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## Localized pollutant emission increases in China due to COVID-19 lockdowns

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Previous studies reported significant decreases in pollutant emissions across industrialized countries during COVID-19 lockdowns in the spring of 2020. However, high-resolution inverse modeling of satellite observations of nitrogen dioxide (NO<sub>2</sub>) by the TROPOMI instrument reveals significant increases in nitrogen oxide (NO<sub>x</sub> = NO + NO<sub>2</sub>) emissions in some locations despite widespread reductions in economic activity and mobility due to COVID-19 control measures. The NO<sub>x</sub> emission increases are associated with supply routes to locked-down cities and urban-to-suburban emission shifts. For example, the total NO<sub>x</sub> emissions over the Jiang-Han Plain region, where the supply routes to Wuhan were located, increased by 25% during the lockdown. After the lockdown measures were lifted, NO<sub>x</sub> emissions showed uneven recoveries of economic activities. Significant increases in NO<sub>x</sub> emissions were observed in the northern part of Jiangsu Province, which has a notable concentration of small-scale or home-based factories, indicating a more rapid resurgence of small enterprises. This research highlights the potential of satellite-based pollutant observations as a valuable tool for assessing socioeconomic activities during pivotal events, such as a pandemic lockdown.

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### Environmental significance

Previous studies reported large decreases in air pollution during the COVID-19 lockdowns in spring 2020. However, high-resolution satellite observations from TROPOMI show a more complex response for nitrogen oxides (NO<sub>x</sub>) in China. Although overall activity declined, NO<sub>x</sub> emissions increased in specific locations, especially along supply routes to locked-down cities and in suburban areas. For example, emissions over the Jiang-Han Plain, which supplies Wuhan, rose by 25% despite urban reductions. Post-lockdown recovery was uneven, with northern Jiangsu Province experiencing strong rebounds linked to small-scale manufacturing. These findings challenge the assumption that lockdowns uniformly improve air quality and demonstrate how emergency responses can shift emission sources. Satellite observations offer a powerful tool for tracking these changes and informing sustainable crisis management.

## 1. Introduction

The COVID-19 outbreak was first reported in December 2019 in the city of Wuhan, China, and the pandemic had far-reaching impacts on global health, economies, and societies.<sup>1,2</sup> As nations grappled with the rapid transmission and uncertain prognosis of COVID-19, lockdown measures were enforced worldwide, significantly altering societal behaviors and levels of activity.<sup>3</sup> In Wuhan, the epicenter of the initial outbreak, stringent lockdown protocols were initiated as early as January 2020 in an attempt to control viral transmission.<sup>4,5</sup>

The impacts of the lockdown measures and subsequent lifting of these measures were often difficult to quantify. However, the associated changes are reflected in satellite observations of air pollutants. Nitrogen oxides, NO<sub>x</sub> (NO + NO<sub>2</sub>), are emitted from anthropogenic sources such as transportation, power plants, and industries, contributing significantly to the formation of photochemical smog, acid rain, and ground-level

ozone, thereby affecting air quality, climate change, and human health.<sup>6–8</sup> Prior studies reported drastic reductions in NO<sub>x</sub> emissions in China during the lockdown due to decreased industrial production and traffic volume.<sup>9–13</sup> However, some areas experienced unexpected surges in NO<sub>x</sub> emissions during the lockdown period.<sup>14,15</sup>

Prior research primarily focused on broader regional transformations rather than examining in-depth emission variations across urban–suburban areas and highways. Moreover, these studies were predominantly interested in the implications of emission reductions due to the COVID-19 pandemic. In contrast, this study employs a high-resolution inversion technique to scrutinize the nuanced details of emission changes. It specifically focuses on the emission enhancements resulting from changes in the supply chain and human activities. An in-depth investigation into this paradoxical phenomenon provides critical insights into the complex interactions between human activities and environmental emissions, a subject that is particularly relevant under unprecedented circumstances such as a pandemic lockdown.

