Response to Reviewer #1

General Comments

This manuscript presents a significant study examining the impacts of meteorology and emission reductions on PM2.5 levels during the COVID-19 lockdown in the North China Plain (NCP). The authors utilize the WRF-Chem model to investigate the complex interactions between anthropogenic emissions, meteorology, and air quality, revealing important regional disparities in PM2.5 responses between the Northern and Southern NCP. The analysis of how adverse meteorological conditions in the Northern NCP negated the benefits of emission reductions is particularly noteworthy. This manuscript aligns with the scope of ACP, and the methodology is sound. However, there are several areas that require enhancement, particularly in clarifying the research objectives, providing more detail in the methodology, and including the rationale for the selected model and specific parameters. I will recommend acceptance of the manuscript after the following minor concerns are addressed.

We appreciate the positive feedback and constructive suggestions. We have carefully reviewed the comments and taken steps to enhance the manuscript. In response, we have made the following revisions and clarifications: (1) Clarifying the research objectives; (2) Providing more detail in the methodology; and (3) Rationale for model selection and specific parameters. We respond to the concerns in detail below.

We respond to each specific comment in detail below. The reviewers' comments are shown in *black italics*. Our replies are in indented black text, and the modified text is in blue. The annotated line numbers refer to the revised copy of the manuscript.

Major comments：

Major.1 *The relationship between air pollution and emission reduction during the COVID-19 lockdown in China is a notable case in air pollution control; however, several existing studies exist on this topic. It is recommended that the author further enhance the discussion by more robustly comparing the results of this study with prior research, thereby underscoring the distinctive contributions of this paper.*

Thank you for your valuable feedback on the novelty of our study. We have revised the manuscript to highlight our approach's unique contributions, particularly the methodologies used and the regional insights provided. Specifically, we clarified how using the WRF-Chem model with sensitivity experiments (e.g., SEN_METEO_EMIS) and factor separation methods offers a new perspective on the relationship between meteorology and emission reductions. Additionally, we emphasized our findings on the differing responses between the northern and southern North China Plain (NCP), which enhanced the understanding of air quality dynamics during the lockdown.

[Lines 24 in *Abstract*]:

Our analysis highlights a marked regional contrast: in the Northern NCP (NNCP), adverse meteorology largely offset emission reductions, resulting in $PM_{2.5}$ increases of 30 to 60 μg m^{-3} during haze episodes. Conversely, the Southern NCP (SNCP) benefited from favourable meteorological conditions that lowered $PM_{2.5}$ by 20 to 40 μg m-3, combined with emission reductions. These findings emphasize the critical role of meteorology in shaping the air quality response to emission changes, particularly in regions like the NNCP, where unfavourable weather patterns can counteract the benefits of emission reductions. Our study provides valuable insights into the complex interplay of emissions, meteorology, and pollutant dynamics, suggesting that adequate air quality strategies must integrate emissions controls and meteorological considerations to address regional variations effectively.

[Lines 79 in *Introduction*]:

We emphasize the localized differences in how meteorological conditions and emission reductions affect air quality within the North China Plain, specifically between the Northern North China Plain (NNCP) and Southern North China Plain (SNCP). Utilizing the WRF-Chem model, we conducted detailed sensitivity experiments that allowed us to isolate and quantify the individual and combined impacts of emissions and meteorology on air quality, which can deepen the understanding of air quality dynamics in different regional contexts.

[Lines 464 in *Conclusions*]:

Previous studies have primarily focused on the overall impacts of meteorological conditions and emission reductions on air quality across the North China Plain and even nationwide. We emphasize the localized differences in how meteorological conditions and emission reductions affect air quality within the North China Plain, specifically between the NNCP and SNCP. Our findings underscore the critical role that meteorological conditions play in modulating the effects of emission reductions. The combination of unfavourable meteorological factors and emission reductions in the NNCP led to overall increases in $PM_{2.5}$ levels, with significant increases during haze episodes. Meanwhile, in the SNCP, meteorological conditions and emission reductions consistently contributed to lower $PM_{2.5}$ concentrations.

