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Quantifying the emission changes and associated air quality impacts during the COVID-19 pandemic in North China Plain: a response modeling study

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Abstract

Quantification of emission changes is a prerequisite for the assessment of control effectiveness in improving air quality. However, the traditional bottom-up method for characterizing emissions requires detailed investigation of emissions data (e.g., activity and other emission parameters) that usually takes months to perform and limits timely assessments. Here we propose a novel method to address this issue by using a response model that provides real-time estimation of emission changes based on air quality observations in combination with emission-concentration response functions derived from chemical transport modeling. We applied the new method to quantify the emission changes in the North China Plain (NCP) due to the COVID-19 pandemic shutdown, which overlapped the Spring Festival holiday. Results suggest that the anthropogenic emissions of NO_2, SO_2, VOC, and primary $PM_{2.5}$ in NCP were reduced by 51%, 28%, 67% and 63%, respectively, due to the COVID-19 shutdown, indicating longer and stronger shutdown effects in 2020 compared to the previous Spring Festival holiday. The reductions of VOC and

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primary $PM_{2.5}$ emissions are generally effective in reducing O_3 and $PM_{2.5}$ concentrations. However, such air quality improvements are largely offset by reductions in NO_x emissions. NO_x emission reductions lead to increases in O_3 and $PM_{2.5}$ concentrations in NCP due to the strongly VOC-limited conditions in winter. A strong NH_3-rich condition is also suggested from the air quality response to the substantial NO_x emission reduction. Well-designed control strategies are recommended based on the air quality response associated with the unexpected emission changes during the COVID-19 period. In addition, our results demonstrate that the new response-based inversion model can well capture emission changes based on variations in ambient concentrations, and thereby illustrate the great potential for improving the accuracy and efficiency of bottom-up emission inventory methods.

Keywords: emission changes, response model, ozone, $PM_{2.5}$, control effectiveness

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1. Introduction

Accurate estimation of anthropogenic emissions is crucial for atmospheric modeling studies and provides the basis for developing effective air pollution controls (Wang et al., 2010). A comprehensive emission inventory consists of the emission rates of primary particulate matter components and gaseous pollutants and precursors that are allocated over time and space. These inventories are usually developed using bottom-up methods that gather detailed information about source activity and other emission parameters (Wang et al., 2011; Xing et al., 2015; Li et al., 2017). The challenge is that such investigation is costly and time consuming, and therefore the latest emission inventories usually lag current conditions by a year or more. Many studies also apply a top-down methods to constrain emission estimates using satellite retrievals and modeling methods (Tang et al., 2013, 2019; Lu et al., 2015; Miyazaki et al, 2017; Cao et al., 2018; Zhang et al., 2018). The top-down inversion method can well reflect the change in emissions in a timely manner, and thus efficiently estimate emissions at high spatial and temporal resolution to complement bottom-up inventories. Previous inversion studies have focused on individual pollutants that can be measured directly; however, studies are lacking that use top-down methods to estimate emissions of multiple pollutants, including those that cannot be directly measured, such as primary fine particular matter (p-$PM_{2.5}$).

The ongoing Coronavirus disease 2019 (COVID-19) pandemic has led to 4,600 deaths in mainland China (by May 24, 2020, https://news.google.com/covid19/), and has resulted in a dramatic curtailment of routine economic and social activities. The shutdown of human activities during the COVID-19 pandemic has led to reduced pollutant emissions and possibly improved air quality (Shi et al., 2020; Wang et al., 2020a). Yet according to ambient concentration measurements, heavy $PM_{2.5}$ pollution still occurred during the COVID-19 period, and formation of secondary pollutants was actually enhanced in China (Li et al., 2020; Huang et al., 2020). Some studies attributed pollution enhancements to atypical weather conditions that are favorable for air pollution formation (Wang et al., 2020b). Meanwhile, the unexpected

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reduction of anthropogenic emissions due to the COVID-19 shutdown might vary significantly for different sectors and species. For example, emissions from domestic sources might have increased due to a greater demand for home heating and other essential consumptions during periods with stay-at-home orders in effect. Moreover, the coincidence of the COVID-19 shutdown and the Spring Festival in China resulted in large numbers of people confined to their rural or small-city hometowns, where consumption patterns differ greatly from their primary residence in megacities. Relative to previous years, both emissions and meteorological conditions varied simultaneously during the 2020 COVID-19 shutdown, and an accurate estimation of the changes in anthropogenic emissions accounting for meteorological variations is needed to characterize the impacts of COVID-19 on air quality.

Here we propose a novel inversion technique based on a multi-pollutant nonlinear response model to estimate the emission changes in NCP during the COVID-19 shutdown. Emission changes for the COVID-19 period are calculated as the difference between emission estimates for actual conditions and hypothetical conditions assuming the shutdown did not occur. The hypothetical emissions are determined by combining top-down emission estimates from before and after the shutdown with estimates of the temporal variation in emissions from a bottom-up emission inventory. Additionally, we estimate the change in emissions associated with the Spring Festival holiday in 2019 to contrast with results for the combined Spring Festival holiday and COVID-19 shutdown in 2020. Finally, we evaluate the impacts on $PM_{2.5}$ and O_3 concentrations of the combined emission changes and for each emitted species to provide insights for the design of effective control strategies in the future.

2. Methods

2.1 Response model to estimate the actual emissions from observed surface concentrations

The principle of the new response-based inversion model (hereafter "the response model") is to adjust the assumed prior emissions such that concentration predictions match observations. The core element of the inversion method is a nonlinear response surface model (RSM) that represents the emission-

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concentration response functions. The framework of the response model is illustrated in Figure 1. We conduct chemical transport model simulations using prior emissions to get the original simulated concentrations of six pollutants (i.e., NO_2; O_3; SO_2; $PM_{2.5}$; sulfate, SO_4^{2-}; and nitrate, NO_3^-), as well as the response functions derived from the RSM (Xing et al., 2011; Wang et al., 2011; Xing et al., 2017; 2018). We then adjust the emission ratio of five pollutants (i.e., NO_2, VOC, SO_2, NH_3 and primary $PM_{2.5}$) to estimate the updated simulated concentrations to match with the observations.

Based on our previous knowledge of emission-concentration response relationships, we first adjust NO_x emissions such that RSM predictions match NO_2 observations (see E1), since NO_2 concentrations have a strong linear relationship with NO_x emissions (Xing et al., 2017).

$$E'_{NOx} = r_{NOx} \times E^*_{NOx} = E^*_{NOx} \times \frac{C^o_{NO2}}{C^s_{NO2}} \quad \text{(E1)}$$

where E'_{NOx} is the adjusted NO_x emissions; E^*_{NOx} is the prior NO_x emissions; r_{NOx} is the adjustment ratio for NO_x emissions; C^o_{NO2} is the observed NO_2 concentrations; and C^s_{NO2} is the simulated NO_2 concentrations.

