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Year-round changes in tropospheric nitrogen dioxide caused by COVID-19 in China using satellite observation

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**ABSTRACT**

The lockdown policy deals a severe blow to the economy and greatly reduces the nitrogen oxides (NOx) emission in China when the coronavirus 2019 spreads widely in early 2020. Here we use satellite observations from Tropospheric Monitoring Instrument to study the year-round variation of the nitrogen dioxide (NO2) tropospheric vertical column density (TVCD) in 2020. The NO2 TVCD reveals a sharp drop, followed by small fluctuations and then a strong rebound when compared to 2019. By the end of 2020, the annual average NO2 TVCD declines by only 3.4% in China mainland, much less than the reduction of 24.1% in the lockdown period. On the basis of quantitative analysis, we find the rebound of NO2 TVCD is mainly caused by the rapid recovery of economy especially in the fourth quarter, when contribution of industry and power plant on NO2 TVCD continues to rise. This revenge bounce of NO2 indicates the emission reduction of NOx in lockdown period is basically offset by the recovery of economy, revealing the fact that China’s economic development and NOx emissions are still not decoupled. More efforts are still required to stimulate low-pollution development.

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**Introduction**

In December 2019, the coronavirus disease 2019 (COVID-19) was reported in Wuhan, China, and then became a global pandemic (WHO, 2020; Wang et al., 2020a). On 23 January 2020, the central government of China imposed a lockdown in Wuhan to fight against COVID-19, and other Chinese cities subsequently implemented similar measures (Wikipedia, 2021). Under the combination effects of lockdown policy and Lunar New Year (LNY) holidays, human activities, especially industry and transportation, were greatly limited in early 2020 (Lv et al., 2020). In turn, the demand for fossil fuels significantly reduced and the nitrogen oxides (NO + NO2= NOx) emissions in China declined by 11.5% compared to the same period in 2019 (Zheng et al., 2020). China’s economy got off to a wobbly start in 2020 (SCPRC, 2021).

As the COVID-19 was gradually brought under control in second half of 2020, the limitation on human activities weakened and China’s economy experienced a strong rebound in the fourth quarter. While some sectors are still feeling the pinch of the COVID-19 outbreak, more have emerged from the negative impacts faster and stronger than expected (NBSC, 2020).

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- NBSC, 2020

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Nitrogen dioxide (NO\textsubscript{2}) is often used to characterize the fossil fuel usage level, which is related to economic activity. Several researches have analyzed the impact of the COVID-19 on environment or economy (Liu et al., 2020; He et al., 2020) using NO\textsubscript{2} tropospheric vertical column density (TVCD) provided by earth-observing satellites such as the Ozone Monitoring Instrument (OMI) (Levelt et al., 2018) or the Tropospheric Monitoring Instrument (TROPOMI) (Veefkind et al., 2012) in early 2020, and found that the anti-pandemic measures could unintentionally bring about environmental benefits, such as the reduction of NO\textsubscript{2} or other air pollutants level (Wang et al., 2020b; Huang et al., 2020). Moreover, studies on driven factors to changes in NO\textsubscript{2} can further detect the impacts of human and society activities on air quality. Generally, linear regression (Liu et al., 2015) and machine learning (Richmond-Bryant et al., 2018) are widely used to quantify the response relationship between continuous parameters such as meteorological factors or land use and NO\textsubscript{2} concentration based on big data. For evaluation of policy, which are discrete values in computation, panel data analysis is more appropriate to reveal the influence of regulations by arranging data in different dimensions. In early stage of COVID-19, the effectiveness of lockdown policy has been investigated from the perspective of air quality (Zheng et al., 2020; He et al., 2020).

Recently, a discussion on how to keep sustainable development in COVID-19 recovery plans is rising: A narrow-sighted focus on fighting the recession could have adverse effects on the environment (Guerrero et al., 2020), and economic recovery packages should help build more resilient social foundations to stimulate innovation for the low-pollution transition (Belesova et al., 2020; Rosenbloom and Markard, 2020). However, little research has paid attention to whether China’s economic recovery is environmentally sustainable and whether the economic development mode is transformed in late 2020. Here we use NO\textsubscript{2} TVCD of China in 2019 and 2020 from TROPOMI to observe its spatiotemporal change from COVID-19 outbreak period to well-controlled period, and employ difference-in-differences (DiD) model to quantify the driving force of NO\textsubscript{2} TVCD.