***Major.2** The authors have distinctly defined two regions of interest, namely the NNCP and the SNCP. Please elaborate on the spece two regions were designated as depicted* *in Figure 1? What were the crucial factors that the authors took into account when defining the boundaries of the two regions?*

Thank you for the thoughtful comment. Strict geographical limits do not bind the delineation of the NNCP and SNCP; instead, it is based on representative features and differences critical for a comprehensive assessment of geographical, meteorological, and emission characteristics. The boundaries were drawn to effectively capture the distinct local attributes of each region, allowing for meaningful comparisons and insights into air quality dynamics. Regional differentiation is crucial for understanding the air quality dynamics across the NCP.

[Lines 96 in *Section 2.1*]:

We defined these regions by thoroughly analyzing geographical features, weather conditions, and emission sources. The NNCP, which generally includes the cities in the Beijing-Tianjin-Hebei (BTH) area, is surrounded by mountains and elevated terrain to the north and west. These features make it harder for pollutants to disperse, leading to pollutant buildup, especially in winter when stagnant atmospheric conditions dominate (Feng et al., 2020; Li et al., 2019). On the other hand, the SNCP is characterized by lower elevations and broad plains, which help disperse pollutants due to more vital wind patterns and higher planetary boundary layer heights (Huang et al., 2021). The emissions in these two regions also differ significantly. The NNCP is mainly affected by concentrated urban and industrial emissions from the BTH area. At the same time, the SNCP has a broader variety of sources, including industrial and agricultural emissions, creating a more diverse pollutant profile(Zheng et al., 2021). These differences in geography, weather, and emissions provide a basis for studying how meteorological factors and emission reductions affect air quality differently across the NCP (**Figure 1**). By examining these sub-regions separately, we can better understand how air quality interventions vary in effectiveness across different areas.

[*References*]

Feng, J., Liao, H., Li, Y., Zhang, Z., & Tang, Y. (2020). Long-term trends and variations in haze-related weather conditions in north China during 1980–2018 based on emission-weighted stagnation intensity. Atmospheric Environment, 240, 117830.

Li, J., Liao, H., Hu, J., & Li, N. (2019). Severe particulate pollution days in China during 2013–2018 and the associated typical weather patterns in Beijing-Tianjin-Hebei and the Yangtze River Delta regions. Environmental Pollution, 248, 74-81.

Huang, X., Ding, A., Gao, J., Zheng, B., Zhou, D., Qi, X., & He, K. (2021). Enhanced secondary pollution offset reduction of primary emissions during COVID-19 lockdown in China. National Science Review, 8(1), nwaa137.

Zheng, B., Zhang, Q., Geng, G., Chen, C., Shi, Q., Cui, M., ... & He, K. (2021). Changes in China's anthropogenic emissions and air quality during the COVID-19 pandemic in 2020. Earth System Science Data, 13(6), 2895-2907.

Major.3 *The authors mainly discuss the spatial differences in the impact of emissions and meteorology on the total PM2.5 concentrations, how about the chemical components within PM2.5, particularly secondary inorganic and organic aerosols? Do these chemical components exhibit the same spatial variation characteristics?*

Thank you for raising this critical point. We examined the spatial variations of chemical components within $PM_{2.5}$ on how the chemical components and added descriptions in the text.

[Lines 362 in *Section 3.3*]:

These meteorological effects also impact secondary aerosols, including secondary organic aerosols (SOAs) and secondary inorganic aerosols (SIAs), with substantial variability between the NNCP and SNCP regions. In the NNCP, stagnant conditions and reduced boundary layer heights limited pollutant dispersion, contributing to the accumulation of SOAs and SIAs. High humidity further exacerbated the formation of secondary aerosols, resulting in elevated concentrations (**Figure S10**). Conversely, the SNCP benefited from higher PBLH (**Figure S7**) and dynamic wind patterns(**Figure 4a**), which enhanced the dispersion of both primary and secondary aerosols, reducing their concentrations. Due to the very low emissions of biogenic secondary organic aerosol (BSOA) precursors during wintertime(Guenther et al., 2012), the BSOA contribution to $PM_{2.5}$ concentrations is insignificant, averaging less than 2 μg m^{-3} throughout the study period (**Figure S11a**). The average BSOA accounted for less than 2% of total $PM_{2.5}$ mass in the BASE simulations (**Figure S11b**), indicating a minor role for biogenic emissions in shaping wintertime air quality.