Next, we adjust VOC emissions such that RSM predictions match observed O_3 concentrations, since O_3 concentrations are solely determined by VOC emissions after NO_x emissions are determined in the previous step. The adjusted VOC emission ratio (i.e., $r_{VOC} = E'_{VOC}/E^*_{VOC}$) is determined by solving the following equation E2:

$$\Delta O_3 = (C^o_{O3} - C^s_{O3}) = RSM_{O3}(r_{NOx}, r_{VOC}) \quad \text{(E2)}$$

where E'_{VOC} is the adjusted VOC emissions; E^*_{VOC} is the prior VOC emissions; ΔO_3 is the difference between observed O_3 concentrations (C^o_{O3}) and simulated O_3 concentrations (C^s_{O3}); and RSM_{O3} is the response function of O_3 concentrations to NO_x and VOC emissions.

Although SO_2 concentrations are linearly related to SO_2 emissions, the chemical transport model overestimates SO_2 concentrations and underestimates SO_4^{2-} concentrations due to large uncertainties in simulating the rapid conversion of SO_2 to SO_4^{2-} during haze episodes (Zhang et al., 2019). To address this

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deficiency, we adjusted the SO_2 emissions using the observed SO_4^{2-}/SO_2 ratio such that the RSM predictions matched both the observed SO_2 and SO_4^{2-} concentrations. Since SO_4^{2-} concentrations are quite linearly related to SO_2 emissions when NH_3 emissions are at moderate levels (Wang et al., 2011), we assume that the unaccounted for SO_2-to-SO_4^{2-} conversion pathway contributes to differences in the observed and simulated SO_4^{2-}/SO_2 ratios. Under this assumption, simulated SO_2 concentrations are overestimated by the same ratio (α) that secondary SO_4^{2-} (C^s_{s-SO4}) concentrations are underestimated (see E3 and E4). The primary SO_4^{2-} concentration (C^s_{p-SO4}) was removed from the total SO_4^{2-} concentration in these calculations, because primary SO_4^{2-} is directly emitted and not related to the conversion of SO_2 to SO_4^{2-} (see E4).

$$C^o_{SO2} = \frac{1}{\alpha} \times r_{SO2} \times C^s_{SO2} \quad \text{(E3)}$$

$$C^o_{SO4} = \alpha \times r_{SO2} \times C^s_{s-SO4} + C^s_{p-SO4} \quad \text{(E4)}$$

$$\alpha = \left(\frac{C^o_{SO2}}{C^o_{SO4} - C^s_{p-SO4}} \Big/ \frac{C^s_{SO2}}{C^s_{SO4}} \right)^{1/2} \quad \text{(E5)}$$

The adjusted SO_2 emission ratio (r_{SO2}) is estimated by taking the ratio of observed SO_2 (C^o_{SO2}) to simulated SO_2 (C^s_{SO2}) multiplied by α, which accounts for the model deficiency in simulating the rapid conversion of SO_2 to SO_4^{2-}. For simplification, here we estimate the α value at a domain and temporal averaged level (i.e., identical across the space and time), though such ratio might vary with time and space. The α is smaller than 1 because the observed SO_4^{2-}/SO_2 is usually greater than the simulation. The inclusion of the α may help the response model avoid the underestimation of SO_2 emissions.

Using the adjusted NO_x, VOC, and SO_2 emissions from previous steps, we next adjusted NH_3 emissions such that RSM predictions of NO_3^- concentrations matched observations:

$$\Delta NO_3^- = (C^o_{NO3} - C^s_{NO3}) = RSM_{NO3}(r_{NOx}, r_{VOC}, r_{SO2}, r_{NH3}) \quad \text{(E6)}$$

where $r_{NH3} = E'_{NH3}/E^*_{NH3}$, E'_{NH3} is the adjusted NH_3 emissions, and E^*_{NH3} is the prior NH_3 emissions.

After updating the emissions of the four gaseous precursors, the secondary portion of $PM_{2.5}$ was

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correspondingly determined, including the secondary organic aerosol contributed by the VOC emissions. Finally, the primary $PM_{2.5}$ emissions were adjusted to provide agreement between simulated and observed total $PM_{2.5}$ concentrations:

$$\Delta PM_{2.5} = (C^{o}_{PM2.5} - C^{s}_{PM2.5}) = RSM_{PM2.5}(r_{NOx}, r_{VOC}, r_{SO2}, r_{NH3}, r_{p-PM2.5}) \quad \text{(E7)}$$

where $r_{p-PM2.5} = E'_{p-PM2.5}/E^{*}_{p-PM2.5}$, $E'_{p-PM2.5}$ is the adjusted primary $PM_{2.5}$ emissions, and $E^{*}_{p-PM2.5}$ is the prior primary $PM_{2.5}$ emissions.

The prior emissions used here were based on a bottom-up inventory developed for 2017. Since our study focuses on periods in 2019 and 2020, we first use the response model to adjust the 2017 emission inventory to match the two study periods. The first study period was defined as 1 January – 31 March 2019 to capture changes in activity due the Spring Festival. The second study period was defined as the same three months in 2020 to capture the COVID-19 shutdown in NCP, which overlapped the 2020 Spring Festival holiday. We defined three sub-periods within the three months in each year as pre-shutdown (Period 1), shutdown (Period 2), and post-shutdown (Period 3). The days selected for sub-periods differed in 2019 and 2020 due to differences in the dates and lengths of the shutdowns. For 2019, we defined Period 1: 1–29 Jan. (29 days); Period 2: 30 Jan. – 18 Feb. (20 days), which is a week before and after the 2019 Lunar New Year holidays; and Period 3: 19 Feb. – 31 Mar. (41 days). For 2020, we defined Period 1: 1–22 Jan. (22 days); Period 2: 23 Jan. – 5 Mar. (33 days), which is from the date that Chinese authorities began targeted transportation shutdowns until all human activities began recovering in early March (http://www.gov.cn/index.htm); and Period 3: 6–31 Mar. (26 days).

The RSM was developed using ambient concentrations from simulations with the Community Multiscale Air Quality (CMAQ, version 5.2.1) model, which incorporated meteorological fields from the Weather Research and Forecasting (WRF, version 3.8) model. The WRF-CMAQ system was configured as in our previous studies, and model performance for meteorological variables and pollutant concentrations was evaluated (Ding et al., 2019). The RSM was developed following the same design as

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our previous study (Xing et al., 2017), in which the polynomial response functions for O_3, $PM_{2.5}$ and $PM_{2.5}$ components were fitted by 40 brute-force CMAQ simulations. Specifically, deep-learning technology was used to fit response surfaces for the three months in 2019 and 2020 using CMAQ simulations for baseline and zero-out emissions conditions (Xing et al., under review) (see Figure 2). The response surfaces were developed using year-specific meteorology based on WRF simulations to account for differences in meteorological conditions between 2019 and 2020.

