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Abstract

An outbreak of the novel coronavirus (COVID-19) was first reported in Wuhan, Hubei Province, China in December 2019. In late January 2020, the Chinese government implemented strict quarantine measures across Hubei Province and other parts of the country to limit the transmission of COVID-19. An effect of these quarantine measures was the reduction in economic activity and associated emissions that contribute to air pollution. In this study, we quantify the spatial extent and magnitude of changes in air pollution concentrations across China by comparing complementary satellite, ground-based, and modeled data from the first two months of 2019 and 2020. We find a 48% reduction in satellite-derived average fine particulate matter (PM_{2.5}) concentrations in eastern China during a three-week period after the Lunar New Year (LNY) in 2020 compared to 2019, which follows significant declines in the pre-LNY period. We also observe a 49% and 11% decline in post-LNY satellite tropospheric column concentrations of nitrogen dioxide (NO₂) and sulfur dioxide (SO₂). These satellite-based results are in general agreement with data collected from ground monitoring stations across the country, which show a decline in post-LNY PM_{2.5}, NO₂, and SO₂ concentrations. Our modeling analysis suggests that these observed air quality improvements are driven primarily by the reduction in NO₂ emissions, which indicate reductions in transportation and industrial pollution sources during COVID-19, but unfavorable meteorological conditions weaken the role of emissions reduction. Finally, we estimate a reduction by 5%, 14%, and 18% of days in the post-LNY period for 2020 that exceed national PM_{2.5} air quality targets for the entire country, eastern China, and Hubei Province. As more information becomes available on population characteristics and air pollution exposure patterns, this analysis can be extended to quantify human health related impacts to sudden changes in air pollution in China and other locations around the world.

1. Introduction

On December 31st, 2019, Chinese authorities reported the first cases of the novel coronavirus (COVID-19) in Wuhan, Hubei Province (World Health Organization WHO 2020a, 2020b). Several weeks later, on January 23rd, 2020, Chinese authorities closed transportation in and out of Wuhan, just before the start of the Lunar New Year (LNY) when large numbers of people typically travel. At least 50 million people were put under a mandatory quarantine that kept most residents in their homes, closed businesses and schools, and severely limited vehicular traffic by up to 90% (World Health Organization WHO 2020b, Xinhua News 2020a, Xinhua News 2020b). Preliminary studies found that the travel ban in Wuhan delayed the progression of COVID-19 by three to five days in mainland China and reduced cases more substantially at the international scale (Chinazzi *et al* 2020). In addition to its impact on disease transmission, these quarantine measures also reduced China's

economic output by an estimated 13.5% during January and February 2020 (National Bureau of Statistics of China 2020). Preliminary results based on ground monitoring stations found a substantial decrease in PM_{2.5}, PM₁₀, and NO₂ concentrations in the city of Wuhan after the COVID-19 outbreak, but PM_{2.5} returned to historical levels by March 8th, 2020 (Malpede *et al* 2020). In this study, we quantify the effect of changes in personal and economic activity on outdoor (ambient) air pollution concentrations and exceedances of national ambient air quality standards in China.

Ambient air pollution is a global public health issue that is especially severe in China (Lelieveld *et al* 2015). PM_{2.5} pollution contributed to 4.2 million deaths per year globally and 1.1 million deaths in China in 2015 (Cohen *et al* 2017). In 2014, more than 90% of China's population experienced at least 120 h of unhealthy air and nearly 40% experienced average conditions considered unhealthy relative to US EPA guidelines (Rohde and Muller 2015).

Air pollution is driven by multiple factors that include emissions sources and meteorology. The dominant emissions sources in China are residential energy, agriculture, and power generation (Lelieveld *et al* 2015). However, not all air pollution originates from local sources and recent studies have pointed to the need for a regional approach to improve China's air quality. For example, approximately half of the air pollution in Beijing and many other cities in northern China is transported in the atmosphere from other source regions (Zhang *et al* 2015). Air pollution sources also change over time. The highest air pollution concentrations in China typically occur during the winter and spring seasons (Cheng *et al* 2013). In eastern China, residential heating emissions contribute to high pollution levels. Eliminating this source would reduce primary PM_{2.5} emissions by 32%, more than the transportation and power sectors but less than industry (Liu *et al* 2016). In addition to seasonal variability, air pollution concentrations change at longer timescales based on demographic and economic trends. For example, while NO₂ emissions growth rates slowed in Chinese megacities from 1996 to 2010, emissions from medium-sized cities increased over the same time period (Zhang *et al* 2012).

Several recent studies have explored the relationship between air pollution exposure and health effects in local Chinese populations. The China Air Pollution and Health Effects Study (CAPES) found that a 10 $\mu\text{g m}^{-3}$ increase in two-day PM₁₀ concentrations is associated with a 0.35% increase in total mortality (Chen *et al* 2012). Women (compared to men), the elderly, and people with lower education levels are at higher risk (Chen *et al* 2012). On a seasonal basis, winter and summer has the strongest association between PM exposure and health outcomes (Chen *et al* 2013). There are also significant associations between PM_{2.5} exposure and health effects in China. A study of 272 cities from 2013–2015 found that a 10 $\mu\text{g m}^{-3}$ increase in two-day PM_{2.5} is associated with 0.22% increase in mortality (Chen *et al* 2017).