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Our study advances this field by implementing a 4 km resolution inversion analysis of NO<sub>x</sub> emissions using the state-of-the-art 3D Regional Chemical Transport Model (REAM) and TROPOMI satellite observations. Through this high-resolution approach, we identify specific regions in China where NO<sub>x</sub> emissions increased during the lockdown, attributing these changes to essential activities such as makeshift hospital construction, emergency goods transportation, and regional support for major cities. Furthermore, we document the uneven post-lockdown recovery in emissions, highlighting distinct regional patterns in the pace and nature of economic resumption.

This investigation examines emission changes across diverse regions in China by dividing East China: the Jiang-Han Plain covering Wuhan city and surrounding areas (Region I), Nanjing–Hefei Area (Region II), and Yangtze River Delta (Region III). This division enables detailed analysis of how COVID-19 lockdown policies impacted these three major populated regions and their distinct behavioural patterns during both lockdown and recovery phases. We analyzed these changes across three distinct temporal phases following:<sup>11</sup> pre-lockdown (January 1–23, 2020) representing the pre-lockdown period, Phase I (January 23–February 20, 2020) corresponding to the main lockdown period, and Phase II marking the initial recovery period in China.

Our research contributes to understanding how global crises like the COVID-19 pandemic influence environmental conditions at local scales. The high-resolution analysis provides crucial insights for developing targeted strategies to mitigate environmental impacts during future crises. These findings will benefit policymakers, environmental scientists, and stakeholders across industry and public health sectors by providing quantitative evidence of how emergency measures affect regional air quality and economic activities.

The remainder of this paper is organized as follows: Section 2 details our methodology, including the REAM model configuration and TROPOMI data processing protocols. Section 3 presents our analysis of regional emission changes during the lockdown period and evaluates post-lockdown recovery patterns across the three subregions. Section 4 summarizes our findings and discusses their implications for future research and policy development, particularly in the context of emergency response planning and environmental protection.

## 2. Methods

### 2.1 Observation

**2.1.1 TROPOMI NO<sub>2</sub> measurements.** We utilized the NO<sub>2</sub> observations from TROPOMI aboard Sentinel-5P. TROPOMI offers significantly improved spatial resolution compared to OMI,<sup>16</sup> with  $5.6 \times 3.6$  km<sup>2</sup> resolution at nadir (following the August 2019 update), approximately ten times finer than OMI's  $13 \times 24$  km<sup>2</sup>. The instrument operates in sun-synchronous orbit with 13:30 local time equatorial crossing, providing daily global coverage *via* its 2600 km swath.<sup>17</sup> This enhanced resolution enables more accurate detection of NO<sub>2</sub> spatial gradients and better source separation in Chinese megacities, making it

particularly suitable for urban-scale studies during the COVID-19 lockdown period.

The KNMI NO<sub>2</sub> retrieval algorithm for TROPOMI builds upon the established DOMINO retrieval system, incorporating several methodological improvements. The algorithm employs differential optical absorption spectroscopy (DOAS) to determine the total NO<sub>2</sub> slant column density, which is then separated into stratospheric and tropospheric components using data assimilation techniques.<sup>18,19</sup> These components are converted to vertical column densities through altitude-dependent air mass factors, utilizing NO<sub>2</sub> vertical profiles from the TM5-MP model and surface albedo information from monthly OMI climatology. For this study, we use the offline (OFFL) level 2 v1.2 NO<sub>2</sub> product, applying a cloud radiative fraction threshold of 0.3 to filter cloudy pixels.<sup>20</sup> Validation studies over major Chinese cities demonstrate that TROPOMI provides more reliable NO<sub>2</sub> retrievals compared to OMI, particularly in highly polluted urban areas where OMI often suffered from saturation effects and coarse spatial resolution.<sup>9,21–23</sup>

**2.1.2 CNEMC data.** Surface O<sub>3</sub> concentrations from the China National Environmental Monitoring Centre (CNEMC) network provided independent validation.<sup>24</sup> The network comprises over 1500 urban and suburban stations measuring criteria pollutants. We selected stations within our study domains (Hubei, Nanjing–Hefei, and Yangtze River Delta regions) and extracted hourly measurements coincident with TROPOMI overpasses (12:00–14:00 local time). Quality control procedures included outlier removal and diagnostic flag screening.<sup>25</sup> We chose O<sub>3</sub> rather than direct NO<sub>2</sub> measurements because surface O<sub>3</sub> formation is tightly coupled to NO<sub>x</sub> emissions through photochemical pathways, providing a robust indicator of both emission magnitudes and chemical transformation accuracy. Additionally, previous studies have documented systematic overestimation biases in NO<sub>2</sub> measurements using molybdenum oxide converters,<sup>26–28</sup> making O<sub>3</sub> a more reliable validation metric for high-pollution environments in China.

