar New Year in 2019 (blue dash line) and 2020 (red solid line). We normalize days around the Lunar New Year (grey vertical line).



Post*Y2020 suggest a 1% smaller decrease in SO_2 concentration in 2020.[4] In other words, the post-LNY decrease in SO_2 in 2020 is about 15%, smaller than the decrease of 16% in 2018-19. For O_3, we find it increases 40% more after LNY in 2020.[5] Thus for China's air quality as a whole, estimated coefficients for the Post*Y2020 interaction term suggest a mixed response to COVID-19 that depends on the pollutant considered.

In Panel B-D, we compare these estimates in Hubei, neighbors, and non-neighbors. Consistent with what we observe in Figure 1, Panel D's interaction term shows that SO_2 decreased by 6% post-LNY in non-neighbor provinces. In contrast, Hubei shows 29% less improvement in SO_2 and a modest 12% improvement in $PM_{2.5}$. Provinces neighboring Hubei also show relatively less improvement in SO_2 of 16%. All loca-

[4]We report percentage changes in text that are transformed from log changes in the tables.

[5]In Supplementary Material Table S2 and Table S3, we report estimates on the changes in pollution levels. We also report robustness checks in Supplementary Material Table S4 and Table S5.

tions show increases in O_3, with Hubei the highest at 108%.

In Table 3, we use a triple-difference design to compare Hubei vs. neighboring provinces (Panel A) and neighboring provinces vs. non-neighboring provinces (Panel B). These triple differences using geography are "on top" of the Table 2 differences by year and Lunar New Year. So, conditional on the time double-differences, was pollution less improved in Hubei and Hubei's surrounding provinces? The coefficient on the `Post*Y2020*Hubei` dummy for $\ln(SO_2)$ is positive and indicates Hubei had an unusually small improvement in SO_2 following the coronavirus outbreak than its neighbors. Similarly, $PM_{2.5}$, CO, and ozone all show modest relative increases in Hubei in the triple-difference. The exception again is NO_2, which has a negative `Post*Y2020*Hubei` coefficient, though it is the smallest in absolute value and borderline statistically significant.

Likewise in Panel B of Table 3, the positive coefficient on `Post*Y2020*Neighbor` for $\ln(SO_2)$ suggests that Hubei's neighbors had smaller improvements in SO_2 than non-neighboring provinces. For O_3, we also find larger increases in concentrations in Hubei's neighbors than non-neighbors (32%). In contrast, NO_2 and $PM_{2.5}$ show no relative change in the DDD. Inconsistent with the above patterns, CO fell in Hubei's neighbors by about 5%.

4 Discussion

There is tremendous interest in understanding COVID-19's sweeping impacts. Among these, air quality impacts have already been assessed, albeit in the popular press. In the COVID-19 context, it is important to reiterate that air quality is multi-dimensional. These dimensions seem to have responded quite differently to the coronavirus outbreak in China. While NO_2 fell precipitously in response to coronavirus shutdowns, SO_2 and ozone did not. For China as whole, $PM_{2.5}$ fell 22%, but ozone concentrations increased 40% and sulfur dioxide has little improvement (relative to 2019 and pre-LNY period). Ozone increases were larger in provinces in and around COVID-19 epicenter, and similarly SO_2 had less improvement.

Because both SO_2 and ground-level ozone compromise health, it is unclear whether decreases in NO_2 were large enough to offset the health damage from increased ozone and relatively smaller improvement in SO_2 around the pandemic's epicenter. Our DDD estimates furthermore indicate that neither $PM_{2.5}$ nor CO fell "enough" in Hubei, given both LNY and secular reductions by year. Insofar as China and Hubei in particular are concerned, claims to a health benefit of reduced, unidimensional "pollution" are premature.

Future research should explore why SO_2 improved less and ozone increased in around Hubei. For China as a whole, why has ground level ozone increased following COVID-19 outbreak? This is all the more surprising given the large decrease in NO_2 we and others find. Unfortunately, the official pollution monitoring data we analyze here do not permit any emission source attribution. To the extent that workers who stayed home increased demand for dirtier sources of residential electricity and heating, esp. that from high-sulfur coal, the increase in residential demand could offset the decrease in industrial demand.