In response to these severe air pollution effects, the Chinese government phased in new air quality regulations (GB3095-2012) over 2013 to 2017. Over this time period, national population-weighted annual PM_{2.5} concentrations decreased from 62 to 42 $\mu\text{g m}^{-3}$ and PM_{2.5}-attributable mortality declined by 0.41 million people. PM_{2.5} concentration changes were largely driven by emissions reductions from industry and promoting clean fuels in the residential sector (Zhang *et al* 2019). This follows earlier efforts to reduce pollution. Annual average PM₁₀ concentrations decreased from 116 to 85 $\mu\text{g m}^{-3}$ over 2001 to 2011 (Cheng *et al* 2013). In addition, there are also examples of short-term efforts to reduce pollution. During the 2008 Olympic Games in Beijing, daily emissions of SO₂, NO_x, PM₁₀, and non-methane volatile organic compounds (NMVOC) were reduced by 41%–57% due to facility closures, halting building construction, and mobile emissions controls (Wang *et al* 2010).

The objective of this study is to quantify changes in China's air pollution levels following the COVID-19 quarantine measures. We use a combination of complementary satellite, ground monitoring, and modeling data that are rapidly available to quantify changes in concentrations of PM_{2.5}, NO₂, and SO₂. We then evaluate changes in exceedances of national air quality standards for PM_{2.5} during these time periods. The effects of China's drastic quarantine measures on air pollution and public health are applicable to other countries around the world also dealing with an economic slowdown during efforts to reduce COVID-19 transmission.

2. Methods

2.1. Overview

Different methods of measuring air pollution have various strengths and weaknesses. To quantify changes in China's air pollution levels after the COVID-19 quarantine actions, we leverage data from multiple sources to present a more comprehensive view of the potential changes. We use complementary information from:

- (1) Satellites, which have broad spatial coverage, but can be inhibited by clouds and quantify changes throughout the atmospheric column rather than at the surface.

- (2) Ground stations, which offer detailed pollution observations for specific point locations, but may not be representative over broad spatial scales.
- (3) Atmospheric models, which are typically coarser spatial resolution, but can provide insight into the role of emissions and meteorology in driving air pollution, depending on the accuracy of these datasets.

We first analyze satellite and ground-based datasets that are available in near-real time to quantify changes in air pollution concentrations between January to February 2019 and 2020. To estimate the impact of meteorology on air pollution changes between these two time periods, we then conduct atmospheric model simulations for both periods and compare with ground observations. Finally, we compare the distribution of daily $\text{PM}_{2.5}$ measurements to national air quality standards. For each stage of the analysis, we compare changes across three spatial domains: China, eastern China, and Hubei Province. In addition, since emissions typically decline each year during the LNY, we examine changes based on the start of the LNY, rather than by calendar date, to limit the influence of the LNY on changing concentrations rather than quarantine measures. Further details on each dataset are provided in the sections below.

2.2. Satellite-based observations

2.2.1. Surface $\text{PM}_{2.5}$

The relationship between column aerosol optical depth (AOD) measured from satellites and surface-level $\text{PM}_{2.5}$ varies over space and time but publicly available datasets are not currently available in near-real time (Xie *et al* 2015, van Donkelaar *et al* 2019). To bridge this gap, we use the near-real time capability of the Copernicus Atmosphere Monitoring Service (CAMS) global reanalysis of atmospheric composition provided by the European Centre for Medium-Range Weather Forecasting (ECMWF). $\text{PM}_{2.5}$ is derived from assimilated AOD observations from the MODerate resolution Imaging Spectroradiometer (MODIS) on board NASA's Aqua and Terra satellites and a forecasting model that incorporates meteorology and atmospheric transport patterns to estimate surface-level $\text{PM}_{2.5}$. Previous comparisons of forecasted $\text{PM}_{2.5}$ with observations show an underestimate in Europe and overestimate in North America (Schulz *et al* 2019). We obtain three-hourly forecasted $\text{PM}_{2.5}$ concentrations at 0.4° spatial resolution across China for the three weeks before and after the start of the LNY for 2019 and 2020 from the CAMS online service (<https://apps.ecmwf.int/datasets/data/cams-nrealtime/levtype=sfc/>). We then average to daily forecasted $\text{PM}_{2.5}$ concentrations.

2.2.2. Column NO_2 and SO_2 Observations

We retrieve offline nitrogen dioxide (NO_2) and sulfur dioxide (SO_2) data from the Tropospheric Monitoring Instrument (TROPOMI) on board the Sentinel-5 Precursor (Sentinel-5P) satellite through the Google Earth Engine platform (Gorelick *et al* 2017). Tropospheric NO_2 and atmospheric SO_2 are provided as a daily column number density (mol/m^2) and have good agreement compared to ground and satellite observations (Theys and Wagner 2019, Eskes and Eichmann 2019). We apply the recommended quality flags for NO_2 (0.75) and SO_2 (0.5), respectively, to account for retrieval errors due to cloud cover, land surface effects, and other errors. Some negative values are due to noise in the data retrievals. For each measure, we extract available data at ($\sim 3.5 \text{ km} \times 7 \text{ km}$ spatial resolution at nadir, increasing to 5.5 km along track after August 2019) for the three weeks before and after the onset of the LNY and average over each period.