Measurements of ambient concentrations of NO_2, SO_2, O_3 and $PM_{2.5}$ were obtained from the China National Environmental Monitoring Centre (http://106.37.208.233:20035/). Measurements of $PM_{2.5}$ chemical components, including NO_3^- and SO_4^{2-}, were provided by the urban PM data analysis platform in the 2+26 cities of Beijing-Tianjin-Hebei and surrounding regions (http://106.37.181.120:9011/bfs). All monitoring data were given as hourly-averaged concentrations at the monitoring sites shown in Figure 2. As in our previous RSM studies, daily daytime O_3 concentrations were analyzed based on afternoon averages (12:00pm-6:00pm local time), and $PM_{2.5}$ concentrations were based on daily 24-hour averages (Xing et al., 2018). Since the monitors sample pollutants at discrete locations and measurements are not available for all days at all sites, provincial average concentrations were used to facilitate adjustments domain-wide for all days in each study period. The provincial average concentrations were calculated using spatially and temporally matched simulated and observed values.

2.2 Hypothetical emissions without shutdown effects

The actual emissions can be derived using observed concentrations and the response model. However, hypothetical emissions under the assumption of no shutdown effects are also needed to estimate the changes in emissions due to the 2019 and 2020 shutdowns. We estimate the hypothetical emissions using the temporal profiles of sectoral emissions from the bottom-up inventory in combination with the derived (actual) emissions for the pre- and post-shutdown periods. We assume that the Spring Festival shutdowns in 2019 have negligible influence on emissions during the periods before and after the

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shutdown (i.e., Period 1 and Period 3, respectively), while the COVID-19 pandemic in 2020 might have had lag effects after the shutdown due to reduced economic activity or relaxed pollutant controls. However, we concentrate our analysis of COVID-19 impacts on emissions and air quality in the official shutdown period only (Period 2). The hypothetical no-shutdown emissions for Period 2 (noted as Period 2H) are estimated using ratios of emissions for Period 2 and Period 1 and 3 based on the temporal profile of the bottom-up inventory which only reflects the natural evolution of emissions across a year for each sector. This approach develops hypothetical emissions following the typical variation in emissions without shutdown effects. Note that we use the temporal profile to determine the change in Period 2 emissions relative to Period 1 and 3, and so emissions from both Period 1 and 3 are needed to estimate Period 2H emissions.

The emission changes due to the COVID-19 shutdown can be estimated by taking the difference of emissions in Period 2, derived from the response model, and emissions in Period 2H, estimated from emissions in Period 1 and 3 using the temporal profile of bottom-up sectoral emissions. The impacts of emission changes during the COVID-19 shutdown on $PM_{2.5}$ and O_3 concentrations are then estimated with the RSM. In addition to the combined impacts of emission changes from multiple species, we estimate the impacts of individual pollutant emissions on $PM_{2.5}$ and O_3. Due to the nonlinearity of emission-concentration response functions, the impacts of individual pollutant emissions can vary significantly when other pollutant emissions are change simultaneously (Xing et al., 2018). To simplify the evaluation, we define an incremental method for analyzing the individual pollutant impacts in this study by adding incremental changes in pollutant emissions to the previous simulation in the following order: NO_x, VOC, NH_3, SO_2 and primary $PM_{2.5}$, as described in Table 1. The impacts of individual pollutant emissions on O_3 and $PM_{2.5}$ concentrations are then estimated from the difference between the incrementally adjusted simulation and the previous one. Note that this approach is an approximation, and the impacts of individual pollutants could change if a different order is used.

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3. Results

3.1 Emission changes due to the shutdown

Using the response model, the daily emissions of NO_x, VOC, NH_3, SO_2 and primary $PM_{2.5}$ in NCP are estimated for three periods in 2019 and 2020, as summarized in Figure 3 and detailed in Table 2 by provinces.

For Period 1 before the activity disruptions, the emissions of NO_x, SO_2, and VOC in NCP decreased by 11%, 25%, and 8% between 2019 and 2020, respectively. These reductions reflect the progress of air pollution controls between 2019 and 2020, and demonstrate the ability of the model to capture emission changes from routine air pollution control actions. The p-$PM_{2.5}$ emissions also significantly decreased in Beijing-Tianjin-Hebei provinces but increased in Shandong and Henan. The NH_3 emissions did not change during this two-year period, since NH_3 is not considered in current policies.

Activity reductions occurred in Period 2 in both 2019 and 2020, although the shutdown due the Spring Festival in 2019 is much shorter than the COVID-19 shutdown in 2020. The emissions of NO_x, SO_2 and p-$PM_{2.5}$ in Period 2 in 2020 are substantially lower than in 2019 (29%, 22% and 73%, respectively). The decreases of NO_x and p-$PM_{2.5}$ for Period 2 between 2019 and 2020 are larger than the decreases for Period 1, which did not experience shutdowns. Such results suggest that the COVID-19 shutdown in 2020 had longer and stronger impacts on emissions than the Spring Festival shutdown in 2019. Interestingly, emissions of NH_3 and VOC increased significantly (by 5% and 14%) from 2019 to 2020 in Period 2. These changes are likely due to the temporal variations of emissions of both species, which are enhanced in warmer months due to stronger evaporation. Period 2 in 2020 extended farther into the Spring (until early March) than Period 2 in 2019, and thus led to increased evaporative emissions of NH_3 and VOC. These results also demonstrate the importance of developing emissions with high temporal resolution.

For Period 3 after the shutdown, the decreases of NO_x emissions (14%) are similar to those in Period

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1 (11%), indicating the recovery of the activity. However, the emissions of VOC and p-$PM_{2.5}$ are much lower in Period 3 in 2020 compared to that in 2019, suggesting the lag effects after the COVID-19 shutdown in 2020. In contrast, the small increases of SO_2 emissions in 2020 (2%) might be associated with the extended central heating activity through the end of March in 2020, compared with mid-March in 2019. Higher NH_3 emissions in Period 3 in 2020 than 2019 are also due to the larger coverage of warm days in Period 3 of 2020. NH_3 emissions show the strongest monthly variations among all pollutants (Figure 3). Similarly, increases in VOC emissions are also driven by the change of meteorological conditions (i.e., the higher air temperature in March leads to a larger evaporative emissions), though the growth of VOC emissions from Period 1 to Period 3 is reduced by the COVID-19 shutdown in 2020. Such results also demonstrate that the response model can capture the temporal variations of emissions even in cases where emissions are strongly coupled with meteorological conditions.

The influence of the shutdown is estimated as the difference in emissions between Period 2H (hypothetical emissions without shutdown effects) and Period 2 (actual emissions), as shown in Figure 3 (grey and red bars respectively) and detailed in Table 3 by NCP province. Due to the COVID-19 shutdown in 2020, emissions of NO_x, VOC and $PM_{2.5}$ decreased substantially by 51%, 67% and 63%, respectively. SO_2 emissions also decreased by 28%, while NH_3 emissions experienced very small increases (+2%) which might be associated with increased activities in rural areas (e.g., potential NH_3 emission sources like stool burning) as many people relocated from megacities to small towns or the countryside. Compared to the effects of the Spring Festival in 2019, the COVID-19 shutdown led to greater reductions in NO_x, SO_2 and $PM_{2.5}$ emissions. The smaller VOC reduction in 2020 compared to 2019 might be due to the difference in temporal coverage of Period 2 in the two years (i.e., there were more warm days in Period 2 in 2020). Note that the hypothetical emissions in Period 2H are estimated based on the assumption of no shutdown effects in both Period 1 and Period 3. Therefore the reduction of those pollutant emissions in 2020 might be even larger considering the lag effects of COVID-19.