Data from the largest emitting firms with Continuous Emissions Monitoring Systems (CEMS) equipment might offer some insight (Karplus, Zhang, and Almond, 2018). We report CEMS results in Supplementary Material Table S6. Unfortunately, there is a large increase in the number of Chinese firms with missing CEMS data following the COVID-19 outbreak, and neither ozone nor VOC concentrations are reported. Focussing on Hubei, the number of reporting firms fell more after LNY compared to other provinces. The number of Hubei firms reporting continuously over this period is only in the low 20s. Thus evidence from this select subset of firms is all but anecdotal. These caveats aside, it appears that while NO_x in these large Hubei firms fell, SO_2 concentrations did not decrease. In other provinces, we observe decreases in both NO_x and SO_2 concentrations among large firms. If real, this could occur due to changes in the scale/intensity of plant operation, fuel input source, reductions in scrubber operation when scrutiny slackened (in Hubei), or other factors. Future research might investigate the mechanisms for the nuanced response of air quality to COVID-19 in China.

Like China, do other countries show an ambiguous pollution response to COVID-19? Presumably, lockdowns have increased demand for residential heating and cooking sources globally. Slackening in the enforcement of environmental regulation and enforcement – even if implicit – may also increase pollution. As a striking case in point, the United States announced on March 26 it would not enforce its environmental regulations during COVID-19.[6] What will the health consequences be? In sum, the "silver lining" story that COVID-19 improves air quality appears excessively sanguine.

[6]PBS March 27, 2020: *Citing outbreak, EPA has stopped enforcing environmental laws*.

Table 2: Double difference results

	$\ln(NO_2)$	$\ln(SO_2)$	$\ln(PM_{2.5})$	$\ln(O_3)$	$\ln(CO)$
Panel A: All China					
Post	-0.314***	-0.174***	-0.062***	0.143***	-0.040***
	(0.003)	(0.003)	(0.004)	(0.003)	(0.002)
Post×Y2020	-0.494***	0.010**	-0.252***	0.334***	-0.245***
	(0.005)	(0.005)	(0.006)	(0.004)	(0.004)
Y2020	-0.059***	-0.219***	-0.063***	-0.081***	0.032***
	(0.004)	(0.004)	(0.005)	(0.004)	(0.003)
Observations	181950	181950	180300	181200	181200
R-square	0.584	0.633	0.409	0.374	0.423
Panel B: Hubei					
Post	-0.436***	-0.431***	-0.024	0.059***	-0.072***
	(0.017)	(0.021)	(0.021)	(0.021)	(0.012)
Post×Y2020	-0.551***	0.254***	-0.132***	0.732***	-0.130***
	(0.024)	(0.029)	(0.028)	(0.029)	(0.017)
Y2020	-0.315***	-0.187***	-0.495***	-0.111***	-0.119***
	(0.029)	(0.035)	(0.034)	(0.035)	(0.021)
Observations	5550	5700	5550	5550	5550
R-square	0.612	0.412	0.356	0.351	0.230
Panel C: Neighbors					
Post	-0.447***	-0.331***	-0.069***	0.116***	-0.029***
	(0.006)	(0.007)	(0.008)	(0.006)	(0.005)
Post×Y2020	-0.498***	0.147***	-0.262***	0.544***	-0.290***
	(0.009)	(0.010)	(0.012)	(0.009)	(0.007)
Y2020	-0.181***	-0.366***	-0.142***	-0.205***	0.006
	(0.008)	(0.009)	(0.010)	(0.008)	(0.006)
Observations	43050	43200	42600	42450	43050
R-square	0.616	0.511	0.387	0.378	0.393
Panel D: Non-neighbors					
Post	-0.270***	-0.110***	-0.055***	0.157***	-0.041***
	(0.004)	(0.004)	(0.005)	(0.003)	(0.003)
Post×Y2020	-0.500***	-0.061***	-0.242***	0.257***	-0.235***
	(0.006)	(0.006)	(0.007)	(0.005)	(0.005)
Y2020	-0.006	-0.158***	-0.027***	-0.037***	0.046***
	(0.005)	(0.005)	(0.006)	(0.004)	(0.004)
Observations	133350	133050	132150	133200	132600
R-square	0.581	0.661	0.402	0.369	0.431
Monitor FEs	Y	Y	Y	Y	Y
Weather	Y	Y	Y	Y	Y
Y2018	Y	Y	Y	Y	Y
DOW FEs	Y	Y	Y	Y	Y

Notes: * significant 10% level; ** significant at 5% level; *** significant at 1% level.