2.3. Ground station observations

We calculate daily averages of $\text{PM}_{2.5}$, NO_2 , and SO_2 (in $\mu\text{g m}^{-3}$) from ground monitoring stations located in 366 Chinese cities from the China National Environmental Monitoring Center (CNEMC) (<http://106.37.208.233:20035/>) by averaging all available hourly station data to daily city-wide estimates. To compare concentration changes between 2019 and 2020, we align the daily monitoring data to the start of the LNY: February 5th 2019 and January 25th 2020. Each of these dates is 'Day 0' from which we assess changes in air quality while controlling for variations in economic activity associated every year with the LNY but not related to the quarantine. With data available for January to February 2019 and 2020, we therefore compared a three-week period before and after the start of the LNY to ensure a consistent temporal window for each year.

2.4. Air quality modeling

We use the Community Multi-scale Air Quality (CMAQ) model (Version 5.2) and the Weather Research and Forecast (WRF) model (Version 3.8) to simulate concentrations of NO_2 , SO_2 and $\text{PM}_{2.5}$ for January to February 2019 and 2020. The configuration of the WRF model is described in detail by Chang *et al* (2018). The CMAQ model is configured with the Carbon Bond 5 (CB05) gas-phase chemical mechanism and AERO6 aerosol module, 14 vertical layers from ground to 100 hPa, and a spatial domain covering China with $27 \text{ km} \times 27 \text{ km}$ horizontal resolution. Anthropogenic emissions are developed by Tsinghua University for 2017 (Ding *et al*

2019). Biogenic emissions are generated by the Model for Emissions of Gases and Aerosols from Nature (MEGAN) version 2.04 (Guenther *et al* 2006). The model's performance has been evaluated with observations in the above-mentioned studies.

The simulation period is 60 days from January to February in both 2019 and 2020 with a five-day prior spin-up period to minimize the influence of initial conditions. Anthropogenic emissions are held constant for both years and do not consider reductions associated with either the LNY or COVID-19 response actions. Therefore, the difference between the simulation and observations suggests impacts from the reduced activity on air pollution, while comparisons between 2019 and 2020 indicate the influence of meteorology on driving air pollutant concentration changes with constant emissions.

2.5. Air quality standards

Air quality standards serve as a rapid metric to assess air pollution concentrations that exceed levels determined to cause harm to population health. China recently implemented new nationwide ambient air quality standards, GB 2095-2012 (table S1 is available online at stacks.iop.org/ERC/2/075003/mmedia). The standards were initially carried out in several cities (such as Beijing and provincial capitals) in 2012 (Ministry of Ecology and Environment of the People's Republic of China 2012), expanded nationwide by 2016, and supplemented in 2018 (Ministry of Ecology and Environment of the People's Republic of China 2018). Class 1 standards are more stringent and apply to specially designated regions such as national parks and other special regions; Class 2 standards apply to all other areas. The Class 1 and Class 2 daily standards for $\text{PM}_{2.5}$ ($35 \mu\text{g m}^{-3}$ and $75 \mu\text{g m}^{-3}$) are more lenient than the World Health Organization air quality guideline ($25 \mu\text{g m}^{-3}$) (World Health Organization WHO 2006). To calculate exceedances over air quality standards, we consider all available daily measurements from cities located in our three spatial regions of interest.

2.6. Statistical analyses

We use two-sample paired t-tests to compare the distribution of our ground station observations for the pre-LNY period in 2019 and 2020 as well as the post-LNY period in 2019 and 2020. To address autocorrelation in time series data (O'Shaughnessy and Cavanaugh 2015), we compare the three-week mean concentrations. Previous studies of spatial correlation in city-level air pollution concentrations in China are low for the pollutants examined in this study (Dai and Zhou 2017). In addition, we compare the three-week mean concentrations from the satellite and forecasting model-based results with the city-wide station averages that fall within the individual grid cells to directly compare the results from our two observational datasets.