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3.2 The shutdown effects on ambient concentrations

Using the RSM, we predicted concentrations based on the updated emissions from the response-based inversion model. In general, the simulated concentrations based on the adjusted emissions matched well with the observed concentrations, as shown in Figure 4 for NCP averages and detailed by province in Figure S1-12. More important, during the shutdown period in both years, the simualtions using adjusted emissions without considering shutdown influcences significantly overestimate the NO_2 concentations in 2019 and 2020 by 61% and 81%, respectively. The high-biases in 2019 and 2020 are reduced to within 1% in the simualtion with consideration of shutdown effects (Figure 4a).

The results for O_3 are quite interesting, as simulated O_3 concentrations are close to observations in both simulations with and without consideration of shutdown influcences (Figure 4b). The apparent insenstivity of O_3 concentrations to emission changes during the shutdown can be explained by the nonlinear response of O_3 to its two percurors, NO_x and VOC. In Figure 5a, we compare the response of O_3 concentrations for two NO_x and VOC emission change pathways starting from the hypothetical emissions for no-shutdown conditions (black symbol in Figure 5a). Since NO_x emissions clearly decreased due to the shutdown, the O_3 concentrations would increase if VOC emissions remained constant (following the green line to the green symbol in Figure 5a). Yet the simulation without consideration of VOC emission changes would result in a high bias of simulated O_3 concentrations compared to the observations by 49% in 2019 and 29% in 2020. The low observed O_3 concentrations during Period 2 in both years indicates that VOC emission reductions must have occurred to maintain the suppressed O_3 level (following the red line to the red symbol in Figure 5a). Consistent with this interpretation, the simulated O_3 concentrations agree well with observations (e.g., normarlized mean bias, NMB < 3%) when both NO_x and VOC emission reductions are represented.

The substantial reduction of NO_x emissions also resulted in noticable decreases in NO_3^- concentrations (black and green lines in Figure 4c). However, the low bias in NO_3^- predictions cannot be

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279 readily mitigated by adjusting the NH_3 emissions, because the substantial decreases in NO_x emissions
280 associated with the shutdown result in a strong NH_3-rich conditions, where NO_3^- concentrations are less
281 sensitive to NH_3 emissions increases. The response of NO_3^- concentrations to pathways of NO_x and NH_3
282 emission changes is depicted in Figure 5b (SO_2 and VOC emissions are also changing simutaneously with
283 NO_x). A larger decrease in simulated than observed NO_3^- concentrations is associated with the NO_x
284 emission reductions, but the change of NH_3 emissions can hardly increase the NO_3^- concentrations under
285 such strong NH_3-rich conditions. Therefore, the model predicted no NH_3 changes in 2019, but very small
286 increases of NH_3 emissions (+2%) in 2020 due to the increased activities in rural areas which slightly
287 reduced the NO_3^- low biases (NMB from -12% to -11%).

288 The large reduction in SO_2 emissions estimated with the response model during the 2020 shutdown
289 considerably reduced the high biases in simulated SO_2 and SO_4^{2-} concentrations (Figure 4d-f). However,
290 the SO_4^{2-} biases are still considerable after the emission adjustment because a large fraction of SO_4^{2-} might
291 come from primary sources, which need further investigation especially for its contribution to p-$PM_{2.5}$.

292 Agreement between the simulated and observed $PM_{2.5}$ concentrations also improves when
293 accounting for the reductions in primary $PM_{2.5}$ emissions estimated with the response model in both years
294 (Figure 4g). Another interesting finding is that the simulated $PM_{2.5}$ concentrations with consideration of
295 all emission changes due to the shutdown (red line in Figure 4g) are quite similar to $PM_{2.5}$ predictions
296 without consideration of the shutdown impacts (black line in Figure 4g). The same behavior is evident for
297 O_3 concentrations (red and black lines in Figure 4b). As discussed above, the reductions in emissions of
298 multiple species during the shutdown had compensating influences on air quality, and the overall effects
299 of the emission changes on O_3 and $PM_{2.5}$ concentrations were neutralized to a relatively small level.

300 **3.3 Impacts of individual emission changes from the shutdown on O_3 and $PM_{2.5}$ concentrations**

301 To further investigate the individual impacts of emission changes of each pollutant on O_3 and $PM_{2.5}$
302 concentrations, we conducted sensitivity analysis by sequentially adding each incremental emission

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change into the model system and then calculating the associated changes in O_3 and $PM_{2.5}$ concentrations. By incrementally adding the impacts of emission changes of five pollutants (ΔNO_x, ΔVOC, ΔNH_3, ΔSO_2, and $\Delta p\text{-}PM_{2.5}$), the concentrations change from the original simulation, without consideration of shutdown impacts (noted as oSIM, shown as grey bar in Figure 6), and ultimately reaching the observed levels (noted as OBS, shown as narrow blue bars in Figure 6).

For O_3, the reduction of NO_x emissions lead to a significant enhancement of O_3 (see ΔNO_x) due to the VOC-limited regime in winter (Xing et al., 2019), while such O_3 enhancement has been largely or completely mitigated thanks to the simultaneous reduction of VOC emissions (see ΔVOC) in both 2019 and 2020. This behavior is particularly evident in Henan and Shandong provinces which experienced substantial VOC reductions during the shutdown (Table 3). Such benefits from simultaneous VOC controls also occurred for $PM_{2.5}$ concentrations. Compared with O_3, the changes in $PM_{2.5}$ concentrations are more complex to interpret due to the influence of emission changes for SO_2 (ΔSO_2), NH_3 (ΔNH_3) and $p\text{-}PM_{2.5}$ ($\Delta p\text{-}PM_{2.5}$) in addition to NO_x and VOC. Results suggest that the reductions of $p\text{-}PM_{2.5}$ emissions tended to favor $PM_{2.5}$ decreases while the ΔSO_2 and ΔNH_3 emission changes have negligible influence. Overall, reductions in $p\text{-}PM_{2.5}$ and VOC emissions helped mitigate potential $PM_{2.5}$ concentration enhancements in most NCP provinces. Similar findings are suggested in Hang et al. (2020), which observed enhanced secondary pollution during the COVID-19 period. The air quality impacts from the unexpected controls during the COVID-19 shutdown suggest that strengthened controls on $p\text{-}PM_{2.5}$ emissions and well-balanced reductions in NO_x and VOC emissions would be an effective strategy for further improving air quality in NCP (Xing et al., 2018).

