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Impacts of COVID-19 lockdown, Spring Festival and meteorology on the NO\textsubscript{2} variations in early 2020 over China based on in-situ observations, satellite retrievals and model simulations

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\textbf{HIGHLIGHTS}

- NO\textsubscript{2} in China decreased by 42\% and 26\% in February and March 2020 due to COVID-19.
- The NO\textsubscript{2} VCDs by satellites were consistent with the surface NO\textsubscript{2} concentrations.
- Spring Festival holiday led to a NO\textsubscript{2} decrease in 30 days with a maximum of 37\%.
- COVID-19 led to a NO\textsubscript{2} decrease from 6 days after SF with a maximum of 51\%.
- NO\textsubscript{2} concentrations and VCDs decreased by 25\% and 40\% in 90 days due to meteorology.

\textbf{ABSTRACT}

The lockdown measures due to COVID-19 affected the industry, transportation and other human activities within China in early 2020, and subsequently the emissions of air pollutants. The decrease of atmospheric NO\textsubscript{2} due to the COVID-19 lockdown and other factors were quantitively analyzed based on the surface concentrations by in-situ observations, the tropospheric vertical column densities (VCDs) by different satellite retrievals including OMI and TROPOMI, and the model simulations by GEOS-Chem. The results indicated that due to the COVID-19 lockdown, the surface NO\textsubscript{2} concentrations decreased by 42\% ± 8\% and 26\% ± 9\% over China in February and March 2020, respectively. The tropospheric NO\textsubscript{2} VCDs based on both OMI and high quality (quality assurance value (QA) ≥ 0.75) TROPOMI showed similar results as the surface NO\textsubscript{2} concentrations. The daily variations of atmospheric NO\textsubscript{2} during the first quarter (Q1) of 2020 were not only affected by the COVID-19 lockdown, but also by the Spring Festival (SF) holiday (January 24–30, 2020) as well as the meteorology changes due to seasonal transition. The SF holiday effect resulted in a NO\textsubscript{2} reduction from 8 days before SF to 21 days after it (i.e. January 17 - February 15), with a maximum of 37\%. From the 6 days after SF (January 31) to the end of...
March, the COVID-19 lockdown played an important role in the NO$_2$ reduction, with a maximum of 51%. The meteorology changes due to seasonal transition resulted in a nearly linear decreasing trend of 25% and 40% reduction over the 90 days for the NO$_2$ concentrations and VCDs, respectively. Comparisons between different datasets indicated that medium quality (QA $\geq 0.5$) TROPOMI retrievals might suffer large biases in some periods, and thus attention must be paid when they are used for analyses, data assimilations and emission inversions.

1. Introduction

NO$_2$ is an important air pollutant which can irritate airways in the human respiratory system and thus directly harms human health, especially over East Asia where the NO$_x$ ($=$NO + NO$_2$) emissions are highest in the world (Kong et al., 2020). NO$_2$ can also react with other atmospheric chemicals to form O$_3$ (Li et al., 2019), which is another important gas pollutant and also harmful to the respiratory system. Huge amounts of NO$_2$ emissions caused significant atmospheric nitrogen deposition in terrestrial and aquatic ecosystems throughout East Asia (Ge et al., 2020; Itahashi et al., 2020). NO$_2$ can be oxidized to form HNO$_3$ which may result in acid rain and harm ecosystems such as lakes and forests. The gaseous HNO$_3$ can react with NH$_3$ to form fine mode nitrate aerosol which is an important component of PM$_{2.5}$ (Ge et al., 2019; Wang et al., 2017a), leading to harming human health, reducing visibility and affecting the climate. The HNO$_3$ can also react with dust and sea salt to form coarse mode nitrate aerosols, and affect the atmospheric nitrogen deposition on the ocean (Wang et al., 2017b, 2018; Z. Wang et al., 2019). A recent study indicates that nitrate aerosol increased significantly over downwind areas of East Asia in recent years (Uno et al., 2020), implying that the nitrate aerosol is increasing in importance over East Asia.