Table 3: Triple difference results

	$\ln(NO_2)$	$\ln(SO_2)$	$\ln(PM_{2.5})$	$\ln(O_3)$	$\ln(CO)$
Panel A: Hubei and Neighbors					
Post	-0.450***	-0.339***	-0.068***	0.117***	-0.033***
	(0.006)	(0.007)	(0.008)	(0.006)	(0.004)
Post×Y2020	-0.497***	0.147***	-0.260***	0.545***	-0.288***
	(0.009)	(0.010)	(0.011)	(0.009)	(0.007)
Post×Y2020×Hubei	-0.042*	0.145***	0.071**	0.122***	0.170***
	(0.025)	(0.029)	(0.033)	(0.027)	(0.020)
Y2020	-0.184***	-0.373***	-0.144***	-0.196***	0.006
	(0.008)	(0.009)	(0.010)	(0.008)	(0.006)
Post×Hubei	-.0226	-.0184	-.0465**	-.0163	-.0499***
	(.0144)	(.0168)	(.0191)	(.0154)	(.0113)
Y2020×Hubei	-.0526***	.149***	-.134***	.0341*	-.0994***
	(.019)	(.0222)	(.0253)	(.0203)	(.0149)
Observations	48600	48900	48150	48000	48600
R-square	0.615	0.501	0.384	0.373	0.383
Panel B: Neighbors and Non-neighbors					
Post	-0.279***	-0.127***	-0.027***	0.160***	-0.036***
	(0.003)	(0.004)	(0.005)	(0.003)	(0.003)
Post×Y2020	-0.496***	-0.052***	-0.255***	0.256***	-0.237***
	(0.005)	(0.006)	(0.007)	(0.005)	(0.004)
Post×Y2020×Neighbor	0.005	0.201***	0.005	0.274***	-0.049***
	(0.011)	(0.011)	(0.014)	(0.010)	(0.009)
Y2020	-0.010**	-0.146***	-0.032***	-0.028***	0.045***
	(0.005)	(0.005)	(0.006)	(0.004)	(0.004)
Post×Neighbor	-.132***	-.162***	-.143***	-.0566***	-.0112**
	(.0062)	(.00653)	(.00808)	(.00568)	(.00498)
Y2020×Neighbor	-.162***	-.266***	-.0906***	-.204***	-.0358***
	(.00819)	(.00862)	(.0107)	(.00751)	(.00658)
Observations	176400	176250	174750	175650	175650
R-square	0.588	0.639	0.411	0.378	0.425
Monitor FEs	Y	Y	Y	Y	Y
Weather	Y	Y	Y	Y	Y
Y2018	Y	Y	Y	Y	Y
DOW FEs	Y	Y	Y	Y	Y

Notes: Variable `Hubei` in Panel A and `Neighbor` in Panel B are absorbed by pollution monitor fixed effects.
* significant 10% level; ** significant at 5% level; *** significant at 1% level.

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Supplementary Appendix Material: Did COVID-19 Improve Air Quality Near Hubei?*

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1 Materials and Methods: Data description and estimation equation

Air quality monitor data

We use monitor-specific hourly data from air quality monitor stations across China. With the increasing concern of air pollution, the Chinese government built the National Urban Air Quality Real-time Publishing Platform and mandated detailed quality assurance and quality control programs at each monitoring station. The Platform is required to report six primary pollutants and air quality index since 2013. By the end of our study period, the reporting system covers 367 prefecture-level cities and 1642 monitors across China.

We collected data from 1642 monitors. To construct a balanced panel, monitors are required to report at least one non-missing data each day over 150 days (day -21 to 28 around the Lunar New Year in 2018-2020). In our final sample, the number of monitors for NO_2, SO_2, $PM_{2.5}$, O_3, CO is 1213, 1213, 1202, 1208, 1208 respectively. Detailed number for each province is shown in Supplementary Material Table S1. For each monitor, we collapse hourly data into daily average. We add monitor fixed effects in our regression to control for possible unobserved monitor-specific factors.

Weather station data

We obtain data on weather conditions including temperature, wind speed and precipitation from NCDC Global Summary of the Day. This dataset is derived from The Integrated Surface Hourly dataset and includes data from over 9000 weather stations. We use all active weather stations in China over our study period. To match weather data with air pollution measure, we average weather indicators for each province-month.

CEMS data

We collect CEMS hourly pollutant emissions data from each province's public platform. The national CEMS network covers most thermal power plants and large industrial pollution sources. Monitors installed on the stacks of emitting units measure the emission concentrations of diverse air pollutants. In this study, we focus on two primary pollutants, SO_2 and NO_x.

We use CEMS data in eleven provinces where data are consistently reported in 2019 and 2020: Anhui, Heilongjiang, Henan, Hubei, Jiangsu, Jiangxi, Liaoning, Inner Mongolia, Shaanxi, Shandong and Zhejiang. Four of them are Hubei's neighboring provinces.