### 2.2 Models

**2.2.1 Regional chemical and transport model (REAM).** We employed the Regional chEmical and trAnsport Model (REAM), which has been extensively validated through numerous applications including emission inversions, ozone simulations, and mechanistic studies of atmospheric processes.<sup>27,29–35</sup> Our model configuration consists of a nested domain structure with an outer grid horizontal resolution of  $12 \times 12$  km and an inner grid horizontal resolution of  $4 \times 4$  km, incorporating 30 vertical layers in the troposphere, the domain information is shown in SI Fig. S1. The model's chemical mechanism is based on GEOS-Chem v11.01 with updated aromatics reactions from SAPRC07, while meteorological fields are provided by the Weather Research and Forecasting (WRF v4.0) model with data nudging using ECMWF Reanalysis v5.<sup>36</sup> The outer domain utilizes anthropogenic emissions from the Multi-resolution Emission Inventory for China (MEIC) 2017,<sup>37</sup> while the inner domain emissions are initially based on MEIC 2017 and subsequently







**Fig. 1** Temporal evolution of  $\text{NO}_x$  emissions during the COVID-19 outbreaks. Daily  $\text{NO}_x$  emissions from January to March 2020 for (a) all domains, (b) Region I: Hubei Province, (c) Region II: Hefei–Nanjing Area, and (d) Region III: Yangtze River Delta. Background shading indicates pre-lockdown (yellow), Phase I lockdown (orange), and Phase II recovery (green) periods. Red and green vertical lines mark lockdown initiation (23 January) and relaxation (20 February), respectively. Error bars show daily inversion uncertainties.

exhibited a 15% decrease. Given our model uncertainty, the difference between Hubei (12%) and Yangtze River Delta (15%) falls within the uncertainty bounds and should not be interpreted as statistically significant. However, the magnitude of reduction in Region II (45%) represents a clearly distinct response, exceeding the reductions in both Regions I and III by more than twice the combined uncertainties. While the  $\text{NO}_x$  emission reductions in Hubei (12%) and Yangtze River Delta (15%) are statistically indistinguishable within our uncertainty bounds, both regions showed markedly smaller reductions than Region II (45%). The relatively modest reduction in Hubei is particularly notable given that it contained Wuhan, the epicenter with the strictest lockdown measures. This apparent paradox is likely attributable to two main factors. First, emission reductions were concentrated in urban centers, and Hubei has a lower density of large cities than the other regions. For example, the emission decrease in Wuhan was 42%, substantially higher than the regional average of 12%. Second, the complete shutdown of Wuhan required logistical support from surrounding areas, potentially leading to increased emissions in those regions. We examine these factors in greater detail in the next section. The effect of population movement away from Wuhan for fear of the COVID-19 outbreak is another factor that partially offset the urban reductions.

Following the initial easing of lockdown measures (Phase II),  $\text{NO}_x$  emissions displayed region-specific responses. In Region I, emissions continued to decline, primarily due to prolonged restrictions in Wuhan, the epicenter of the outbreak. Conversely, Region II experienced a notable increase in emissions, attributable to intensified goods transportation activities.<sup>49</sup> Region III showed a slight increase before stabilizing.

The observed emission changes must be interpreted considering that our baseline period (January 1–23, 2020)

coincides with the Chunyun travel rush period preceding Spring Festival 2020 (January 25). During Chunyun, which typically begins two weeks before Spring Festival, industrial  $\text{NO}_x$  emissions decrease substantially as factories reduce operations and workers migrate to their hometowns. The satellite-derived  $\text{NO}_x$  emission time series do not exhibit a significant decline from January 1 to 23 (Fig. 1), suggesting that increased transportation-related emissions more than offset the reductions from industrial activities leading up to the Spring Festival in the study regions.