The industry, transportation and power plants are the three most important sources of anthropogenic NO$_x$ emissions, and contribute 42.0%, 35.2% and 19.2% respectively to total anthropogenic NO$_x$ emissions over China in 2017, according to the Multi-resolution Emission Inventory for China (Zheng et al., 2018). Therefore, the changes in industry and transportation could result in significant changes in NO$_x$ emissions. For example, during the Spring Festival (SF) holiday, the longest holiday in China (one day before SF to five days after it), many factories will stop production and thus the NO$_2$ emissions from the industry will decrease.

The Coronavirus Disease 2019 (COVID-19) was first reported in Wuhan city, the capital of Hubei province, in late December 2019. Due to rapid transmission of COVID-19, lockdown measures were implemented by the government of Wuhan city and other cities of Hubei on January 23 and 24, 2020, respectively, followed by other provinces (Zhang et al., 2020). Although most provincial governments allowed to resume work after February 10, only 32.8% of small and medium-sized enterprises (SMEs) had resumed work by February 26 and this number gradually rose to 76.8% as of March 28 according to the Ministry of Industry and Information Technology of China. Compared to SMEs, large enterprises were less affected by COVID-19, with operating rates of 83.1% and 98.6% on February 23 and March 28, respectively. The lockdown measures affected not only the industry but also transportation and other human activities within China in early 2020, and thus significantly reduced the atmospheric NO$_2$ as revealed by the TROPOMI satellite retrievals (NASA Earth Observatory et al., 2020) which were also used for NO$_2$ emission inversions over Eastern China (Zhang et al., 2020). OMI satellite retrievals and in-situ monitors were also used for discussing the effects of the Chinese lockdown on atmospheric NO$_2$ (Bauwens et al., 2020; Ding et al., 2020; Liu et al., 2020; Shi and Brasseur, 2020).

However, the TROPOMI satellite retrievals also showed some quite unexpected results, e.g. the atmospheric NO$_2$ decreased dramatically even before the COVID-19 lockdown over Wuhan area on January 1–20, 2020 compared to the same period in 2019, which pre-dated the Spring Festival holidays began on January 24 (NASA Earth Observatory et al., 2020). To better understand the effects of the COVID-19 lockdown on atmospheric NO$_2$, comparisons of different datasets are necessary to avoid errors in a certain dataset. And it’s also important to confirm the effects of other factors on NO$_2$ variation, e.g. the effects of SF holiday (January 24–30, 2020), the monthly variations in emissions and the changes in meteorology (e.g. wind speed, wind direction, and PBL height) due to seasonal transition (C. Wang et al., 2019; Zhang et al., 2007). For example, several recent research discussed the effects of natural variability on NO$_2$ concentrations (Goldberg et al., 2020; Venter et al., 2020).

In this study, we analyzed the decreases of atmospheric NO$_2$ based on surface concentrations by in-situ observations, and tropospheric vertical column densities (VCDs) by OMI and TROPOMI retrievals. Based on the GEOS-Chem model, the impacts of meteorology changes due to seasonal transition on atmospheric NO$_2$ over China were estimated. By comparing the NO$_2$ observations and retrievals with the model simulations using fixed emissions between 2015 and 2019, the impacts of the SF holiday on daily variations of atmospheric NO$_2$ were estimated. And finally, the impacts of the COVID-19 lockdown were revealed by comparing the atmospheric NO$_2$ in 2020 with those in previous years.

2. The observation data and numerical model

In-situ NO$_2$ concentration observations and satellite NO$_2$ VCD retrievals used in this study are summarized in Table 1 and described in the next two subsections.