We require firms with non-missing data at least 10 days over day -21 to -1 and 14 days over day 0 to 28 in both 2019 and 2020. We average hourly emissions to firm-pollutant-day level data and add firm fixed effects in the regression. When using the number of firms as dependent variable, we construct our sample at province-day level and control for province fixed effects.

Table S1: Number of monitors

Province	Hubei's neighbor	NO_2	SO_2	$PM_{2.5}$	O_3	CO
Anhui	Y	61	61	61	61	61
Beijing	N	12	12	12	12	12
Chongqing	Y	11	11	11	11	11
Fujian	N	33	33	31	33	33
Gansu	N	27	27	27	27	27
Guangdong	N	87	86	86	86	88
Guangxi	N	44	44	44	41	44
Guizhou	N	31	31	31	31	31
Hainan	N	7	7	7	7	7
Hebei	N	46	46	47	46	47
Heilongjiang	N	42	43	42	42	42
Henan	Y	63	63	61	61	63
Hubei		37	38	37	37	37
Hunan	Y	64	65	63	63	65
Inner Mongolia	N	37	37	36	37	37
Jiangsu	N	62	62	62	62	58
Jiangxi	Y	46	46	46	45	45
Jilin	N	29	29	27	29	29
Liaoning	N	74	74	74	74	72
Ningxia	N	17	17	17	17	17
Qinghai	N	9	10	10	10	10
Shaanxi	Y	42	42	42	42	42
Shandong	N	62	60	61	62	61
Shanghai	N	10	10	10	10	10
Shanxi	N	51	51	51	51	51
Sichuan	N	84	84	85	85	84
Tianjin	N	15	15	15	15	15
Tibet	N	8	8	7	9	9
Xinjiang	N	34	34	32	33	34
Yunnan	N	29	28	29	29	28
Zhejiang	N	39	39	38	40	38
Neighbors		287	288	284	283	287
Non-neighbors		926	925	918	925	921
All China		1213	1213	1202	1208	1208

Triple-difference estimation equation

Using Panel A of Table 3 as an example, we estimate the following triple-difference estimation equation:

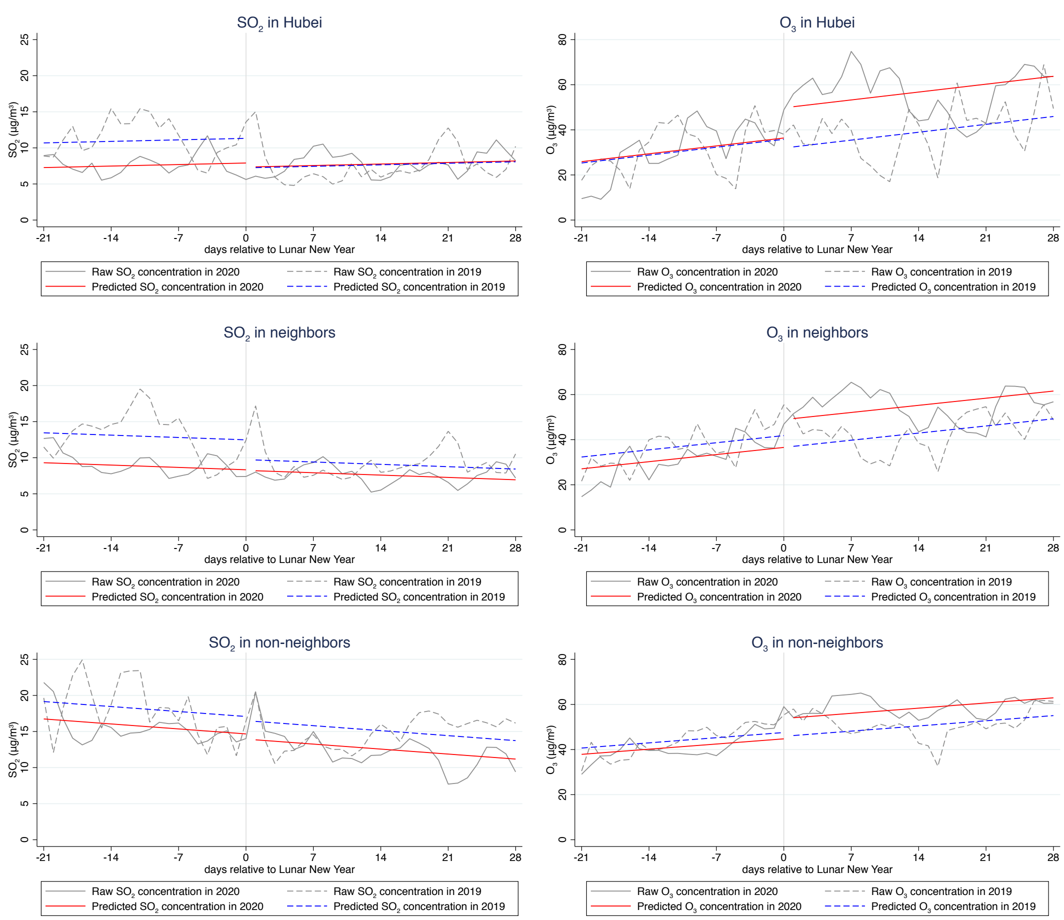
$$y_{it} = \alpha_0 + \beta_1 Post_t + \beta_2 Y2020_t + \beta_3 Post_t * Y2020_t + \beta_4 Post_t * Y2020_t * Hubei_i \\ + \beta_5 Post_t * Hubei_i + \beta_6 Y2020_t * Hubei_i + \gamma_i + \tau_t + X_{it} + u_{it} \quad (1)$$