4. Summary and Conclusion

In summary, this study developed a response-based inversion modeling framework and applied it to characterize the emission changes and associated air quality impacts during the 2019 Spring Festival and the 2020 COVID-19 pandemic shutdown. Our results indicate that the response model can effectively

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adjust the assumed prior emissions such that air quality predictions match well with observed concentrations. The model also captures the temporal variations of emissions associated with changes in meteorological conditions. The model may suffer some uncertainties from deficiencies in model chemical mechanisms (e.g., conversion of SO_2 to SO_4^{2-}), as well as the quality of prior emissions and limited coverage of observations. Difficulties are also found in estimating the NH_3 emission changes under strong NH_3-rich conditions by using the current inversion method based on the concentration of PM chemical components. However, with the continued growth in observational datasets from both surface monitors and satellite retrievals, improvements in knowledge of atmospheric science, and development of advanced assimilation technologies, the new response-based inversion model has great potential to further improve the accuracy and efficiency of emission inventory updates. The importance of reliable bottom-up inventories for defining prior emissions by sector, combined with the ability of the top-down inversion model to rapidly adjust emissions for consistency with observations, demonstrates how bottom-up and top-down emissions modeling methods are complementary.

The response model was applied in investigating the emission changes during the COVID-19 shutdown. The emission changes were estimated by comparing emissions for actual conditions with emissions for hypothetical conditions assuming that the shutdown did not occur. Emission levels during the COVID-19 shutdown period were estimated by applying the temporal profiles of sectoral emissions from the bottom-up inventory. These estimates may suffer some uncertainties associated with the temporal profiles and the assumption of no shutdown impacts during the post-shutdown period. Our results suggest that the shutdowns in 2019 and 2020 had considerable impacts on air pollutant emissions. Longer and stronger impacts are found in 2020 due to the COVID-19 pandemic compared to the Spring Festival of the previous year. The anthropogenic emissions of NO_2, SO_2, VOC, and primary $PM_{2.5}$ in NCP were reduced by 51%, 28%, 67% and 63%, respectively, due to the COVID-19 shutdown in 2020. The estimated ratio might be slightly underestimated considering the lag effects after the COVID-19 shutdown. We also

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found that emission changes associated with the shutdown periods had limited impacts on surface O_3 and $PM_{2.5}$ concentrations due to compensating effects of emission changes in different pollutants. Based on our analysis, careful controls on NO_x emission sources in NCP are recommended in combination with simultanous controls on VOC and NH_3 sources. Such a comprehensive strategy would minimize the potential negative impacts on air quality of NO_x emission reductions during VOC-limited conditions in winter. This study also illustrates that air quality improvements do not necessary follow from precursor emission reductions, and multi-pollutant nonlinear response models are therefore critical tools for representing the nonlinear relationship between emissions and concentrations in designing effective control strategies.

Data and code availability

The original data and code used in this study are available upon request from the corresponding authors.

Author contribution

JX & SL designed the methodology, conducted the analysis, and wrote the original draft. YJ conducted the WRF-CMAQ simulation. SW & DD & ZD & JH helped with the bottom-up emission inventory. YZ helped with the RSM model. All authors contribute to writing the paper.

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Competing interests

The authors declare no competing financial interests.

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446 **Table 1** Sensitivity analysis for quantifying the impacts of individual pollutant emission changes on air
447 quality

No.	Emission	Objective	Noted
Sim-1	All pollutants are used as the hypothetical emissions of Period 2H	To estimate the hypothetical concentrations without COVID impacts	oSIM
Sim-2	Same as Sim-1 except NO_x emissions are updated to actual emissions in Period 2	To estimate the impacts of NO_x emission changes on O_3 and $PM_{2.5}$ based on the difference between Sim-2 and Sim-1	ΔNO_x
Sim-3	Same as Sim-2 except VOC emissions are updated to actual emissions in Period 2	To estimate the impacts of VOC emission changes on O_3 and $PM_{2.5}$ based on the difference between Sim-3 and Sim-2	ΔVOC
Sim-4	Same as Sim-3 except NH_3 emissions are updated to actual emissions in Period 2	To estimate the impacts of NH_3 emission changes on $PM_{2.5}$ based on the difference between Sim-4 and Sim-3	ΔNH_3
Sim-5	Same as Sim-4 except SO_2 emissions are updated to actual emissions in Period 2	To estimate the impacts of SO_2 emission changes on $PM_{2.5}$ based on the difference between Sim-5 and Sim-4	ΔSO_2
Sim-6	Same as Sim-5 except primary $PM_{2.5}$ emissions are updated to actual emissions in Period 2	To estimate the impacts of primary $PM_{2.5}$ emission changes on $PM_{2.5}$ based on the difference between Sim-6 and Sim-5	Δp-$PM_{2.5}$

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Table 2 Daily emissions of five pollutants in NCP provinces based on the response model (unit: kt/day)

2019	Period 1 (29 days, Jan 1 to Jan 29)					Period 2 (20 days, Jan 30 to Feb 18)					Period 3 (41 days, Feb 19 to Mar 31)				
	NO_x	SO_2	NH_3	VOC	p-$PM_{2.5}$	NO_x	SO_2	NH_3	VOC	p-$PM_{2.5}$	NO_x	SO_2	NH_3	VOC	p-$PM_{2.5}$
Beijing	0.49	0.07	0.20	0.69	0.12	0.26	0.05	0.19	0.20	0.01	0.48	0.05	0.23	0.94	0.16
Tianjin	0.65	0.17	0.15	0.92	0.05	0.42	0.17	0.15	0.24	0.04	0.79	0.21	0.25	1.37	0.15
Hebei	5.64	2.01	1.18	3.67	1.97	3.47	1.62	1.27	1.43	1.51	5.95	1.90	2.77	6.26	1.92
Shandong	7.35	3.21	1.34	8.58	0.76	4.45	2.88	1.52	2.41	0.88	6.90	3.45	3.54	9.59	1.19
Henan	5.34	1.49	1.31	4.08	1.54	3.04	1.31	1.74	0.71	1.84	4.46	1.84	4.27	4.46	1.33
NCP	19.47	6.96	4.17	17.94	4.43	11.65	6.03	4.87	5.00	4.28	18.58	7.45	11.07	22.62	4.76

2020	Period 1 (22 days, Jan 1 to Jan 22)					Period 2 (33 days, Jan 23 to Mar 5)					Period 3 (26 days, Mar 6 to Mar 31)				
	NO_x	SO_2	NH_3	VOC	p-$PM_{2.5}$	NO_x	SO_2	NH_3	VOC	p-$PM_{2.5}$	NO_x	SO_2	NH_3	VOC	p-$PM_{2.5}$
Beijing	0.38	0.04	0.20	0.65	0.01	0.23	0.03	0.20	0.27	0.01	0.28	0.04	0.24	0.70	0.09
Tianjin	0.64	0.12	0.15	0.87	0.02	0.44	0.12	0.17	0.44	0.03	0.71	0.18	0.30	1.20	0.10
Hebei	5.28	1.34	1.18	3.12	1.73	3.15	1.16	1.54	1.92	0.81	4.97	1.67	3.49	4.72	0.75
Shandong	6.57	2.55	1.34	8.02	0.85	3.28	2.25	1.88	2.44	0.16	5.87	3.57	4.52	8.44	0.14
Henan	4.50	1.15	1.31	3.84	2.26	1.13	1.14	1.31	0.64	0.16	4.09	2.13	5.49	3.13	0.10
NCP	17.37	5.19	4.17	16.51	4.88	8.23	4.69	5.10	5.71	1.17	15.93	7.59	14.03	18.18	1.19
Δ2020-2019	-11%	-25%	0%	-8%	10%	-29%	-22%	5%	14%	-73%	-14%	2%	27%	-20%	-75%