2.1. The in-situ observations

In-situ air quality observations (e.g. NO$_2$, SO$_2$, O$_3$, CO, PM$_{2.5}$ and PM$_{10}$) are conducted by the China national monitoring network. The observation data are collected by the China National Environmental Monitoring Centre (CNEMC), and the real-time hourly concentrations of the six air pollutants are publicly available through the internet (http://106.37.208.233:20035/) since 2013. As of 2015, the monitoring network included 1436 monitoring sites in all 338 cities at or above prefecture-level and other prefecture-level administrative regions (i.e. prefectures, autonomous prefectures and leagues). The hourly NO$_2$ concentrations are automatically measured by either chemiluminescence or differential optical absorption spectroscopy (DOAS) instruments. The chemiluminescence monitors often have a high bias when measuring NO$_2$ (Dickerson et al., 2019).

2.2. The satellite retrievals

2.2.1. The OMI NO$_2$ retrieval

Compared with ground-based observations, satellite retrievals enable independent, global and consistent monitoring, and are easier to access, and thus widely used in research. One of the most widely used satellite NO$_2$ products is OMI (Levelt et al., 2006), which provided the longest data record currently available. OMI was the first satellite hyperspectral UV/Visible spectrometer and was launched in July 2004 on NASA’s EOS-Aura sun-synchronous polar satellite with an equator-crossing time of about 13:45 local time (ascending node) (Schoeberl et al., 2006). The swath width of OMI is 2600 km, enabling global daily coverage with a nadir field-of-view (FOV) size of 13 km $\times$ 24 km (along track $\times$ across track). The operational OMI NO$_2$ standard product version 3 (SPv3) by NASA was used in this study (Krotkov et al., 2020).
The observed variations in atmospheric NO$_2$ were affected by changes in both emissions and meteorology. The numerical chemical transport model is a useful tool that can quantify the impacts from changes in emissions and meteorology. In this study, the 3-D Goddard Earth Observing System chemical transport model (GEOS-Chem) (version 12.6.3) (Bey et al., 2001; Park et al., 2004) was run with the full tropospheric chemistry mechanism (i.e. NO$_2$–O$_3$–HC-Aer-Br-Cl-I mechanism) to simulate the physical (e.g. advection, diffusion and deposition) and chemical (e.g. gas-phase reactions, aqueous reactions, heterogeneous reactions and aerosol thermodynamic equilibrium) processes of atmospheric tracer gases (e.g. NO$_2$, NO, O$_3$, SO$_2$, NH$_3$, CO) and aerosols (e.g. sulfate, nitrate, ammonium, dust, sea salt, BC, POA, SOA). The tropospheric VCDs of NO$_2$ were calculated as follows:

$$VCD = \sum_{i=1}^{n} \rho_{x,C} C_{NO_2} H_i,$$

where $k$ represents the model layer, and the $\rho_{x,C}$ is the layer of tropopause based on thermal estimate according to MERRA2 data, $\rho_{x,C}$ is the density of dry air (mol/m$^3$), $C_{NO_2}$ is the concentration of NO$_2$ (µmol/mol), $H$ is the thickness of the model layer $k$. The GEOS-Chem model has been successfully used over East Asia in our previous studies (Uno et al., 2017a, 2017b; 2017c; Wang et al., 2020). In this study, the Community Emissions Data System (CEDS) inventory at the year of 2014 (Hoesly et al., 2018) was used for anthropogenic emission, and the fourth version of the Global Fire Emissions Database (GFED4) (van der Werf et al., 2017) was used for biomass burning emission. NO$_2$ emissions from soil and lighting were calculated online based on previous studies (Hudman et al., 2012; Murray et al., 2012). Emissions of biogenic VOCs were based on the Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGANv2.1) (Guenther et al., 2012). The meteorological fields of GEOS-Chem model used the Modern-Era Retrospective analysis for Research and Applications, version 2 (MERRA-2) reanalysis data with a horizontal resolution of 0.5° × 0.625° (Gelaro et al., 2017). The GEOS-Chem simulations over East Asia used the same horizontal resolution. The simulation period is from December 2014 to March 2020. Two sets of GEOS-Chem simulations were conducted to investigate the impacts of meteorology and monthly varied emissions on NO$_2$ variations as summarized in Table 2.