3. Results

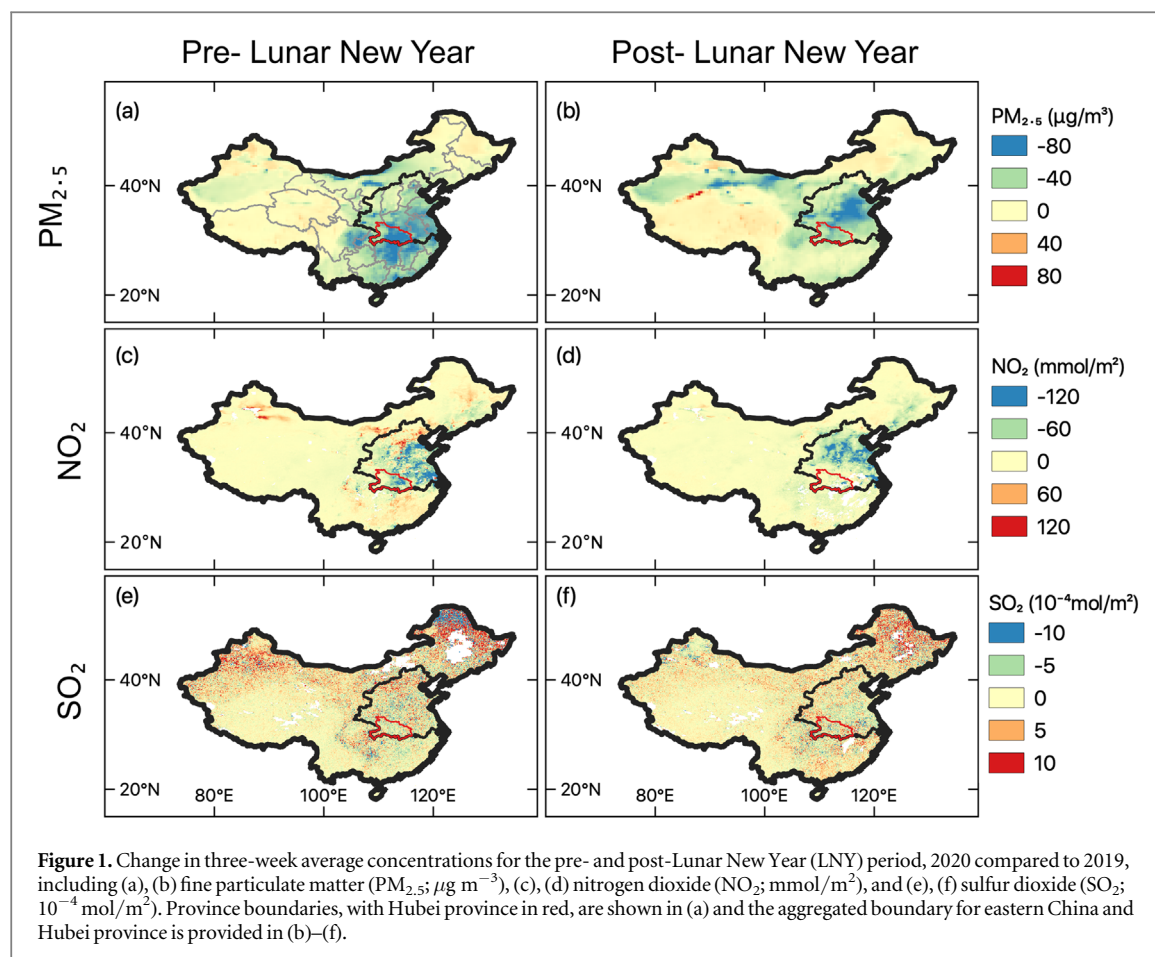
3.1. Satellite-based observations

We first compared satellite-derived estimates of three-week mean $\text{PM}_{2.5}$, NO_2 , and SO_2 concentrations across our three regions of interest for 2019 and 2020 for the pre- and post-LNY period (figure 1 and table S2). The CAMS satellite and modeling forecast system estimates a decline in surface $\text{PM}_{2.5}$ by $12 \mu\text{g m}^{-3}$ (-37%) across China averaged over the three-week period after the LNY in 2020 compared 2019. $\text{PM}_{2.5}$ concentrations were also lower in the pre-LNY period for 2020 compared to 2019 (-47%). The ten contiguous provinces and municipalities in eastern China (i.e., Anhui, Beijing, Hebei, Henan, Hubei, Jiangsu, Shaanxi, Shandong, Shanxi, and Tianjin) with the largest $\text{PM}_{2.5}$ change (hereafter referred to as eastern China) have an average decline of $41 \mu\text{g m}^{-3}$ (-48%) for the post-LNY period, following similar changes in the pre-LNY period (-50%). The largest absolute changes are in Tianjin, Shandong, and Henan with monthly declines of 42 – $63 \mu\text{g m}^{-3}$. Hubei province has the fifth largest change at $-37 \mu\text{g m}^{-3}$ (-49%) over the post-LNY three-week time period, following a -67% decline in the pre-LNY period.

We also explore changes in three-week average TROPOMI column NO_2 and SO_2 , which indicate potential changes in emissions sources. We observe the largest reductions in NO_2 for 2020 relative to 2019 for the post-LNY period, following similar declines in the pre-LNY period that were more prominent in the southeastern part of China. We observe declines of 34% across the entire country, 49% in eastern China, and 30% in Hubei in the post-LNY period. SO_2 is 11% lower in eastern China and 74% lower in Hubei province in the post-LNY, but increases across China as a whole. This follows mixed changes for the pre-LNY period as well.

3.2. Ground station observations

We average daily $\text{PM}_{2.5}$, NO_2 , and SO_2 concentrations across all cities in China ($n = 366$), eastern China ($n = 132$), and Hubei province ($n = 13$) and compare 2019 and 2020 (figure 2 and table 1). Figures S1 and S2 show the distribution of daily pollutant concentrations for individual cities in each of our time periods. For all three spatial areas and pollutants, we observe reduced air pollutant concentrations in the post-LNY period for



2020 versus 2019. In particular, we observe more pronounced declines in daily $PM_{2.5}$ and NO_2 in eastern China and Hubei province compared to whole country. Daily SO_2 changes are smaller compared to the other pollutants. The spatial patterns are similar between satellite and ground stations, except the satellite record generally shows more substantial declines in Hubei province. In addition, ground stations indicate fewer declines for the post-LNY versus pre-LNY period for 2020 compared to 2019. We note that the low number of stations in the western part of the country precludes a direct comparison in the average concentrations of satellite-derived and ground station observations, particularly in the country-wide averages.