1. Method

1.1. TROPOMI NO\textsubscript{2} observations

We use retrieved NO\textsubscript{2} TVCD from TROPOMI. TROPOMI is a pushbroom spectrometer with spectral bands in the ultraviolet (UV), visible (VIS), near infrared (NIR) and shortwave infrared (SWIR) (Veefkind et al., 2012). It measures key atmospheric constituents including ozone, nitrogen dioxide, carbon monoxide, sulfur dioxide, methane, formaldehyde, aerosols and clouds. TROPOMI builds upon the heritage of its predecessors SCIAMACHY and OMI, and further improves on their performances, with daily global coverage pixels of 3.5 km by 5.5 km (3.5 km by 7 km before August 2019) (Veefkind et al., 2012). On October 2017, European Space Agency (ESA) launched the Sentinel 5 precursor (S5P) satellite with TROPOMI and started to release daily satellite data of pollution gases to global users.

We use TROPOMI Level 2 offline NO\textsubscript{2} data for 2019 and 2020 (van Geffen et al., 2020). Valid pixels with quality assurance values > 0.75 and cloud fractions < 40% are selected and then aggregated to resolution of 0.05° × 0.05° in this study (van Geffen et al., 2019). We calculated 7-days moving average of NO\textsubscript{2} TVCD to smooth fluctuations.

1.2. GEOS-Chem simulation

The GEOS-Chem version 12.3.0 we use is driven by assimilated meteorological fields from the NASA Global Modeling and Assimilation Office’s Modern-Era Retrospective analysis for Research and Applications Version 2 (MERRA-2) (Gelaro et al., 2017) and includes complete NOx-Ox-HC-aerosol chemistry (Park et al., 2004) at a spatial resolution of 2° × 2.5°. We use GEOS-Chem and calculate (Ω\textsubscript{i,j,TROPMI,2020}/Ω\textsubscript{i,j,TROPMI,2019}) − (Ω\textsubscript{i,j,SIM,2020}/Ω\textsubscript{i,j,SIM,2019}) to represent the NO\textsubscript{2} TVCD changes excluding meteorological impacts:

\[
\frac{\Delta \Omega}{\Omega}_{i,j,\text{TROPMI,2020}} = \frac{\Omega_{i,j,\text{TROPMI,2020}}}{\Omega_{i,j,\text{TROPMI,2019}}} - \frac{\Omega_{i,j,\text{SIM,2020}}}{\Omega_{i,j,\text{SIM,2019}}}
\]

where \(\Omega_{i,j,\text{TROPMI,2020}}\) and \(\Omega_{i,j,\text{TROPMI,2019}}\) represent the satellite observation in 2020 and 2019, \(\Omega_{i,j,\text{SIM,2020}}\) and \(\Omega_{i,j,\text{SIM,2019}}\) represent the simulated value by GEOS-Chem and \(\Omega_{i,j,\text{SIM,2020}}\) represents the simulated value with emissions fixed in 2019 driven by meteorological fields in 2020.

1.3. Weather data

Weather conditions contains daily maximum temperature, daily minimum temperature, daily maximum steady wind and rainfall as control variables. These city-level data are downloaded from the FREEMETEO (see https://freemeteo.cn/weather).

1.4. Sector information

We select 389,912 industries, including factories and companies, 1,070 power plants, highway and population information to represent the industrial, power and transportation level of each grid (Fig. S1). For details, see Section 1.5.