### 3. Spatiotemporal distribution of atmospheric NO$_2$

#### 3.1. Horizontal distribution of NO$_2$ before and during the COVID-19 lockdown

Fig. 1 shows the horizontal distributions of mean NO$_2$ concentrations by in-situ observations and VCDs by different satellite retrievals before and during the COVID-19 lockdown, as well as the relative differences between the two periods. To avoid the effect of the SF holiday (January 24–30, 2020), the period to represent before COVID-19 lockdown was January 1–20, same with (NASA Earth Observatory et al., 2020), while the period to represent during COVID-19 lockdown was February 10–29.
4 days longer than February 10–25 used by (NASA Earth Observatory et al., 2020), so each period had 20 days. The relative differences were not shown for satellite pixels with NO$_2$VCD less than 10 $\mu$mol/m$^2$ due to large uncertainty, i.e. the estimated overall error is larger than 100% for the TROPOMI pixel with a NO$_2$VCD of 10 $\mu$mol/m$^2$.

Fig. 2 shows the probability distribution of NO$_2$ change between these two periods in surface observation sites and satellite pixels for different retrievals. Only the satellite pixels with one or more surface observation sites were used for quantitative analysis to keep consistency with the analysis of in-situ concentrations. The mean NO$_2$ concentrations and VCDs during these two periods as well as their relative differences between these two periods were summarized in Table 3.

The mean surface NO$_2$ concentrations over China decreased from 39.4 $\mu$g/m$^3$ during January 1–20 to 19.6 $\mu$g/m$^3$ during February 10–29, with a reduction rate of 50.3% on average over China (a 2015–2019 average will be discussed later), and more than 60% over the Hubei area and northern China (Fig. 1 and Table 3). As shown in Fig. 2, the decrease of NO$_2$ concentrations occurred in almost all observation sites, except only for 4 sites which were located in rural areas with low NO$_2$ concentrations and not significantly affected by the lockdown.

The OMI retrievals showed the highest NO$_2$ VCDs with maximum values larger than 300 $\mu$mol/m$^2$ over East China before COVID-19 lockdown (Fig. 1). The NO$_2$ VCDs based on high quality (QA $\geq$ 0.75) TROPOMI retrievals showed lower levels with the medium quality (QA $\geq$ 0.5) TROPOMI VCDs (c1-c3) and medium quality (QA $\geq$ 0.5) TROPOMI VCDs (d1-d3) before (1–20 January, a1, b1, c1 and d1) and during (10–29 February, a2, b2, c2 and d2) the COVID-19 lockdown period as well as relative differences between these two periods (a3, b3, c3 and d3, in %). The grey shadings in b3, c3 and d3 indicate satellite pixels with NO$_2$ VCD less than 10 $\mu$mol/m$^2$. 

Fig. 1. Horizontal distributions of mean surface NO$_2$ concentrations (a1-a3, unit: $\mu$g/m$^3$), OMI NO$_2$ VCDs (b1-b3, unit: $\mu$mol/m$^2$), high quality (QA $\geq$ 0.75) TROPOMI VCDs (c1-c3) and medium quality (QA $\geq$ 0.5) TROPOMI VCDs (d1-d3) before (1–20 January, a1, b1, c1 and d1) and during (10–29 February, a2, b2, c2 and d2) the COVID-19 lockdown period as well as relative differences between these two periods (a3, b3, c3 and d3, in %). The grey shadings in b3, c3 and d3 indicate satellite pixels with NO$_2$ VCD less than 10 $\mu$mol/m$^2$. 

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The roles of other factors in the variations of NO$_2$ concentrations in Q1 of not only 2020, but also 2015 to 2019, to reveal concentrations. The probability distributions of NO$_2$ are shown in Fig. 2. Although the NO$_2$ VCD levels were different, the decrease rates of NO$_2$ VCDs over China were similar for different satellite retrievals. The OMI, high quality TROPOMI and medium quality TROPOMI VCDs decreased at 57.5% and 57.3%, respectively, which were about 7% larger than the decrease rate based on in-situ NO$_2$ concentrations. The probability distributions of NO$_2$ change based on satellite retrievals were similar with that based on in-situ observations, but with slightly larger dispersion (Fig. 2), which might be due to lower temporal resolution (one or two days) of satellite retrievals compared to that of in-situ observations (hourly).