[Lines 377 in *Section 3.4*]:

In addition to the overall $PM_{2.5}$ reductions, emission controls significantly impacted SOAs and SIAs in the NNCP and SNCP (**Figure S10b, 10d**). The reductions in SOAs and SIAs were driven by decreased availability of precursors such as VOCs for SOAs and SO_2 and NO_x for SIAs(Huang et al., 2021).

[Figure S10]

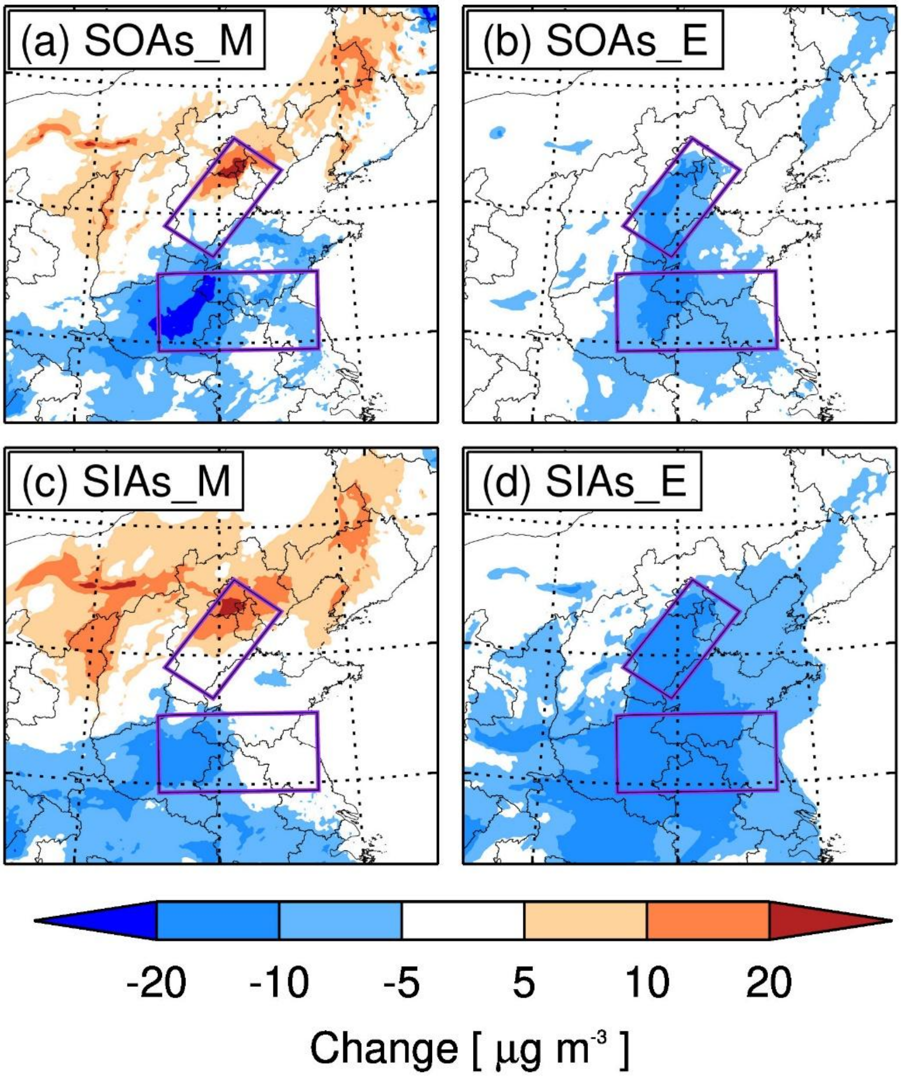

Figure S10. Comparison of simulated changes in chemical components during the study period between the "BASE" scenario and two sensitivity cases: (a,c) " METEO" and (b,d) "EMIS". The chemical components include (a,c) secondary organic aerosols and (b,d) secondary inorganic aerosols (SIAs), including sulfate, nitrate, and ammonium.