The largest changes between the two years are for the cities in eastern China. In the three-week pre-LNY period, the average $PM_{2.5}$ across all cities in eastern China is $78\ \mu g\ m^{-3}$ in 2019 and $91\ \mu g\ m^{-3}$ in 2020. In the post-LNY period, the average is $82\ \mu g\ m^{-3}$ in 2019 and $64\ \mu g\ m^{-3}$ in 2020. For NO_2 , the average of all cities in eastern China is $45\ \mu g\ m^{-3}$ and $42\ \mu g\ m^{-3}$ before the LNY in 2019 and 2020, and $32\ \mu g\ m^{-3}$ and $19\ \mu g\ m^{-3}$ afterwards. SO_2 concentration changes are less pronounced, partly because concentrations are much lower in the pre-LNY period in 2020 ($14\ \mu g\ m^{-3}$ in 2019 and $11\ \mu g\ m^{-3}$ in 2020). In the post-LNY period, SO_2 concentrations are $11\ \mu g\ m^{-3}$ and $10\ \mu g\ m^{-3}$, respectively.

We also sampled our satellite-derived three-week average concentrations for the pre- and post-LNY period in 2019 and 2020 based on the location of individual cities (figure S3). We find strong linear relationships for $PM_{2.5}$ ($R^2 = 0.51$ – 0.68) and NO_2 ($R^2 = 0.52$ – 0.70), but weak correlations for SO_2 ($R^2 = 0.08$ – 0.12).

3.3. Air quality modeling simulations

We use modeling simulations to explore the effects of changing emission and meteorology on air pollution concentrations (table 2 and figure S4). The difference between observations and the modeling simulations can be attributed to the uncertainties in emissions, meteorology, and the model itself. Since detailed emission changes from the pre- and post-LNY period are unavailable, we conduct modeling simulations with constant emissions across the whole simulation period. Therefore, the difference between the simulation and observations during the three-week post-LNY period roughly represents the impact of the reduced activity on emissions, which could be due to the LNY, quarantine measures, and/or other year-to-year changes. We define the ratio of observation to the simulation as the ‘E-ratio’ to represent the difference between observations and simulated values. The CMAQ model tends to underestimate $PM_{2.5}$ and NO_2 (E-ratio > 1) and overestimate SO_2 (E-