### Table 3

| Datasets               | January 1–20 | February 10–29 | Relative difference |
|-----------------------|--------------|----------------|---------------------|
| In-situ concentrations| 39.4 µg/m$^3$| 19.6 µg/m$^3$  | −50.3%              |
| OMI VCDs              | 195.8 µmol/m$^2$ | 83.2 µmol/m$^2$ | −57.5%              |
| TROPOMI VCDs (QA>0.75)| 105.3 µmol/m$^2$ | 46.1 µmol/m$^2$ | −56.2%              |
| TROPOMI VCDs (QA>0.5 )| 131.6 µmol/m$^2$ | 56.2 µmol/m$^2$ | −57.3%              |

≥ 0.5) ones, but both were significantly lower than OMI retrievals (Fig. 1 and Table 3). Although the NO$_2$ VCD levels were different, the decrease rates of NO$_2$ VCDs over China were similar for different satellite retrievals. The OMI, high quality TROPOMI and medium quality TROPOMI NO$_2$ VCDs decreased at 57.5%, 56.2% and 57.3%, respectively, which were about 7% larger than the decrease rate based on in-situ NO$_2$ concentrations. The probability distributions of NO$_2$ change based on satellite retrievals were similar with that based on in-situ observations, but with slightly larger dispersion (Fig. 2), which might be due to lower temporal resolution (one or two days) of satellite retrievals compared to that of in-situ observations (hourly).

#### 3.2. Daily variations of NO$_2$ concentrations

Although both the in-situ observations and satellite retrievals showed significant decreases of NO$_2$ during the COVID-19 lockdown period compared to before the lockdown, it was not clear whether these decreases were only due to the lockdown. Monthly variations in emissions and meteorology might also contribute to these decreases. Therefore, in this subsection, we showed the daily variations of NO$_2$ concentrations in Q1 of not only 2020, but also 2015 to 2019, to reveal the roles of other factors in the variations of NO$_2$ concentrations in years without COVID-19 lockdown. Fig. 3 shows the variations of daily mean and 11-day moving average NO$_2$ concentrations from in-situ monitors over China during the first quarter (Q1) of 2020 and previous years (2015–2019).

It can be seen that the 11-day moving average can effectively remove the NO$_2$ variations on a synoptic scale (3–7 days). During 2015, 2019, the minimum of 11-day moving average NO$_2$ concentrations always appeared during the SF holiday (circles in Fig. 3), indicating that the SF holiday have a significant role in the decrease of NO$_2$ concentrations. The NO$_2$ concentrations decreased from about 8 days before the SF, and gradually recovered in 21 days after the SF.

In 2020, the NO$_2$ concentrations showed similar decreases before and during the SF holiday as found during 2015 and 2019, but did not show rapid recovery after the SF holiday, indicating the effect of the COVID-19 lockdown. Therefore, both the SF holiday and the COVID-19 lockdown significantly contributed to variations of NO$_2$ in early 2020.

#### 3.3. NO$_2$ concentrations

To separate and quantify the effects of the SF holiday and the COVID-19 lockdown on the NO$_2$ decrease, the variations of the 11-day moving average NO$_2$ concentrations during 2015–2019 (green lines) and 2020 (red line) were shown together in Fig. 4 according to the days relative to the SF rather than the calendar dates. A significant general decreasing trend can be seen during the whole period shown in Fig. 4 in every single year, which might be due to the monthly variations of meteorology and emissions. To reveal the factors leading to this decreasing trend, the simulated NO$_2$ concentrations by GEOS-Chem with monthly (blue lines) and fixed (orange line) emissions are also shown in Fig. 4. The simulated NO$_2$ concentrations were averaged over all of the model grids with one or more in-situ monitors located within their range. Since the years of observations and model emissions were different (Table 2), the model results were adjusted based on the ratio of observations to simulations during the first 15 days, which were not affected by the SF holiday and the COVID-19 lockdown.