Satellite observations during Spring Festival periods have documented significant reductions in tropospheric  $\text{NO}_2$  column density, with decreases in megacities ranging from 32% to 45%, primarily attributed to reduced industrial activity and transportation during the holiday period.<sup>50,51</sup> Emission reductions show a sharp decline around the Spring Festival period with cities experiencing reductions of 20–50%.<sup>52</sup> Therefore, the 35% overall emission decrease we observed during Phase I likely represents a modest reduction beyond typical Spring Festival decreases.

### 3.2 $\text{NO}_x$ emission distribution change during the COVID lockdown

#### 3.2.1 Urban–suburban emission dynamics.

High-resolution analysis revealed that  $\text{NO}_x$  emission reductions were not spatially uniform but exhibited complex redistribution patterns, which were related strongly to changes in anthropogenic activities (Fig. 2). Metropolitan areas experienced pronounced decreases in emissions, while many suburban and rural areas showed contrasting patterns of increased emissions, reflecting significant shifts in economic activities and population movement away from urban areas during lockdown.

Regional  $\text{NO}_x$  emission patterns during the lockdown period revealed contrasting trends between major urban centres and smaller cities in the Hefei–Nanjing region. SI Fig. S3 shows time series data for three distinct subregions within the Hefei–



**Fig. 2** Spatial distribution of  $\text{NO}_x$  emission differences between lockdown phases and pre-lockdown baseline over eastern China. (a) Phase I (strict lockdown) and (b) Phase II (early recovery) emission changes. Black boxes denote three study regions: (1) Region I: Hubei Area, (2) Region II: Nanjing–Hefei Area, and (3) Region III: Yangtze River Delta. Negative values (blue) indicate emission reductions; positive values (red) indicate increases.



Nanjing metropolitan area. Fig. 3 illustrates the spatial distributions of emission differences between each lockdown phase and the pre-lockdown baseline for the Hefei–Nanjing region. While the metropolitan areas of Hefei and Nanjing experienced significant  $\text{NO}_x$  emission reductions, smaller cities including Ma'anshan and Anqing paradoxically showed increased emissions (Fig. 3). This spatial heterogeneity likely reflects population redistribution during the lockdown, with workers migrating from major urban centres to their hometowns and residents relocating to suburban areas, effectively transferring emission sources from large to small cities.<sup>53,54</sup>

This pattern of emission redistribution extended beyond the Hefei–Nanjing region to the Yangtze River Delta region. SI Fig. S4 presents time series data for three distinct subregions within the Yangtze River Delta. Fig. 4 illustrates the spatial distributions of emission differences between each lockdown phase and the pre-lockdown baseline for the Yangtze River Delta region. Similar urban-to-suburban transfer dynamics emerged. Hangzhou—a major technology hub—demonstrated substantial emission reductions (50%) during the lockdown period, primarily attributable to widespread remote work adoption among technology sector employees.<sup>55–57</sup> Consistent with the pattern observed in the Hefei–Nanjing region, this urban reduction coincided with a notable increase in  $\text{NO}_x$  emissions in the adjacent Xiaoshan region, where many urban workers relocated during the work-from-home mandate.<sup>56</sup> These similar urban–suburban emission dynamics emerged across other major regions. Shanghai, one of the world's most densely populated urban areas, likewise exhibited consistent decreases in  $\text{NO}_x$  emissions throughout both Phase I and Phase II of the lockdown,<sup>58,59</sup> further exemplifying the complex redistribution of emissions as urban activities shifted to suburban residential areas during the pandemic response.