1.5. Fixed effect model

We use grid-level industries, power plants, highway and population distributions to describe the industrial, power, transportation and resident level respectively, and quantify their impact on NO\textsubscript{2} TVCD, by fitting the DiD model:

\[
\ln(\text{NO}_{2,i,t}) = \alpha \times [\text{INDUSTRY}]_i + \beta \times [\text{POWER}]_i + \gamma \\
\times [\text{TRANSPORT}]_i + \varphi \times [\text{POPULATION}]_i + \delta \times CV_i + \pi_t + \epsilon_{i,t}
\]

where [INDUSTRY]_i is set to 1 if there is at least one industry in grid i and 0 otherwise, [POWER]_i and [TRANSPORT], are set similar to [INDUSTRY], according to whether there is a power plant or road in grid i. [POPULATION]_i, is set to 1 if the grid i is in high population group (population in this grid is higher than the mean population) and 0 otherwise (He et al., 2020), CV_i is a set of control variables including daily temperature,
daily maximum steady wind and rainfall, \( \pi_i \) is the date fixed effects and \( \varepsilon_{i,t} \) is a stochastic error term. In this study, the spatial resolution of grid we use is 0.05° × 0.05°.

2. Results and discussion

2.1. Annual NO\(_2\) TVCD in 2019 and 2020

Fig. 1 shows the 7-day averages of NO\(_2\) TVCD during 2019 and 2020. The overall research period was divided into three sub-periods according to the COVID-19 pandemic: The Outbreak period (January to March), the Stable period (April to September) and the Post-pandemic period (October to December). The NO\(_2\) TVCD in 2019 and 2020 shows a common feature, which is high concentration in winter and low concentration in summer. The NO\(_2\) TVCD in the beginning of 2019 is higher than it is in the end of the year, while in the end of 2020, the NO\(_2\) TVCD shows a winter peak and is significantly higher than that in the same period of 2019.

In Outbreak period, the NO\(_2\) TVCD shows a substantial reduction during the approximately 2 weeks leading up to LNY, consistent with the gradual decrease of factory production and traffic flow. The trend of NO\(_2\) TVCD in this period is similar to 2019, but a reduction of 24.1% is observed over China due to the lockdown policy in response to COVID-19. This can be also explained by the previous research that, during lockdown period, human activities such as traffic flow (declined by 37.3%-59.8% in Beijing) were greatly limited (Lv et al., 2020), and the daily NOx emission in 2020 declined by about 50%, compared to 2019 (Zheng et al., 2020).

The seasonal variation in NO\(_2\) concentration shows a winter peak and summer minima due to the coal-fired heating (Geddes et al., 2009; Sadanaga et al., 2008; Streets and Waldhoff, 2000). In Stable period, the COVID-19 is well controlled and the NO\(_2\) TVCD slightly fluctuates around the lower level (1.39 × 10\(^{15}\) mole/cm\(^2\)) of the year. The decrease in NO\(_2\) TVCD from 2019 to 2020 is inappreciable (declined by 4.1%).

As the coronavirus pandemic eases in Post-pandemic period, human activities are basically unlimited, and the NO\(_2\) TVCD in 2020 rises rapidly and far beyond that of 2019 especially in end of year (increase by 18.5% compared to 2019 in December). This bounce-back effect, which can offset the annual decline in overall emissions, is called “revenge pollution”, and economic rebound led by heavy industry may play a key role in this effect. According to Statistical Communiqué of the People’s Republic of China on the 2020 National Economic and Social Development, although the economy shrank in the first half of 2020 (especially drop by 6.8% in the first quarter), the annual gross domestic product (GDP) was up by 2.3% over the previous year, and the GDP in industry grew by 2.4%. As shown in Table S1, the output of almost all heavy industrial sector experienced a positive growth year-on-year (y-o-y). Cement production first decreased by nearly 5% in the first six months, and then sharply increased by 8% since June. Electricity demand increased by 3.7%, of which thermal power generation increased by 2.1%. Additionally, the annual output of crude steel rose by 7%, which was 4 times the GDP growth rate, reaching 10% (Fig. S2). As consequence, stimulus plan (Shen, 2020) promoted by government accelerated the economic recovery, and further led to the revenge pollution.