The model results indicated that meteorology changes (e.g. wind speed, wind direction, and PBL height) due to seasonal transition resulted in a nearly linear decreasing trend of 25% reduction over 90 days for the NO$_2$ concentrations (blue lines in Fig. 4), while the monthly...
variations of emissions have a very small effect on this decreasing trend (orange line in Fig. 4). The simulated general decreasing trend showed good agreement with observations during 2015 and 2019 (green lines in Fig. 4) except for the period around the SF holiday. Therefore, the effect of SF holiday on NO\textsubscript{2} decrease can be estimated by the difference of simulations and observations during 2015 and 2019. Based on this estimation, the SF holiday resulted in a NO\textsubscript{2} reduction from 8 days before SF to 21 days after SF (i.e. January 17 - February 15) with a daily maximum of 37%.

The decrease of NO\textsubscript{2} concentrations before and during the SF holiday in 2020 showed good agreement with the decreases in 2015–2019, which means the decrease of NO\textsubscript{2} was dominated by the SF holiday effect at the beginning of the COVID-19 epidemic. While from 6 days after SF, the NO\textsubscript{2} concentrations in 2020 (red line) were significantly lower than those in 2015–2019 (green lines), indicating that the COVID-19 lockdown played an important role in the NO\textsubscript{2} reduction, with a daily maximum of 51%. The NO\textsubscript{2} concentrations gradually recovered to a similar level as in previous years by the end of March 2020 as the lockdown was lifted in most areas of China. Based on these analyses, the impacts of meteorology changes due to seasonal transition, SF and COVID-19 lockdown on daily variations of NO\textsubscript{2} concentrations are shown in Fig. 4b by shadings in different color.

Since the effect of COVID-19 lockdown was estimated based on the comparison of NO\textsubscript{2} between 2020 and previous years, the coefficient of variation (i.e. the ratio of the standard deviation to the mean) of NO\textsubscript{2} at the same day during 2015 and 2019 could be used as a estimation of the uncertainty, and was calculated as follows:

\[
CV_i = \sqrt{\frac{\Sigma NO_{2,i}^y / n}{\Sigma NO_{2,i}^y/n}}\]

where \(i\) represents the \(i\)th day relative to SF, \(y \in \{2015, 2019\}\) and \(n = 5\). The \(CV\) of NO\textsubscript{2} concentrations ranged from 2.3% to 15.4% with a mean value of 9.0%.

3.4. NO\textsubscript{2} VCDs

Fig. 5 is similar to Fig. 4, but for the OMI NO\textsubscript{2} VCD retrievals. The OMI NO\textsubscript{2} VCDs were re-gridded onto the model grids, and then averaged over all of the grids with one or more in-situ monitors located within their range. The \(CV\) for OMI VCDs during 2015–2019 ranged from 3.2% to 17.2% with a mean value of 9.8%, larger than in-situ observations, which may be due to the low temporal resolution (global coverage in 2 days) of OMI, indicating that the estimation based on OMI VCD retrievals might have larger bias than in-situ observations. The model results indicated meteorology changes due to seasonal transition resulted in a larger decreasing trend in NO\textsubscript{2} VCDs compared to surface concentrations, with about 40% reduction over 90 days for the NO\textsubscript{2} VCDs. The retrieved NO\textsubscript{2} VCDs after the SF holiday showed lower values and larger variation compared with the simulations, consistent with larger CV, as discussed previously. In Fig. 5b, the OMI NO\textsubscript{2} VCD retrievals in 2017 rather than the mean values between 2015 and 2019 (Fig. 4b) were used to represent the NO\textsubscript{2} VCD variations without COVID-19 lockdown, due to better agreement with the simulated general trend in NO\textsubscript{2} VCDs during the whole period.