where the dependent variable y_{it} denotes pollution measures at monitor i in date t. Our independent variables include a binary variable $Post_t$ that is 1 after the New Year day and 0 otherwise, a binary variable $Y2020_t$ that is 1 for year 2020 and 0 otherwise, their interaction term $Post_t * Y2020_t$, a triple interaction term $Post_t * Y2020_t * Hubei_i$, and other double interaction terms between location and time. The binary variable $Hubei_i$ is 1 if the monitor is located in Hubei and 0 otherwise, and this single term is absorbed by station fixed effects. The coefficient β_1 measures the change in pollution before and after the New Year day in year 2018-19. β_2 measures the annual change in average pollution in 2020 from that in 2018-19. β_3 measures the difference in pollution changes before and after the New Year day between year 2020 and year 2018-19. The coefficient of chief interest, β_4 measures change in pollution before and after the New Year day between year 2020 and year 2018-19 in Hubei, relatively to that in neighboring provinces. We also control for τ_t that includes a year 2018 dummy and day of week fixed effects, γ_i pollution monitor fixed effects, and X_{it} weather controls.

2 Figures with regression lines

Figure S1 provides raw and predicted SO_2 and O_3. We run a simplified difference-in-difference model and plot predicted values after regression. Control variables include `Post`, `Y2020`, `Post*Y2020` and `time`. `time` is the same as X-axis in Figure S1, defined as day number relative to LNY. The parallel lines are to smooth the raw data and to show the trend and level change before and after LNY in year 2019 and 2020. They are consistent with our difference-in-difference level estimates with full set of controls reported in Table S2, which indicates our results are robust with and without weather controls, day of week and monitor fixed effects.

Figure S1: SO_2 and O_3 concentration by day before and after the Lunar New Year in 2019 (dash) and 2020 (solid). We normalize days around the Lunar New Year (grey vertical line). Trend lines predicted from a simplified difference-in-difference model are in blue and red, raw concentrations are in grey.



3 Level estimates

Table S2: Double difference results

	NO_2	SO_2	$PM_{2.5}$	O_3	CO
Panel A: All China					
Post	-9.155***	-2.139***	1.109***	5.873***	-0.036***
	(0.092)	(0.072)	(0.251)	(0.112)	(0.003)
Post×Y2020	-10.969***	0.240**	-16.829***	11.286***	-0.235***
	(0.139)	(0.109)	(0.380)	(0.171)	(0.004)
Y2020	-2.854***	-2.733***	-0.964***	-1.583***	0.039***
	(0.121)	(0.094)	(0.329)	(0.148)	(0.004)
Observations	181950	181950	180300	181200	181200
R-square	0.514	0.554	0.347	0.410	0.431
Panel B: Hubei					
Post	-15.249***	-4.757***	-3.623***	1.870***	-0.099***
	(0.555)	(0.234)	(1.281)	(0.657)	(0.013)
Post×Y2020	-6.872***	2.927***	-6.071***	26.192***	-0.083***
	(0.765)	(0.323)	(1.767)	(0.906)	(0.018)
Y2020	-11.269***	-2.056***	-28.614***	-5.408***	-0.143***
	(0.924)	(0.390)	(2.132)	(1.093)	(0.022)
Observations	5550	5700	5550	5550	5550
R-square	0.533	0.396	0.367	0.402	0.218
Panel C: Neighbors					
Post	-13.600***	-3.815***	3.909***	3.790***	-0.029***
	(0.179)	(0.102)	(0.534)	(0.228)	(0.005)
Post×Y2020	-8.645***	2.362***	-20.569***	18.495***	-0.258***
	(0.262)	(0.150)	(0.784)	(0.335)	(0.007)
Y2020	-8.125***	-4.192***	-8.341***	-4.970***	-0.001
	(0.234)	(0.133)	(0.699)	(0.299)	(0.006)
Observations	43050	43200	42600	42450	43050
R-square	0.540	0.409	0.353	0.388	0.400
Panel D: Non-neighbors					
Post	-7.425***	-1.450***	1.162***	6.775***	-0.034***
	(0.110)	(0.093)	(0.293)	(0.134)	(0.003)
Post×Y2020	-12.213***	-0.831***	-15.488***	8.774***	-0.236***
	(0.167)	(0.140)	(0.444)	(0.203)	(0.005)
Y2020	-0.658***	-2.188***	1.948***	-0.351**	0.061***
	(0.143)	(0.121)	(0.381)	(0.174)	(0.004)
Observations	133350	133050	132150	133200	132600
R-square	0.515	0.558	0.342	0.408	0.441
Monitor FEs	Y	Y	Y	Y	Y
Weather	Y	Y	Y	Y	Y
Y2018	Y	Y	Y	Y	Y
DOW FEs	Y	Y	Y	Y	Y