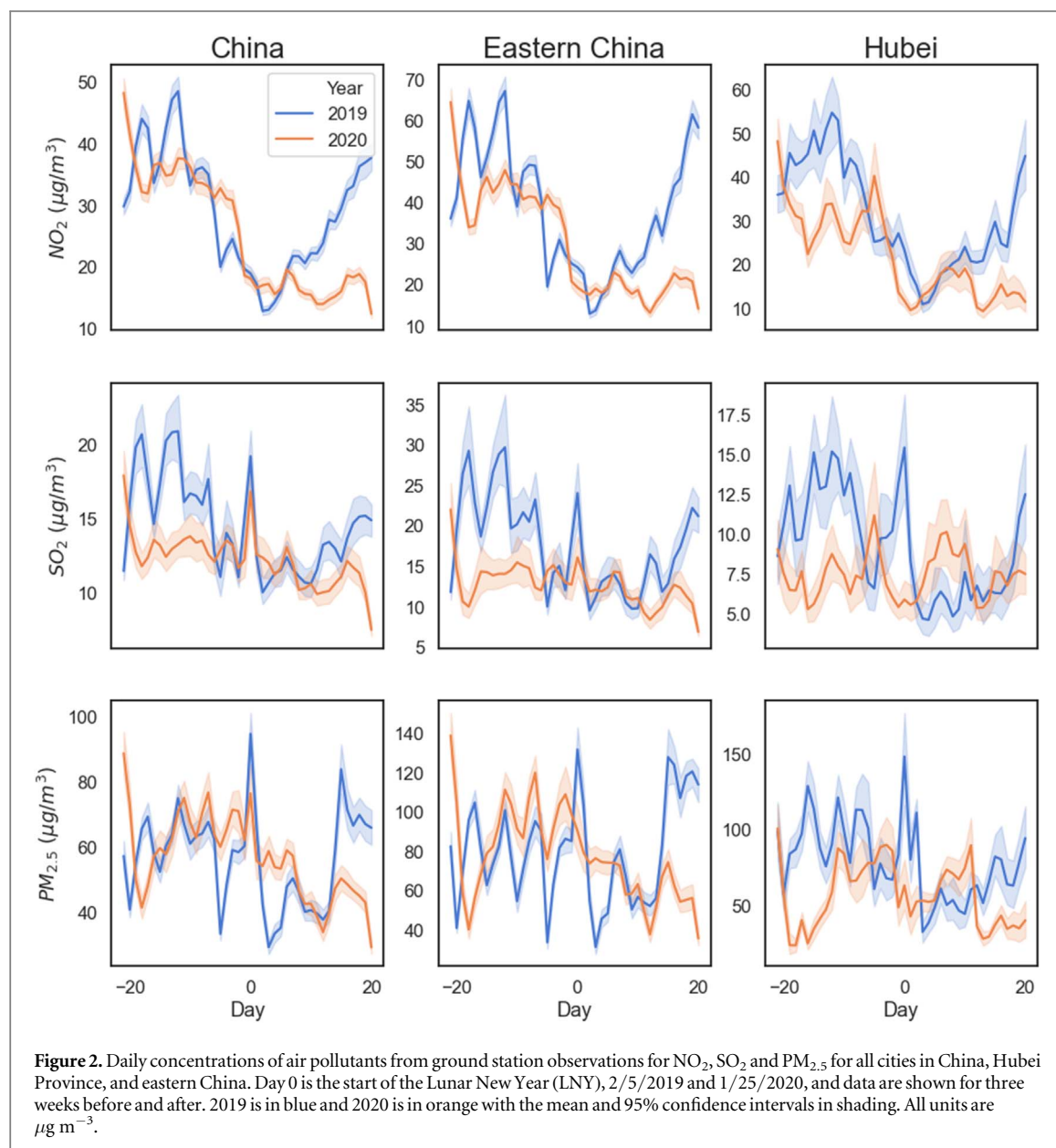


Figure 2. Daily concentrations of air pollutants from ground station observations for NO_2 , SO_2 and $\text{PM}_{2.5}$ for all cities in China, Hubei Province, and eastern China. Day 0 is the start of the Lunar New Year (LNY), 2/5/2019 and 1/25/2020, and data are shown for three weeks before and after. 2019 is in blue and 2020 is in orange with the mean and 95% confidence intervals in shading. All units are $\mu\text{g m}^{-3}$.

Table 1. Three-week mean concentrations of $\text{PM}_{2.5}$, NO_2 , and SO_2 ($\mu\text{g m}^{-3}$) for cities in China, eastern China, and Hubei Province with standard deviation in parentheses. The pre- and post-Lunar New Year (LNY) periods represent the three weeks before and after the onset of the LNY in 2019 and 2020. For each period, we calculate percentage change as $(2020-2019)/2019$.

Pollutant	Location	Pre-LNY		Post-LNY		Change	
		2019	2020	2019	2020	Pre	Post
$\text{PM}_{2.5}$	China (n = 366)	59.3 (38.4)	64.7 (50.9)	54.0 (46.8)	48.9 (49.5)	9%**	-9%**
	E. China (n = 132)	77.5 (38.9)	91.1 (56.1)	81.9 (55.2)	64.0 (39.6)	18%**	-22%**
	Hubei (n = 13)	90.8 (35.5)	61.9 (32.3)	67.7 (37.1)	51.5 (24.7)	-32%**	-24%**
NO_2	China (n = 366)	34.0 (18.5)	34.1 (17.4)	24.2 (15.9)	16.5 (10.0)	0%	-32%**
	E. China (n = 132)	44.8 (18.9)	41.6 (16.9)	31.9 (18.4)	18.7 (9.1)	-7%**	-41%**
	Hubei (n = 13)	39.5 (13.9)	30.2 (10.4)	22.9 (10.7)	14.0 (6.4)	-24%**	-39%**
SO_2	China (n = 366)	16.2 (15.9)	13.2 (11.3)	12.8 (11.4)	11.3 (9.8)	-19%**	-12%**
	E. China (n = 132)	20.2 (18.8)	13.9 (12.3)	14.6 (12.8)	11.5 (8.8)	-20%**	-12%**
	Hubei (n = 13)	11.3 (5.1)	7.4 (3.2)	7.2 (4.3)	7.5 (3.2)	-12%**	-8%

* $p < 0.05$, ** $p < 0.01$. Note that four stations were removed from China results and one from E. China for the paired t-test because of missing data in one time period.

Table 2. Ratio of observed and modeled concentrations of air pollutants within the three regions of interest for the three weeks before and after the onset of the Lunar New Year (LNY), which indicates the influence of reduced emissions on air pollution levels (noted as ‘E-ratio’ in the text). The ratio of 2020 to 2019 simulations, with emissions held constant, indicates the influence of changing meteorology (noted as ‘M-ratio’ in the text).

Pollutant	Location	E-ratio (Observed: Simulated)				M-ratio (2020: 2019)	
		Pre- LNY		Post- LNY		Pre- LNY	Post- LNY
		2019	2020	2019	2020		
PM _{2.5}	China	1.82	1.74	1.89	1.29	1.14	1.33
	Hubei	1.73	1.14	1.33	0.84	1.04	1.20
	E. China	1.97	1.93	1.87	1.24	1.20	1.19
NO ₂	China	1.53	1.40	1.09	0.71	1.10	1.05
	Hubei	1.71	1.24	0.92	0.59	1.06	0.96
	E. China	1.44	1.24	1.03	0.59	1.08	1.04
SO ₂	China	0.78	0.61	0.82	0.57	1.05	1.28
	Hubei	0.37	0.40	0.42	0.30	0.83	1.27
	E. China	0.52	0.39	0.49	0.37	1.06	1.20

Table 3. Percent exceedances above daily the Class 2 PM_{2.5} air quality standard ($75 \mu\text{g m}^{-3}$) in the three weeks before and after the Lunar New Year (LNY) for 2019 and 2020. Spatial domains are shown in figure 1 for reference.