Fig. 4. Impacts of meteorology changes due to seasonal transition, Spring Festival and COVID-19 lockdown on daily variations of in-situ NO\textsubscript{2} concentration in early 2020. The red line represents the observed 11-day moving average NO\textsubscript{2} concentrations in 2020. The thin green lines represent the adjusted GEOS-Chem simulated surface NO\textsubscript{2} concentrations with fixed and monthly emissions, respectively. The two periods in Fig. 1 were shown as grey shadings. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

Fig. 5. Impacts of meteorology changes due to seasonal transition, Spring Festival and COVID-19 lockdown on Daily Variations of NO\textsubscript{2} VCDs over China in early 2020 based on OMI retrievals. The red line represents the retrieved 11-day moving average NO\textsubscript{2} VCDs in 2020. The thin green lines represent the retrieved NO\textsubscript{2} VCDs from 2015 to 2019, and the thick line represents the mean values. The blue and orange lines represent the adjusted GEOS-Chem simulated surface NO\textsubscript{2} VCDs with fixed and monthly emissions, respectively. The two periods in Fig. 1 were shown as grey shadings. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)
The NO2 VCDs based on high quality (solid lines) and medium quality (dotted-dashed lines) TROPOMI retrievals are shown in Fig. 6, as well as the adjusted GEOS-Chem simulation with fixed emissions (blue lines). The TROPOMI NO2 VCDs were re-gridded onto the model grids, and then averaged over all of the grids with one or more in-situ monitors located within their range. The adjustments were based on the ratio of either high or medium quality TROPOMI retrievals to simulations during the first 15 days, and shown as dark blue solid line and light blue dashed line in Fig. 6, respectively. The impacts of meteorology changes due to seasonal transition, SF holiday and COVID-19 lockdown on variations of NO2 VCDs based on high quality TROPOMI retrievals (Fig. 6b) generally showed similar results with OMI (Fig. 5b), except that the SF holiday effect was overestimated by TROPOMI from 15 days after the SF.

The medium quality TROPOMI NO2 VCDs before SF of 2019 (green dotted-dashed lines) was 38% higher than that of 2020 (red dotted-dashed lines). This difference was much larger than the difference based on all the other datasets, i.e. high quality TROPOMI VCDs (16%, green and red solid lines), OMI VCDs (7%, Fig. 5) and surface concentrations (2%, Fig. 4). The general trend over the whole period by the medium quality TROPOMI retrievals was quite different with that by model simulations, while the high quality TROPOMI retrievals showed good agreement with simulations. Based on these analyses, it could be indicated that the medium quality TROPOMI retrievals might suffer large bias during some periods, and attentions must be paid when they are used for analysis, data assimilations and emission inversions.

3.5. Implication for analysis of NO2 decreases between different periods

As discussed in section 3.1, the surface NO2 concentrations decreased by 50.3%, and the NO2 VCDs decreased by 56.2%-57.5% in different satellite retrievals on average over China from 1–20 January to 10–29 February 2020 (Table 3). In this section, the impacts of different factors on these NO2 decreases were discussed based on analysis in sections 4.1 and 4.2. These two periods were shown as grey shadings in Figs. 4–6. It can be seen that the areas of green shadings in Figs. 4b–5b were small and had similar values during the two periods, indicating that the SF holiday effect did not significantly affect the decrease of atmospheric NO2 during these two periods. As discussed in the previous section, the TROPOMI QA75 retrievals overestimated the holiday effect on the decrease of NO2 after the SF, and therefore were not used for the quantitative analysis in this section.

Based on model simulations with fixed emissions, the surface NO2 concentration and NO2 VCDs during 10–29 February decreased by 11.1% (blue lines in Fig. 4) and 17.8% (blue lines in Fig. 5), respectively, compared to those during 1–20 January (blue bars in Fig. 7). In other words, the differences in meteorology contributed to 22.1% of the decrease (20 μg/m3) in observed NO2 concentrations, and 31.0% of the decrease (113 μmol/m3) in OMI retrieved NO2 VCDs from 1–20 January to 10–29 February (pie charts in Fig. 7). Since the TROPOMI QA75 overestimated the holiday effect on the decrease of NO2 after the SF, it was not used for quantitative analysis here.