(p-$PM_{2.5}$ = primary $PM_{2.5}$)

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455 **Table 3** The shutdown-impacts on the emission of five pollutants in NCP provinces

2019	NO_x		SO_2		NH_3		VOC		p-$PM_{2.5}$	
	kt/Day	%	kt/Day	%	kt/Day	%	kt/Day	%	kt/Day	%
Beijing	-0.23	-47%	-0.01	-21%	0.00	0%	-0.56	-73%	-0.15	-93%
Tianjin	-0.30	-41%	-0.02	-10%	0.00	0%	-0.95	-80%	-0.07	-62%
Hebei	-2.33	-40%	-0.34	-17%	0.00	0%	-3.54	-71%	-0.51	-25%
Shandong	-2.67	-37%	-0.46	-14%	0.00	0%	-6.78	-74%	-0.10	-10%
Henan	-1.85	-38%	-0.48	-27%	0.00	0%	-3.39	-83%	0.39	27%
NCP	-7.38	-39%	-1.31	-18%	0.00	0%	-15.23	-75%	-0.43	-9%

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2020	NO_x		SO_2		NH_3		VOC		p-$PM_{2.5}$	
	kt/Day	%	kt/Day	%	kt/Day	%	kt/Day	%	kt/Day	%
Beijing	-0.10	-30%	-0.01	-18%	0.00	2%	-0.39	-59%	-0.07	-85%
Tianjin	-0.24	-35%	-0.03	-18%	0.00	2%	-0.60	-58%	-0.04	-59%
Hebei	-1.98	-39%	-0.31	-21%	0.03	2%	-1.89	-50%	-0.43	-35%
Shandong	-2.95	-47%	-0.75	-25%	0.04	2%	-5.80	-70%	-0.31	-66%
Henan	-3.16	-74%	-0.76	-40%	0.03	2%	-3.10	-83%	-1.10	-87%
NCP	-8.42	-51%	-1.85	-28%	0.10	2%	-11.77	-67%	-1.95	-63%

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458 (p-$PM_{2.5}$ = primary $PM_{2.5}$)

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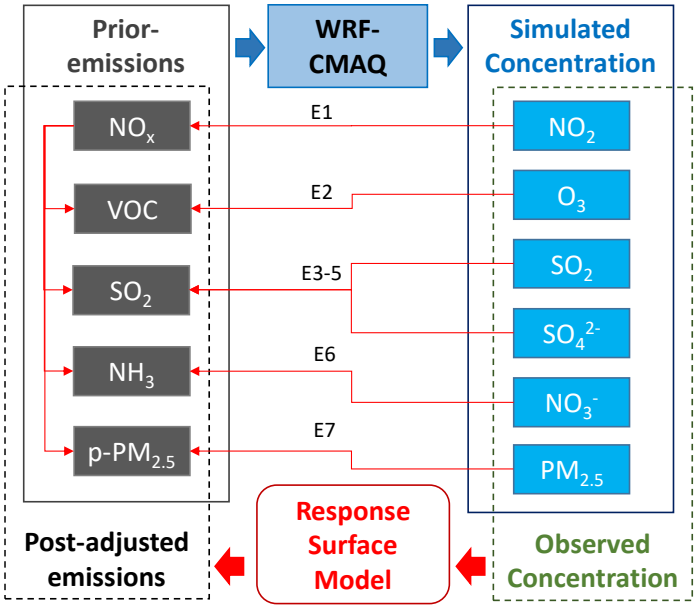

Figure 1 The response modeling framework for adjusting the emissions (the E1-7 are equations used to adjusted emissions, which are detailed in the text)

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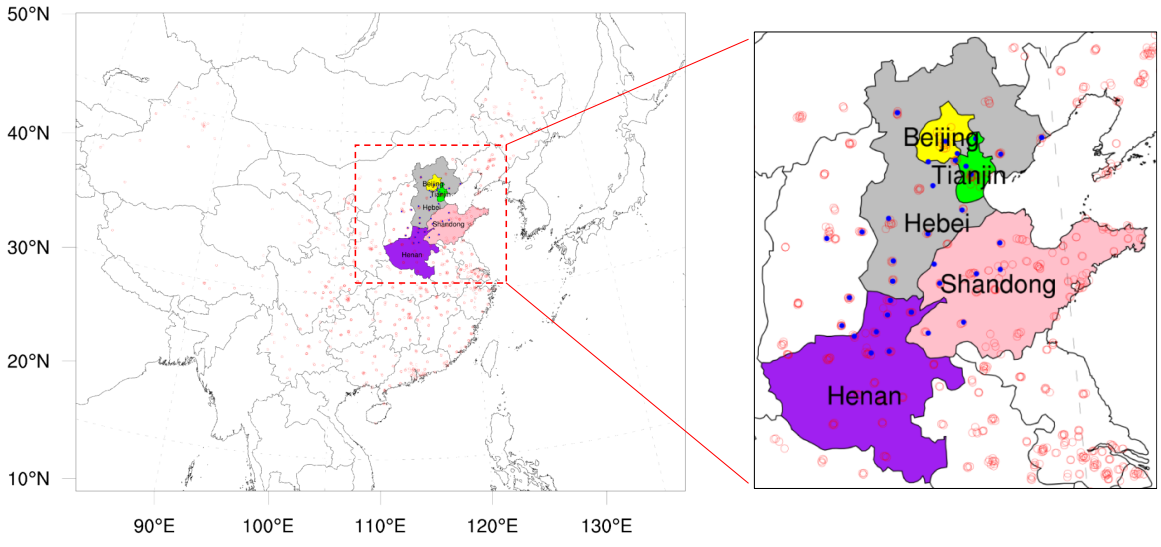

Figure 2 Simulation domain and observation sites in five provinces of North China Plain (red dots: surface monitor sites for NO_2, SO_2, O_3 and $PM_{2.5}$; blue dots: monitor sites for $PM_{2.5}$ chemical compoments)