Notes: * significant 10% level; ** significant at 5% level; *** significant at 1% level.

Table S3: Triple difference results

	NO_2	SO_2	$PM_{2.5}$	O_3	CO
Panel A: Hubei and Neighbors					
Post	-13.704***	-3.903***	3.658***	3.851***	-0.034***
	(0.175)	(0.097)	(0.513)	(0.223)	(0.005)
Post×Y2020	-8.606***	2.358***	-20.409***	18.541***	-0.256***
	(0.262)	(0.146)	(0.765)	(0.332)	(0.007)
Post×Y2020×Hubei	2.919***	1.087***	12.925***	4.258***	0.185***
	(0.764)	(0.420)	(2.222)	(0.963)	(0.020)
Y2020	-8.176***	-4.268***	-8.533***	-4.775***	-0.002
	(0.232)	(0.129)	(0.678)	(0.294)	(0.006)
Post×Hubei	-1.92***	.17	-8.62***	-1.91***	-.064***
	(.441)	(.243)	(1.28)	(.557)	(.0117)
Y2020×Hubei	-3.4***	1.43***	-12.9***	2.13***	-.122***
	(.583)	(.321)	(1.7)	(.736)	(.0154)
Observations	48600	48900	48150	48000	48600
R-square	0.539	0.410	0.353	0.389	0.387
Panel B: Neighbors and Non-neighbors					
Post	-7.727***	-1.823***	3.411***	7.061***	-0.030***
	(0.104)	(0.083)	(0.286)	(0.128)	(0.003)
Post×Y2020	-12.018***	-0.619***	-16.340***	8.597***	-0.237***
	(0.162)	(0.129)	(0.445)	(0.199)	(0.005)
Post×Y2020×Neighbor	3.285***	2.905***	-3.300***	9.491***	-0.018*
	(0.322)	(0.255)	(0.885)	(0.397)	(0.010)
Y2020	-0.764***	-2.194***	1.187***	-0.125	0.061***
	(0.137)	(0.109)	(0.377)	(0.169)	(0.004)
Post×Neighbor	-5.05***	-.921***	-8.64***	-4.07***	-.0152***
	(.186)	(.147)	(.509)	(.229)	(.00548)
Y2020×Neighbor	-6.89***	-1.94***	-5.68***	-5.69***	-.0634***
	(.245)	(.194)	(.673)	(.302)	(.00724)
Observations	176400	176250	174750	175650	175650
R-square	0.520	0.554	0.350	0.411	0.435
Monitor FEs	Y	Y	Y	Y	Y
Weather	Y	Y	Y	Y	Y
Y2018	Y	Y	Y	Y	Y
DOW FEs	Y	Y	Y	Y	Y

Notes: Variable `Hubei` in Panel A and `Neighbor` in Panel B are absorbed by pollution monitor fixed effects.
* significant 10% level; ** significant at 5% level; *** significant at 1% level.

4 Robustness checks

There is a tradition for many Chinese families to set off fireworks and commemorate their ancestors during the Lunar New Year, particularly in suburban and rural areas, which leads to heavy bout of pollution. Air quality concerns have caused hundreds of cities to ban fireworks. To our knowledge, there is no ban due to COVID-19, but the quarantine and heavy sadness could result in different fireworks patterns this year. We drop the Lunar New Year's Eve, the second day and the Lantern Festival Day to address this concern. Results in Table S4 and S5 Panel A confirm the robustness of estimates.