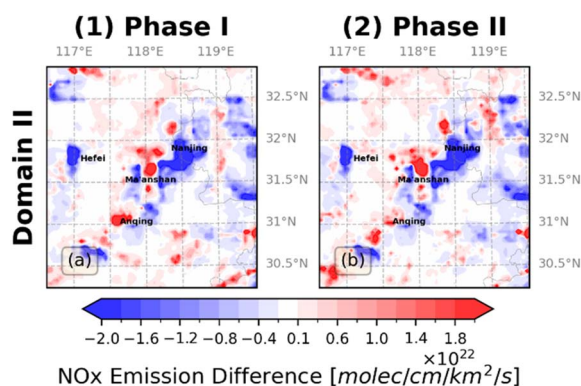


Fig. 3 High-resolution  $\text{NO}_x$  emission changes across study domains during COVID-19 lockdown phases relative to pre-lockdown baseline. Spatial distribution of  $\text{NO}_x$  emission differences ( $\times 10^{22}$  molecules  $\text{cm}^{-2} \text{km}^{-2} \text{s}^{-1}$ ) for (a) Phase I (lockdown period, left column) and (b) Phase II (recovery period, right column) compared to pre-lockdown levels across Domain II (Hefei–Nanjing Area). Blue colors indicate emission decreases while red colors represent emission increases relative to baseline conditions. Major cities are labeled within each domain.



Fig. 4 High-resolution  $\text{NO}_x$  emission changes across study domains during COVID-19 lockdown phases relative to pre-lockdown baseline. Spatial distribution of  $\text{NO}_x$  emission differences ( $\times 10^{22}$  molecules  $\text{cm}^{-2} \text{km}^{-2} \text{s}^{-1}$ ) for (a) Phase I (lockdown period, left column) and (b) Phase II (recovery period, right column) compared to pre-lockdown levels across Domain III (Yangtze River Delta). Blue colors indicate emission decreases while red colors represent emission increases relative to baseline conditions. Major cities are labelled within each domain.

Regionally, the about 45% decrease over the Hefei–Nanjing corridor exceeds that over the core Yangtze River Delta (YRD). Prior studies report large but regionally varying  $\text{NO}_x$  emission reductions during the early-2020 lockdown, including a peak reduction in the YRD on the order of 41%, and an average 30% reduction over eastern China.<sup>60</sup> Population mobility data shows that movements dropped sharply after the Lunar New Year and remained suppressed into mid-February, indicating a delayed workforce return that is consistent with stronger inland activity declines.<sup>61</sup> At the same time, research on port operations and liner-shipping networks documented a substantial disruption but also continuity and early reconfiguration in major Chinese and Asian ports, helping explain comparatively sustained coastal logistics activity near the YRD.<sup>62,63</sup> City-scale analyses for Nanjing report pronounced  $\text{NO}_2$  decreases during lockdown, consistent with the stronger inland reduction we infer for the Hefei–Nanjing corridor.<sup>64</sup>

Jiangsu Province accounts for one-eighth of national manufacturing production and is home to numerous small-scale and home-based factories.<sup>65–67</sup> Compared to other regions, this region exhibited the most pronounced  $\text{NO}_x$  emission rebound relative to pre-COVID levels. Within Jiangsu, cities with distinct industrial profiles showed varying recovery patterns (Fig. 5). Wuxi and Suzhou, recognized for their labor-intensive small-scale manufacturing and furniture industries,<sup>67–69</sup> experienced  $\text{NO}_x$  emission rebounds of 27% above pre-COVID baselines after lockdown. Similarly, Huai'an, known for kitchenware and sportswear production,<sup>67–69</sup> demonstrated a 186% increase in  $\text{NO}_x$  emissions compared to pre-pandemic levels after the lockdown. The particularly strong recovery in these export-oriented manufacturing centres likely reflects intensified production efforts to fulfill accumulated international orders following the lifting of initial lockdown restrictions.<sup>70–72</sup>





The Poyang Lake region also showed an unexpected but significant increase in NO<sub>x</sub> emissions (Fig. 7), serving as a crucial logistics hub in the emergency response network. This area functioned as a strategic staging ground for supplies originating from the Nanjing–Hefei region and Nanchang city, facilitating the temporary storage and redistribution of medical and essential supplies to support Wuhan.<sup>79–81</sup> The increased emissions in this region reflect the intensified activities associated with its role as a critical connection point in the emergency supply chain. NO<sub>x</sub> emissions from the Poyang Lake region increased by 259% during the Phase I period compared to the pre-lockdown baseline period.