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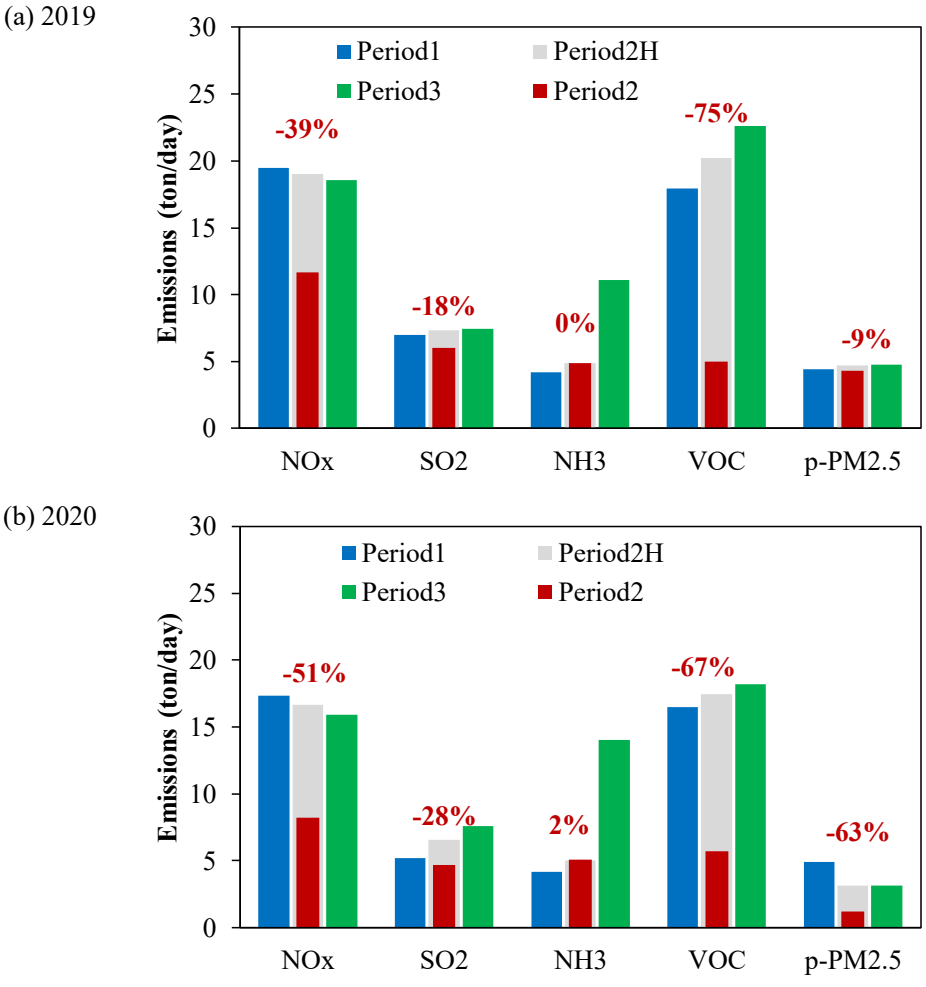

470 **Figure 3** Daily emissions during pre-shutdown (Period 1, blue), shutdown (Period 2, red), and post-
471 shutdown (Period 3, green) periods in 2019 and 2020. Period 2H (grey) is the hypothetical emissions
472 without reduced activity during the 2019 holiday or 2020 COVID-19 shutdown; the red number
473 indicates the percent change in emissions due to the shutdown in Period 2.

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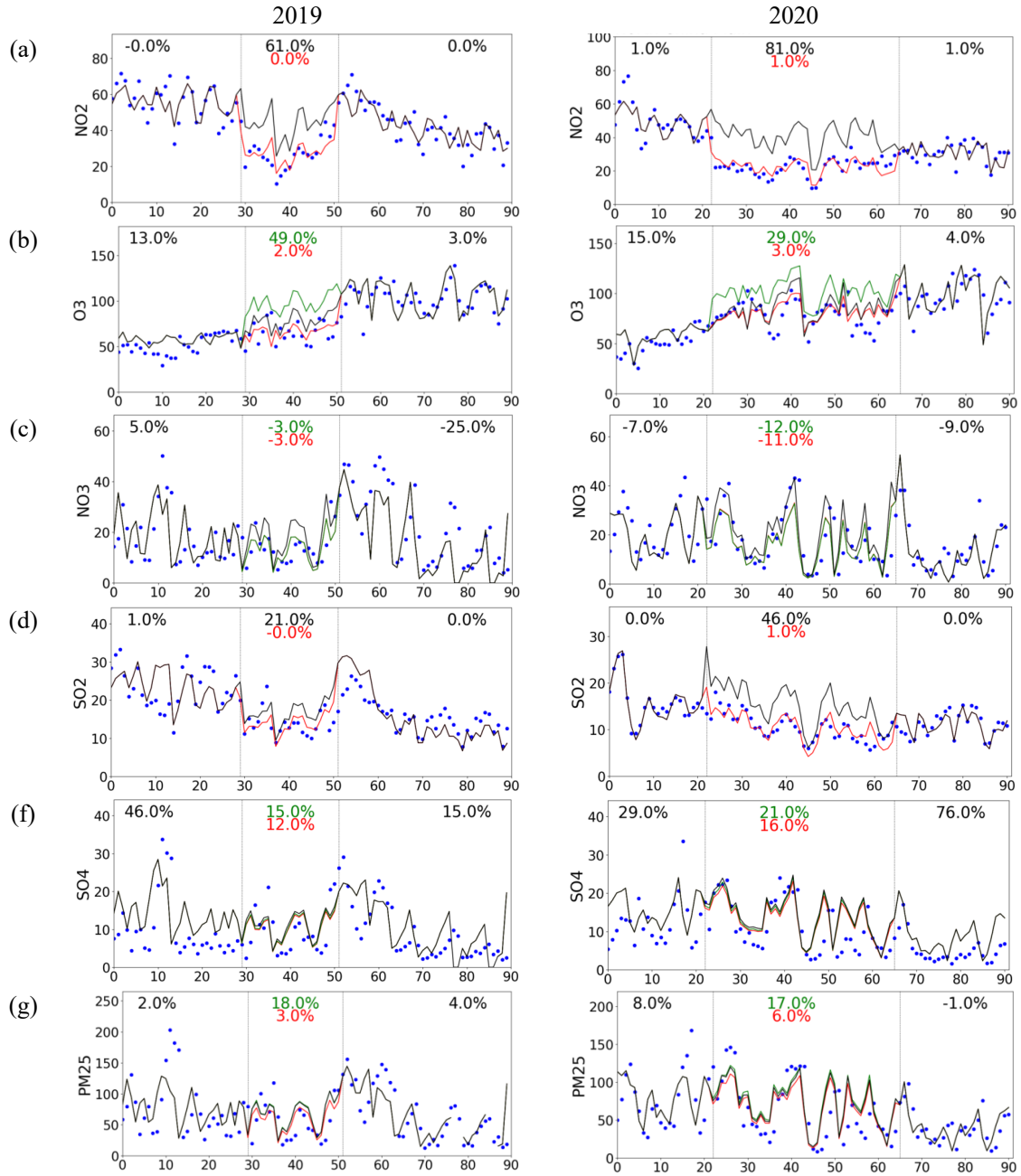

Figure 4 Comparison of the simulated and observed average concentrations in NCP (the percentage numbers indicate the normalized mean biases in hypothesis and actual simulations respectively for Period 2. Blue dots: observations; Black line: simualtions using adjusted emission with no consideration of shutdown influcences; Red line: simualtions using adjusted emission with consideration of shutdown influcences; Green line: simualtions using adjusted emission with consideration of shut-down influcences without VOC for O_3, NH_3 for NO_3^-, SO_2 for SO_4^{2-}, primary $PM_{2.5}$ for $PM_{2.5}$; unit: μg m^{-3})