Location	Pre-LNY		Post-LNY		Change	
	2019	2020	2019	2020	Pre	Post
China	28	31	23	18	+3	−5
E. China	49	54	45	31	+5	−14
Hubei	66	35	33	15	−31	−18

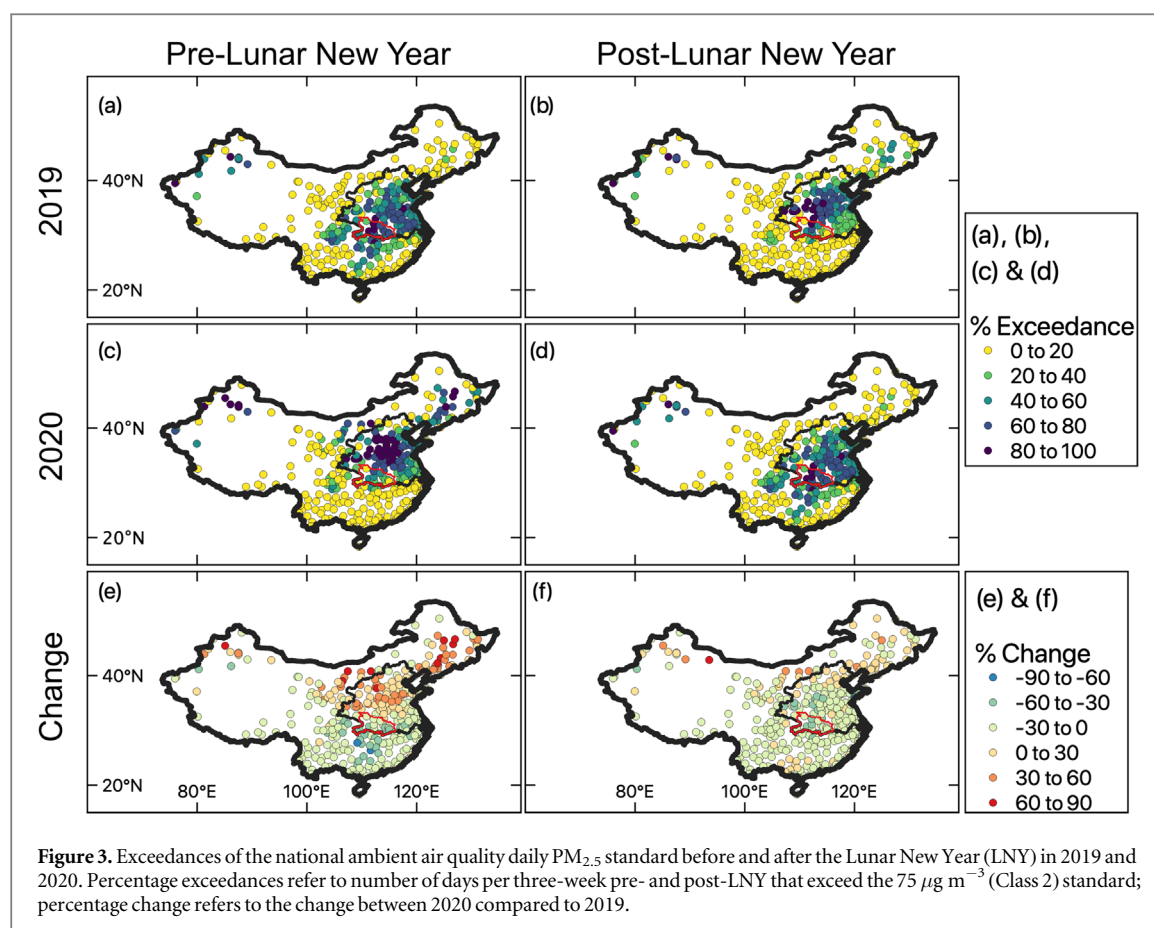
ratio < 1). However, the E-ratio for PM_{2.5}, NO₂, and SO₂ is consistently lower in 2020 compared to 2019, particularly for the three-week post-LNY period. The observed values are much lower than simulated values in the three-week post-LNY period for 2020. For example, in the post-LNY period in Hubei Province, the E-ratio is 1.3 in 2019 and 0.8 in 2020 for PM_{2.5} and 0.9 in 2019 and 0.6 in 2020 for NO₂.

The difference between 2019 and 2020 provides preliminary insight into the influence of meteorology on air pollution concentrations from year to year. Since we held constant emissions in both year simulations, the ratio of the simulation in 2020 to that in 2019 (noted as ‘M-Ratio’) represents the influence of meteorology, although, the influence of meteorology may vary with the emission levels and also the interaction between the air-pollution and meteorology (e.g., aerosol radiative forcing), which is not included in this study. In general, the comparison of meteorology indicates slight increases in PM_{2.5} and SO₂ concentrations in 2020 compared to 2019 (M-ratio > 1), with less of an effect in NO₂. In the three-week 2020 post-LNY period, we observe higher M-ratios in PM_{2.5} and SO₂ (1.2–1.3) across the three regions, which indicates increased formation of pollutants in the absence of emissions changes, which may be due to meteorological conditions. NO₂ M-ratios show less change between the two years (1–1.1).

3.4. Exceedances of PM_{2.5} air quality standards

We use city-wide averages of ground station data to compare daily exceedances over PM_{2.5} air quality standards for the three-week period before and after the LNY in 2019 and 2020 (table 3). Figure 3 shows the percentage of days that exceed the daily Class 2 national PM_{2.5} standard ($75 \mu\text{g m}^{-3}$) for the three weeks before and after the LNY in 2019 and 2020 for individual cities across China, highlighting improvements in air quality standard attainment in the 2020 post-LNY period as well as the incidence of persistent high pollution during the COVID-19 response. When comparing the pre-LNY period across the country, exceedances are similar in 2019 and 2020: 28% and 31% exceedances of the Class 2 standard, respectively. In the post-LNY period, the exceedance rates in 2019 and 2020 are 23% and 18%. This translates to one additional day that achieves the Class 2 standard over the three-week post-LNY period.