These findings reveal the complex environmental implications of emergency response measures during the pandemic. The observed increases in NO<sub>x</sub> emissions in logistics support zones demonstrate how large-scale humanitarian operations can create unexpected environmental impacts, even as they fulfil crucial public health needs. The spatial distribution of these emission changes provides valuable insights into the relationship between human mobility patterns, economic activities, and environmental impacts during crisis periods, offering important lessons for future public health emergency responses. The varying patterns of NO<sub>x</sub> emissions derived from satellite observations across different regions and logistics support zones highlight the intricate interplay between emergency response measures and environmental impacts, which can inform more effective and environmentally conscious approaches to crisis management while maintaining the capability to respond rapidly to public health emergencies. Understanding these patterns is crucial for developing policies that can better balance immediate emergency needs with longer-term environmental considerations in future crisis scenarios.

### 3.3 Ground-based validation of emission patterns

To strengthen our analysis of satellite-derived emission changes, we synthesize findings from previously published

studies on ground-based activity indicators during the COVID-19 lockdown period. The convergence of evidence from multiple independent data sources validate our satellite-based observations and sheds light on the underlying processes that generated the observed emission patterns.

#### 3.3.1 Activity indicators and spatial redistribution.

Multiple ground-based data sources documented the dramatic activity changes that drove the emission change patterns we observed. China's Ministry of Transport reported that total passenger volume across all transport modes dropped 50.9% during January–February 2020, while freight volume declined only 19.7%,<sup>82</sup> underscoring the essential role of supply chains despite restrictions on passenger movement. Detailed analysis showed long-haul trucking volumes fell below 15% of 2019 levels between January 24 and February 26, 2020, but rebounded quickly to 50% by late February and 92% by March.<sup>83</sup> This recovery timeline closely matches the emission rebound we observed along transportation corridors. Regional analysis confirmed that Wuhan's highway freight transport dropped approximately 90%, while other cities maintained relatively high freight activity,<sup>84</sup> consistent with our spatially resolved emission observations showing persistent hotspots along key supply routes despite urban emission reductions.

Population mobility data from the Baidu migration index platform, which tracks movements of hundreds of millions of mobile phone users, revealed that approximately 20.2 million at-risk population movements occurred from Wuhan between January 1–31, 2020, with 84.5% within Hubei Province.<sup>85,86</sup> Following the January 25 national emergency response, analysis of 358 Chinese cities showed intra-city movement intensity decreased substantially, with mobility falling by as much as 80% compared to normal days and by 58% compared to the same lunar period in 2019.<sup>87,88</sup> Notably, mobility data documented substantial urban-to-suburban population redistribution as residents temporarily relocated or adopted remote work arrangements,<sup>88</sup> directly accounting for the suburban emission increases we observed in our satellite data. Quantitative analysis further demonstrated that daily COVID-19 infection cases correlated significantly with local mobility ( $R^2 = 0.77$ ), and the reproduction number declined by 3% for every 10% reduction in mobility,<sup>87,89,90</sup> establishing the close link between movement restrictions, disease control, and emission changes.

Electricity consumption served as a real-time proxy for industrial activity. China's national electricity consumption in Q1 2020 declined 6.5% year-over-year, a dramatic reversal from the 5.5% increase in Q1 2019.<sup>91</sup> The secondary (industrial) sector experienced approximately 14% consumption decrease in February 2020, while residential consumption increased modestly by 6.6% and 4.5% in Q1 and Q2, respectively, due to stay-at-home measures.<sup>92,93</sup> Regionally, Hubei Province experienced the largest declines, exceeding 20% during January–February, while coastal provinces reported smaller reductions.<sup>92,94</sup> Analysis of multiple industries revealed heterogeneous impacts even within sectors, with some firms maintaining production for essential goods or export commitments.<sup>95</sup> By April 2020, consumption began recovering, with weather-corrected demand exceeding 2019 levels by August in



Fig. 7 High-resolution NO<sub>x</sub> emission changes across Staging Area during COVID-19 lockdown phases relative to pre-lockdown baseline. Spatial distribution of NO<sub>x</sub> emission differences ( $\times 10^{22}$  molecules  $\text{cm}^{-2} \text{km}^{-2} \text{s}^{-1}$ ) for (a) Phase I (lockdown period, left column) and (b) Phase II (recovery period, right column) compared to pre-lockdown levels across Poyang Lake Staging Area. Blue colors indicate emission decreases while red colors represent emission increases relative to baseline conditions. Major cities are labeled within each domain.





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