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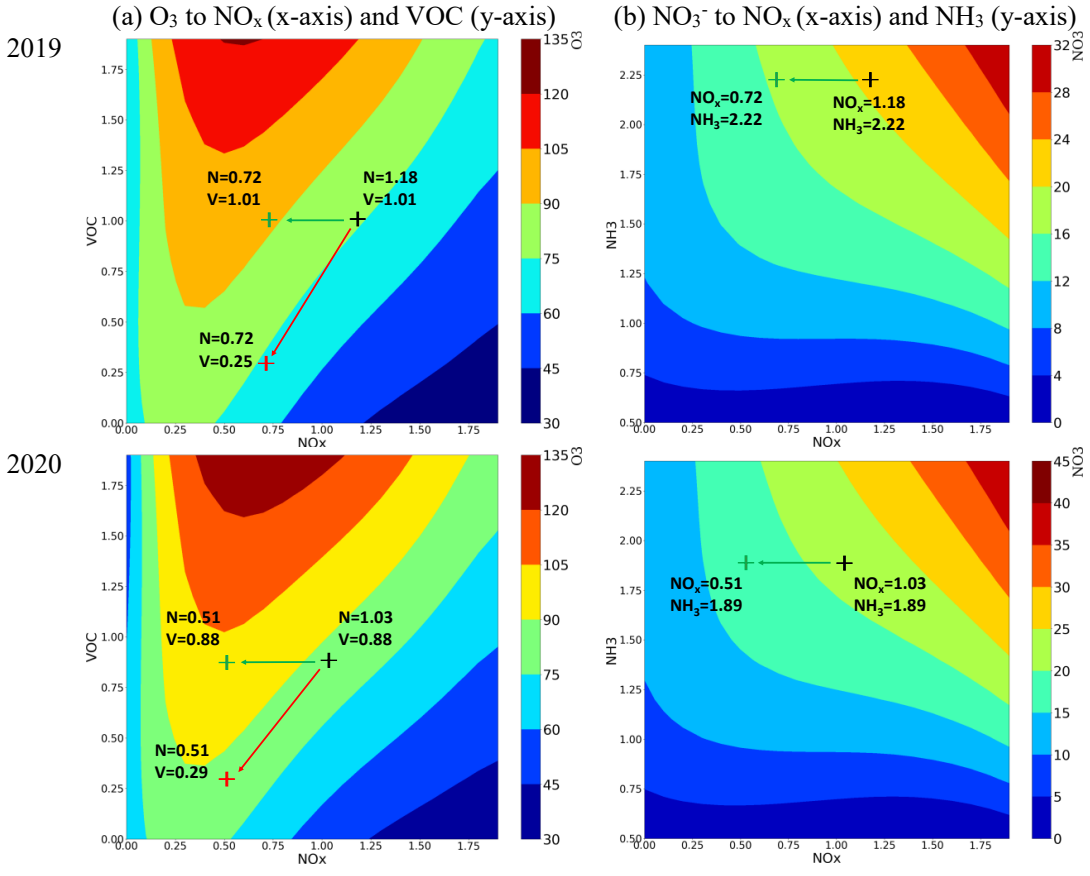

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483 **Figure 5** Implication of emission changes from the O_3 and NO_3^- response isopleths during shutdowns
484 (the axes indicate emission ratios relative to the prior emissions; black symbol: adjusted emission ratios
485 with no consideration of shutdown; red symbol: adjusted emission ratios with consideration of
486 shutdown; green symbol: adjusted emission ratios without considering simutanous VOC changes for O_3,
487 and NH_3 changes for NO_3; backgroud color: O_3 and NO_3^- concentrations, μg m^{-3})

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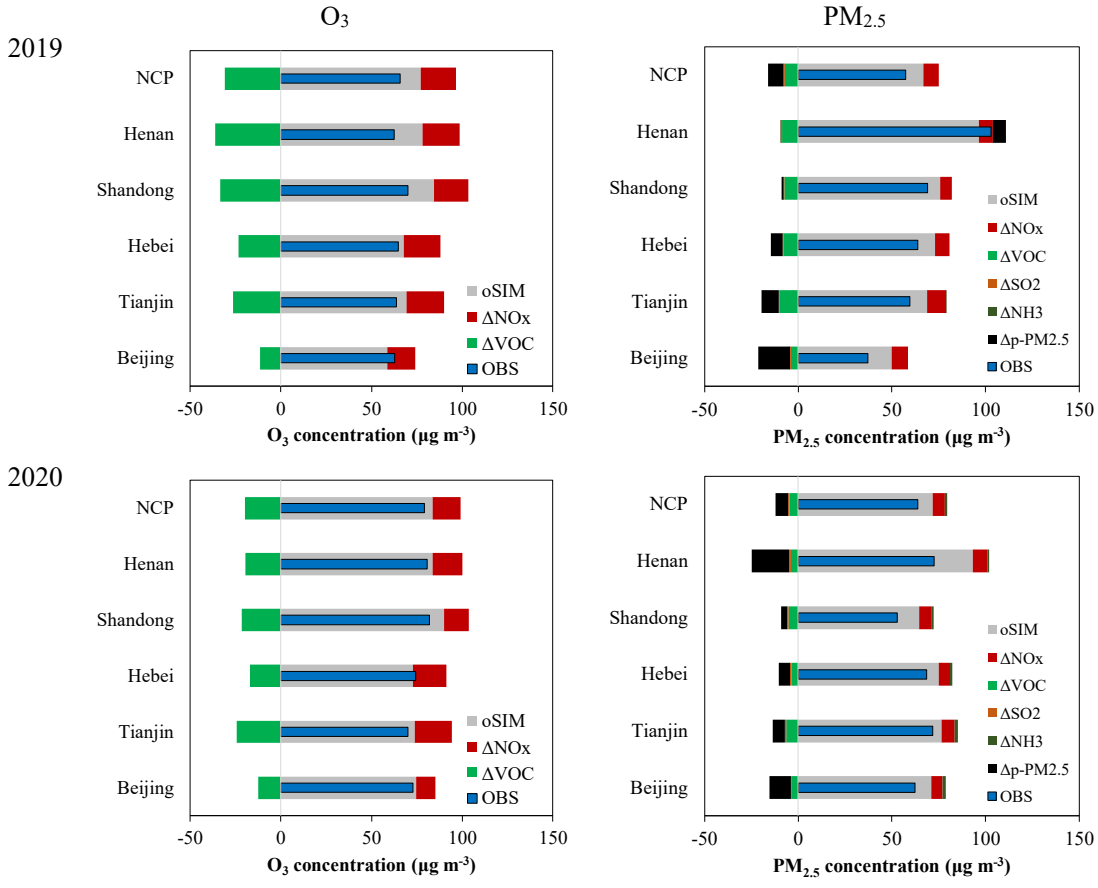

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491 **Figure 6** Contributions to the changes of O_3 and $PM_{2.5}$ concentrations during Period-2 (OBS:
492 observation; oSIM: no consideration of shutdown; ΔNO_x: impacts due to the change of NO_x emissions;
493 ΔVOC: impacts due to the change of VOC emissions; ΔNH_3: impacts due to the change of NH_3
494 emissions; ΔSO_2: impacts due to the change of SO_2 emissions; $\Delta p\text{-}PM_{2.5}$: impacts due to the change of
495 primary $PM_{2.5}$ emissions)