The shock of COVID-19 on the economy and the late back-to-work time this year provide incentives for China's speeding up on economic recovery. If pollution increase during recovery is larger this year than that in the back-to-work in previous years especially for Hubei and neighboring provinces, our observed pollution increase is driven by recovery rather than COVID-19. We use a shorter post period to rule out the recovery story. Results in Panel B still show less reduction in SO_2 and more increase in O_3 in Hubei and neighboring provinces.

As mentioned in Background Point 1., China's air quality gets improved in recent years under the efforts the central and provincial governments. Hubei, neighboring and non-neighboring provinces are in some ways different in industrial structures and provincial pollution control. Different baseline pollution levels do not threaten our results but do suggest the importance of allowing for different air quality trajectories. We address this by including province specific linear day trends. Results in Panel C show our estimates remain robust.

Table S4: Triple difference results, Hubei and neighbors

	$\ln(NO_2)$	$\ln(SO_2)$	$\ln(PM_{2.5})$	$\ln(O_3)$	$\ln(CO)$
Panel A: Drop firework days					
Post	-0.439***	-0.370***	-0.129***	0.101***	-0.056***
	(0.006)	(0.007)	(0.008)	(0.007)	(0.005)
Post×Y2020	-0.509***	0.181***	-0.225***	0.564***	-0.293***
	(0.009)	(0.010)	(0.012)	(0.010)	(0.007)
Post×Y2020×Hubei	-0.022	0.149***	0.086**	0.101***	0.205***
	(0.026)	(0.030)	(0.034)	(0.028)	(0.020)
Observations	45684	45966	45261	45120	45684
R-square	0.608	0.500	0.381	0.373	0.385
Panel B: 14 days as post period					
Post	-0.560***	-0.397***	-0.162***	0.088***	-0.046***
	(0.006)	(0.007)	(0.008)	(0.007)	(0.005)
Post×Y2020	-0.363***	0.175***	0.011	0.640***	-0.202***
	(0.010)	(0.012)	(0.013)	(0.011)	(0.008)
Post×Y2020×Hubei	0.061**	0.184***	0.107***	0.158***	0.111***
	(0.028)	(0.034)	(0.039)	(0.032)	(0.022)
Observations	34992	35208	34668	34560	34992
R-square	0.637	0.524	0.341	0.388	0.364
Panel C: Add province by day trend					
Post	-0.593***	-0.370***	0.013	-0.142***	0.087***
	(0.008)	(0.009)	(0.011)	(0.008)	(0.006)
Post×Y2020	-0.508***	0.149***	-0.254***	0.530***	-0.281***
	(0.009)	(0.010)	(0.011)	(0.009)	(0.007)
Post×Y2020×Hubei	-0.041*	0.144***	0.071**	0.130***	0.167***
	(0.025)	(0.029)	(0.033)	(0.026)	(0.019)
Observations	48600	48900	48150	48000	48600
R-square	0.621	0.506	0.390	0.399	0.394
Monitor FEs	Y	Y	Y	Y	Y
Weather	Y	Y	Y	Y	Y
Y2018	Y	Y	Y	Y	Y
DOW FEs	Y	Y	Y	Y	Y

Notes: * significant 10% level; ** significant at 5% level; *** significant at 1% level.

Table S5: Triple difference results, neighbors and non-neighbors

	ln(NO_2)	ln(SO_2)	ln($PM_{2.5}$)	ln(O_3)	ln(CO)
Panel A: Drop firework days					
Post	-0.259***	-0.141***	-0.054***	0.149***	-0.042***
	(0.004)	(0.004)	(0.005)	(0.003)	(0.003)
Post×Y2020	-0.520***	-0.047***	-0.249***	0.264***	-0.249***
	(0.006)	(0.006)	(0.007)	(0.005)	(0.004)
Post×Y2020×Neighbor	0.017	0.226***	0.026*	0.284***	-0.043***
	(0.011)	(0.012)	(0.014)	(0.010)	(0.009)
Observations	165816	165675	164265	165111	165111
R-square	0.587	0.636	0.406	0.379	0.424
Panel B: 14 days as post period					
Post	-0.371***	-0.151***	-0.096***	0.178***	-0.067***
	(0.004)	(0.004)	(0.005)	(0.004)	(0.003)
Post×Y2020	-0.374***	0.015**	-0.098***	0.251***	-0.132***
	(0.006)	(0.007)	(0.008)	(0.006)	(0.005)
Post×Y2020×Neighbor	0.033***	0.179***	0.109***	0.364***	-0.062***
	(0.012)	(0.013)	(0.016)	(0.012)	(0.010)
Observations	127008	126900	125820	126468	126468
R-square	0.619	0.654	0.432	0.395	0.442
Panel C: Add province by day trend					
Post	-0.434***	-0.100***	0.001	0.026***	0.024***
	(0.005)	(0.005)	(0.006)	(0.004)	(0.004)
Post×Y2020	-0.529***	-0.041***	-0.264***	0.224***	-0.228***
	(0.005)	(0.006)	(0.007)	(0.005)	(0.004)
Post×Y2020×Neighbor	0.018*	0.184***	0.010	0.289***	-0.055***
	(0.011)	(0.011)	(0.014)	(0.010)	(0.009)
Observations	176400	176250	174750	175650	175650
R-square	0.603	0.649	0.422	0.394	0.431
Monitor FEs	Y	Y	Y	Y	Y
Weather	Y	Y	Y	Y	Y
Y2018	Y	Y	Y	Y	Y
DOW FEs	Y	Y	Y	Y	Y