The results are more pronounced in eastern China. In the three-week pre-LNY period in 2019, 49% of stations in eastern China exceed the daily Class 2 standard and 54% exceed in 2020. In the post-LNY period in 2019, 45% of stations exceed the Class 2 standard but only 31% exceed in 2020. Four additional days achieve the



Class 2 air quality standard in the three-week post-LNY period in 2020. For the pre-LNY period in Hubei Province in 2019 and 2020, 66% and 35% of days exceed the Class 2 standard. Exceedances in the post-LNY period in 2020 are 15% compared to 33% for 2019, corresponding to an additional three days that achieve the standard.

4. Discussion

This study provides a preliminary assessment of changes in China's air quality during the COVID-19 quarantine. We observe a significant decrease in air pollution concentrations measured both by satellites and ground monitoring stations. The most pronounced changes detected by satellite-derived estimates are in surface $\text{PM}_{2.5}$ and column NO_2 : -48% and -49% across eastern China and -37% and -34% across the country for the three-week post-LNY period, following lower concentrations in the pre-LNY period as well. However, the satellite-derived $\text{PM}_{2.5}$ estimates are lower than ground station observations, particularly in 2020. These estimates are based on a forecasting model that integrates satellite observations, and points to the need for future in-depth analysis of satellite and surface $\text{PM}_{2.5}$ relationships before calculating population-level health effects. Air quality standard exceedances are comparable between the three-week period leading up to the LNY for 2020 versus 2019 (except for Hubei Province) but declined for the post-LNY period. Further, despite the dramatic declines in air pollution that we observe, air pollution in many parts of eastern China remains high and many areas still experience significant exceedances over national air quality guidelines for $\text{PM}_{2.5}$. This may be partially due to sustained emissions from residential heating and essential industrial sources, even as some industrial and transportation-related sources declined. Meteorology may also play a role in high air pollution levels despite emissions declines (Wang *et al* 2020a, 2020b).

There are several sources of uncertainty in this analysis. First, the Chinese government had previously implemented various policies to reduce air pollution and meteorological conditions vary from day to day, so we cannot attribute all emissions reductions to the COVID-19 outbreak. In 2013, the State Council of China issued the Air Pollution Prevention and Control Action Plan (APPCAP) which requires $\text{PM}_{2.5}$ levels to be reduced by at least 18% by 2020 compared with 2015 (Huang *et al* 2018). As a result, the annual $\text{PM}_{2.5}$ concentrations from 496 stationary monitors in 74 cities of China have decreased from 72.2 to $47.0 \mu\text{g m}^{-3}$ between 2013 and 2017 (Huang *et al* 2018). However, by focusing our analysis on the comparison between 2020 and 2019, we reduce the

influence of government policies not related the COVID-19 response. In addition, our CMAQ modeling results suggest that some of the changes can be attributed to changing meteorology. Second, there are uncertainties in both sources of air pollution data: both with inferring surface-level changes from satellites and with extrapolating from station point measurements. Further, we do not know at this time how the COVID-19 pandemic will evolve over time and affect the global economic activity. Longer-term health benefits will depend on sustained air quality improvements rather than the relatively short time periods analyzed here.

Recent studies have explored various aspects of changes in air pollution related to COVID-19 response actions. This includes analysis of ground station observations collected in China and other locations around the world. Cole *et al* (2020) applied a machine learning approach to control for the effect of meteorology on air pollution, and find that the lockdown in Wuhan was associated with a reduction in NO₂ and PM₁₀ concentrations. Shi and Brasseur (2020) compared station observations before and after the LNY. They found 35% and 60% reductions in surface PM_{2.5} and NO₂ concentrations. Wang *et al* (2020b) linked NO₂ emissions reductions to the transportation sector, but found that SO₂ reductions were only linked to the industrial sector. Both Wang *et al* (2020b) and Shi and Brasseur (2020) found increasing ozone (O₃) concentrations and point to the need for future work on non-linear relationships between emissions changes and air pollution concentrations. Liu *et al* (2020) estimated a 48% decline in satellite column NO₂ observations for the twenty days before versus after LNY period in 2020, which was 20% larger than previous years. They related NO₂ reductions to province-level public announcements of COVID-19 infections and lockdown measures. A modeling-based study estimated a decline in PM_{2.5} concentrations attributable to large reductions in transportation and industrial emissions during the quarantine, but unfavorable meteorological conditions limited the reduction of severe air pollution (Wang *et al* 2020a). Bauwens *et al* (2020) found a 40% decline in column NO₂ measured by TROPOMI across Chinese cities in 2020 relative to 2019 with persistent changes after the LNY in 2020 versus 2019. Our study adds to this body of work by examining air pollution changes across several spatial scales (province, regional, and country) and by incorporating evidence from ground station, satellite, and an atmospheric model to tease apart the influence of the Lunar New Year, meteorology, and the COVID-19 response.

There are several steps for future analyses. One is to understand underlying population characteristics that influence the relationship between PM_{2.5} exposure and health effects. This includes interactions between air pollution and respiratory disease, building on previous research during the SARS epidemic that suggested that air pollution had a detrimental effect of SARS case fatality (Cui *et al* 2003). Second, improved modeling and measurement data are critical to accurately estimate spatial and temporal variations in population-level exposure. Finally, with COVID-19 spreading to many other countries at the time of writing this paper, there is an increasing need to understand changes in the global economic slowdown, air pollution, and health.

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