2.2. NO\(_2\) TVCD changes in different regions as of three stages

Fig. 2, Fig. S3 and Table S2 show provincial changes on NO\(_2\) TVCD and GDP in three periods. We observe almost 51.7% NO\(_2\) TVCD reduction in Hubei province which was the outbreak center of COVID-19, due to stricter control measures. The provinces of Henan and Anhui that have the largest industrial economies (CRECA, 2020) both reduced their NO\(_2\) TVCD by almost 50% (Fig. 2a). Half of the provinces in North China and Yangtze River Delta experienced a reduction of more than 30% in NO\(_2\) TVCD compared to 2019 during Outbreak period. Note that the NO\(_2\) TVCD increases slightly in low-risk provinces
such as Yunnan, and Guangxi provinces, where the residential emissions are dominated, caused by the return of migrant workers (Feng et al., 2020). As of the Outbreak period, in most province, GDP contracted in nearly every province, with an average fall of 6.8% y-o-y, and it especially posts a significant drop by 36.7% to Hubei province and other economic developed regions such as Yangtze River Delta (YRD) and North China Plain, while the impacts of COVID-19 have done little to curb GDP growth in Tibet and Xinjiang, where the pandemic is mild.

During Stable period, the differences in NO₂ TVCD relative changes in almost all provinces are basically within 10% (Fig. 2b). Accumulated to this period, the reductions of NO₂ TVCD y-o-y for almost all provinces are lessened (within 30%, shown in Fig. S3). This is caused by the turning for the better of GDP occurred in this period. As the COVID-19 is well controlled, most provinces emerge from the economic recession in the previous period, and nationwide GDP slightly reverses 2.5% growth on average. Note that the NO₂ TVCD basically remains unchanged in Beijing due to the second wave of COVID-19 occurred in XinFaDi Market in June.

NO₂ TVCD rebounds in most provinces during the Post-pandemic period, with significant increases observed in provinces characterized by energy intensive heavy industries and large-scale coal-fired power plants. This rebound effect is most obvious in the Northeast Plain, where Heilongjiang and Jilin provinces rise by 94.0% and 59.8%, respectively (Fig. 3). As is shown in Fig. S3, by the end of 2020, the decline of NO₂ TVCD in most provinces is less than 5%, while annual average NO₂ TVCD experiences a reverse growth in Heilongjiang, Jilin, Liaoning and Ningxia provinces. For one hand, due to a new round small-scale breakout of pandemic in winter, the nationwide passenger capacity decreases by 32.7% and 35.5% in November and December y-o-y, which leads to a decrease in population who choose the south areas for vacation. Therefore, the large heating demand in northern China contributes part to the 2.4% y-o-y increase in coal production, and further results in more NOx emissions (NBSC, 2021). For another hand, this revenge pollution corresponds to the rebound of GDP from the Stable period. Except Hubei province, the national GDP grows by 2.1% by the end of 2020, especially with a 6.5% growth in the fourth quarter (Table S2). The rapid economy recovery driven by the boom of production activities offsets the NOx reduction in early 2020.

This human-made revenge pollution can also be proved by our GEOS-Chem simulation results. Fig. 3a shows that the NO₂ TVCD drops by 10% nationwide when only considering the meteorological impacts from 2019 to 2020 in December, and in the Northeast Plain, where the bounce-back effect is more obvious, the meteorological factors make NO₂ TVCD decline by 12%. Fig. 3b gives the estimation of NO₂ TVCD changes excluding meteorological impacts. The NO₂ TVCD rises by 41% nationwide and 122% in the Northeast Plain, mainly caused by changes in anthropogenic emission due to economic recovery.

2.3. The driving force of NO₂ TVCD change

We then explore the driving force of NO₂ TVCD in three periods during 2020 by fitting DiD models when including weather controls and grid fixed effects. The estimates are not sensitive to weather conditions, indicating the weather influence on change in NO₂ TVCD is weak.

As shown in Table 1, in the Outbreak period, the industry, power plant and transportation group bring an increase of 11.8%, 22.2% and 12.7% points in NO₂ TVCD, while the contribution of these sectors to NO₂ TVCD reduces by 4.2%, 6.2% and 1.5% points respectively, comparing to that in 2019 (Table S3), due to factory shutdown and travel limits caused by lockdown policy. In contrast, the contribution of population rises up to 37.8%, indicating an increase in residential emissions when residents spent most time at home during this period.

As the pandemic is well controlled, industry production and power plant recover gradually and contribute 15.4% and 25.3% points of growth to NO₂ TVCD in the Stable period. In the Post-pandemic period, as economic activities have fully recovered, both contribution of industry and power plants on NO₂ TVCD exceeds the same period last year. Meanwhile, the
transportation contribution has reached the level of that in 2019 (Table S2).