Notes: * significant 10% level; ** significant at 5% level; *** significant at 1% level.

5 Results using CEMS data

Using firm-level, hourly emission data from the CEMS, we do similar difference-in-difference estimations in Hubei and non-Hubei provinces in Table S6. First of all, we examine the change in the number of firms reporting emission data before and after the New Year day. In all Chinese firms in the CEMS, the number of firms that report emission data went down more after the New Year day in 2020 than that in 2019. Hubei has more firms that do not report data after the New Year day, compared to that in other provinces. This pattern is consistent with more firms shut down in Hubei given the strictest lockdown policy. Therefore, our analyses on the changes in emissions are limited to firms that consistently report data before and after the New Year day. Within this subsample, we find that a similar 18% decrease in NO_x concentration among firms in Hubei and other provinces. In contrast, for SO_2, there is little change in concentration in Hubei, while a 18% decrease is observed in other provinces. These findings provide suggestive evidence for explaining the less improvement in ambient SO_2 in Hubei during the COVID-19.

Table S6: Double difference results using CEMS data

	Number of firms reporting NO_x	NO_x	$\ln(NO_x)$	Number of firms reporting SO_2	SO_2	$\ln(SO_2)$
Panel A: All China						
Post	-7.002*	-3.714***	-0.078***	-5.980	-0.683**	-0.023**
	(3.735)	(0.414)	(0.010)	(3.727)	(0.284)	(0.010)
Post×Y2020	-17.755***	-5.335***	-0.201***	-19.072***	-0.606	-0.189***
	(5.283)	(0.552)	(0.014)	(5.271)	(0.377)	(0.014)
Y2020	30.823***	-7.759***	-0.141***	31.658***	-2.954***	-0.079***
	(4.021)	(0.450)	(0.011)	(4.012)	(0.307)	(0.011)
Observations	1100	60719	60719	1100	61445	61445
R-square	0.833	0.819	0.662	0.833	0.835	0.781
Panel B: Hubei						
Post	0.016	4.118	0.008	-0.141	-0.274	-0.194**
	(1.760)	(2.925)	(0.055)	(1.793)	(2.661)	(0.078)
Post×Y2020	-34.969***	-10.737**	-0.203**	-35.813***	3.843	-0.038
	(2.489)	(4.795)	(0.091)	(2.535)	(4.180)	(0.123)
Y2020	27.952***	-59.543***	-0.627***	29.857***	-31.868***	-0.962***
	(1.894)	(4.249)	(0.080)	(1.930)	(3.831)	(0.113)
Observations	100	985	985	100	1013	1013
R-square	0.829	0.792	0.642	0.836	0.643	0.838
Panel C: Non-Hubei						
Post	-7.704*	-3.945***	-0.081***	-6.564	-0.727**	-0.021**
	(4.100)	(0.417)	(0.010)	(4.091)	(0.284)	(0.010)
Post×Y2020	-16.034***	-5.420***	-0.202***	-17.398***	-0.761**	-0.195***
	(5.798)	(0.555)	(0.014)	(5.786)	(0.377)	(0.014)
Y2020	31.110***	-7.283***	-0.137***	31.838***	-2.652***	-0.069***
	(4.414)	(0.452)	(0.011)	(4.404)	(0.307)	(0.011)
Observations	1000	59734	59734	1000	60432	60432
R-square	0.828	0.819	0.661	0.829	0.838	0.780
Province FEs	Y			Y		
Firm FEs		Y	Y		Y	Y
DOW FEs	Y	Y	Y	Y	Y	Y

Notes: * significant 10% level; ** significant at 5% level; *** significant at 1% level.