Since the two periods were not significantly affected by the SF holiday effect, the difference between the decrease in observations and the decrease due to meteorology was mainly due to the impact of the COVID-19 lockdown. As a result, both the concentration and VCDs of NO2 during 10–29 February decreased by about 39% due to the COVID-19 lockdown, compared to those during 1–20 January (red bars in Fig. 7).

3.6. Decrease of NO2 due to COVID-19 lockdown in February and March 2020

Based on the analysis in sections 4.1 and 4.2, the impacts of COVID-19 lockdown on the decreases of NO2 in February and March 2020 based on different datasets were summarized in Table 4. The COVID-19 lockdown resulted in the surface NO2 concentrations decreased by 42% and 26% over China in February and March 2020, respectively. Both the OMI and high quality TROPOMI NO2 VCDs showed similar results as the

| Table 4 | Decrease of NO2 over China due to COVID-19 lockdown in February and March 2020. |
|---------|---------------------------------|
|         | February                       | March |
| In-situ concentrations | 42% ± 8%                      | 26% ± 9%|
| OMI VCDs | 43% ± 9%                      | 27% ± 13%|
| TROPOMI VCDs (QA≥0.75) | 41%                           | 23% |
surface NO₂ concentrations. The uncertainties (mean CV) for in-situ observations and OMI retrievals were less than 10% except for OMI in March due to larger variations as discussed before.

4. Conclusions

The lockdown measures due to COVID-19 affected the industry, transportation and other human activities within China in early 2020, and subsequently the emissions of air pollutants. In this study, the decrease of atmospheric NO₂ due to the COVID-19 lockdown and other factors were quantitatively analyzed based on the surface concentrations by in-situ observations, the tropospheric vertical column densities (VCDs) by different satellite retrievals including OMI and TROPOMI, and the model simulations by GEOS-Chem.

The results indicated that due to the COVID-19 lockdown, the surface NO₂ concentrations decreased by 42% ± 8% and 26% ± 9% over China in February and March 2020, respectively. The tropospheric NO₂ VCDs based on both OMI and high quality TROPOMI showed similar results as the surface NO₂ concentrations.

The daily variations of atmospheric NO₂ during the first quarter of 2020 were not only affected by the COVID-19 lockdown, but also by the SF holiday effect as well as the meteorology changes due to seasonal transition. At the beginning of the COVID-19 epidemic, the decrease of NO₂ was dominated by the SF holiday effect, which resulted in a NO₂ reduction from 8 days before SF to 21 days after it, with a maximum of 37%. From the 6 days after SF to the end of March, the COVID-19 lockdown played an important role in the NO₂ reduction, with a maximum of 51%. The meteorology changes due to seasonal transition resulted in a nearly linear decreasing trend of 25% and 40% reduction over the 90 days for the NO₂ concentrations and VCDs, respectively.

The decreases in atmospheric NO₂ were analyzed between two periods before and during the COVID-19 lockdown and both were not significantly affected by the SF holiday. The results indicated that the mean NO₂ concentration and the NO₂ VCD during 10–29 February were 50% and 57% lower than those during 1–20 January 2020, and meteorology changes due to seasonal transition was responsible for the difference in reduction rates by resulting in decreases of 11% and 18% in the NO₂ concentrations and VCDs, respectively. As a result, both the concentrations and the VCDs of NO₂ decreased about 39% between these two periods due to the COVID-19 lockdown.

The medium quality TROPOMI retrievals showed unreasonable large differences in VCDs before SF and 2019 and 2020 when compared with all the other datasets, indicating it might suffer large biases in some periods, and attention must be paid when they are used for analyses, data assimilations and emission inversions.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.atmosenv.2020.117972.

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