3. Conclusions

In this work, we provide the analysis of variation on NO\textsubscript{2} TVCD and give a quantitative description of changes in NOx emissions. The lockdown unintentionally brings an environmental benefit to China in early 2020, with significant reductions in NOx emission. Under the influence of the pandemic, China’s NO\textsubscript{2} TVCD experiences three stages of sudden drop, stability and rapid rebound y-o-y. This is corresponding to China’s economic development trend, which emerges from the shrinkage and reverses to growth by the end of 2020. The economic and pollution rebound effect is the most intense in the fourth quarter, when the economy grows by 6.5%, and NO\textsubscript{2} TVCD rises by 15.8%.

The NO\textsubscript{2} TVCD has been decreasing rapidly nationwide (Feng et al., 2020; NBSC, 2020a; de Foy et al., 2016) under the influence of clean air regulations issued in recent years, and the annual nationwide NO\textsubscript{2} TVCD is predicted to decline by 11.0% in 2020 if not affected by the COVID-19 (Fig. S4a). However, the economic rebound in the Post-pandemic period slows down the pace on air pollution control, which leads to the y-o-y reduction of NO\textsubscript{2} TVCD is only 3.4% by the end of 2020. According to CarbonBrief (Carbon Brief, 2021a; NBSC, 2020b), Chinese government published the stimulus plan to balance the sluggishness of other sectors by increasing the stimulation of the most energy-consuming industries such as construction and heavy industries. Although the pollutant emissions still met the emission standards, the production and expansion were stimulated by economic recovery plan (Carbon Brief, 2021b), which led to more emissions compared with 2019. Therefore, the economic rebound did not advance but retreat in the pursuit of high-quality development and the journey of building a green economy.

Although it is encouraged to stimulate innovation for the low-pollution transition taking the opportunity of the COVID-19, we find that economic development of China and NOx emissions are still decoupled, and industry remains the main source of pollution. From the first quarter to the fourth quarter in 2020, the GDP experienced a variation trend from recession to growth, same as the trend of NO\textsubscript{2} TVCD (Fig. S4b). This correlation is the most significant in the fourth quarter, when the GDP grow by 6.5% with the cost of 18.5% growth in

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**Table 1 – Regression for full samples of 2020.**

| Outcome variable | ln (NO\textsubscript{2} TVCD) (10\textsuperscript{15} molecules/cm\textsuperscript{2}) |  |  |
|------------------|---------------------------------|--|--|
|                   | Outbreak period | Stable period | Post-pandemic period |
| Industry, \(\alpha\) | 0.118*** (0.011) | 0.154*** (0.007) | 0.183*** (0.006) |
| Power, \(\beta\)   | 0.222*** (0.023) | 0.253*** (0.014) | 0.248*** (0.013) |
| Transportation, \(\gamma\) | 0.127*** (0.005) | 0.141*** (0.004) | 0.124*** (0.005) |
| Population, \(\varphi\) | 0.378*** (0.018) | 0.392*** (0.012) | 0.299*** (0.012) |
| Weather Control, \(R^2\) | Y | 0.503 | 0.587 |
| Adjusted \(R^2\) | 0.480 | 0.502 | 0.586 |
| Observations      | 86,319 | 199,427 | 77,684 |

*** P < 0.001.
NO2 TVCD. And since the economy started to recover in the second quarter, industry has always been the biggest contributor to NO2 TVCD.

From the perspective of annual statistics, China leads the world in economic recovery, and is indeed on the green recovery paves. Unfortunately, China’s industrial structure has not fully transferred. Government should stimulate industrial transition by promoting new infrastructure, business models, and industrial capacity in renewable energy technology, electric vehicles and others (Richmond-Bryant et al., 2018). The COVID-19 recovery plan can provide guidance for environmental sustainability development. Recovery and stimulus packages that foster the use of renewable energies are required not only to mitigate the rebound of emissions but also to encourage the transition to a green economy. China should grasp this chance to realign embracing green and inclusive development.

**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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**Appendix A Supplementary data**

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.jes.2022.01.013.

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