Minor comments：

Minor.1 *Provide a rationale for using the WRF-Chem model, highlighting its advantages for simulating meteorological and chemical interactions. Include specific parameters used in the WRF-Chem model simulations, such as resolution, boundary conditions, and initial conditions. This detail will help readers understand the modeling approach and assess its performance*

Thank you for your constructive feedback. We provided a clear rationale for using the WRF-Chem model and detailing its setup parameters to facilitate a better understanding of our modeling approach and its strengths in capturing the complex interactions between meteorological processes and chemical transformations.

[Lines 143 in *Section 2.2*]:

We employed a specific version (version 3.5.1) of the WRF-Chem model (Grell et al., 2005). We chose the WRF-Chem model because it can simulate coupled atmospheric processes, including emissions, transport, chemical transformations, and aerosol-cloud interactions. This "online" approach allows for dynamic feedback between meteorological conditions and air pollutants. It is well-suited for assessing the interplay between emission reductions and meteorology on $PM_{2.5}$ concentrations during the COVID-19 lockdown period. The model's ability to simultaneously simulate meteorology and chemistry provides advantages over models that treat these processes separately, ensuring that interactions such as aerosol-radiation and aerosol-cloud effects are effectively captured (Li et al., 2011).

Further details regarding the model settings, initial and lateral meteorological and chemical fields, and anthropogenic and biogenic emission inventory(**Table S1**). We used physical schemes of the WRF single-moment(WSM) 6-class graupel microphysical scheme(Hong and Lim, 2006), the Mellor–Yamada–Janjic (MYJ) turbulent kinetic energy planetary boundary layer scheme (Janić, 2001), the unified Noah land-surface model (Chen and Dudhia, 2001) and the Monin-Obukhov surface layer scheme (Janić, 2001).

[Lines 165 in *Section 2.2*]:

The simulation domain, centered at (116 °E, 38 °N), consisted of 300 × 300 horizontal grid cells with a 6 km resolution (**Figure 1**). The vertical resolution consisted of 35 levels, extending from the surface to 50 hPa, allowing for a detailed representation of boundary layer processes and pollutant dispersion. The initial and boundary meteorological conditions were derived from the National Centers for Environmental Prediction (NCEP) Final (FNL) reanalysis data at a 1° × 1° spatial resolution and six-hour temporal intervals (Kalnay et al., 2018). Chemical initial and boundary conditions were interpolated from the CAM-Chem (Community Atmosphere Model with Chemistry) global chemistry model(Danabasoglu et al., 2020). The anthropogenic emissions inventory for 2020 was based on a bottom-up approach, incorporating near-real-time data (Zheng et al., 2021), and biogenic emissions were computed online using the Model of Emissions of Gases and Aerosols from Nature (MEGAN)(Guenther et al., 2006). For the episode simulations, the spin-up time is 3 days.

[*References*]

Hong, S.-Y., and Lim, J.-O. J.: The WRF single-moment 6-class microphysics scheme (WSM6), J. Korean Meteor. Soc, 42, 129-151, 2006.

Janić, Z. I.: Nonsingular implementation of the Mellor-Yamada level 2.5 scheme in the NCEP Meso model, US Department of Commerce, National Oceanic and Atmospheric Administration, National Weather Service, National Centers for Environmental Prediction, 2001.

Chen, F., and Dudhia, J.: Coupling an advanced land surface–hydrology model with the Penn State–NCAR MM5 modeling system. Part II: Preliminary model validation, Monthly Weather Review, 129, 587-604, 2001.

Emmons, L. K., Schwantes, R. H., Orlando, J. J., Tyndall, G., Kinnison, D., Lamarque, J.-F., et al., (2020). The Chemistry Mechanism in the Community Earth System Model version 2 (CESM2). Journal of Advances in Modeling Earth Systems, 12, e2019MS001882, https://doi.org/10.1029/2019MS001882

[*Table S1*]:

Table S1 Model configuration for the simulation domain, meteorological schemes, chemical mechanisms, initial and lateral conditions, and emission inventories.

Domain	
Size	300 × 300 horizontal grid cells
Center	116°E, 38° N
Horizontal resolution	6 km × 6 km
Vertical resolution	35 vertical levels, uneven intervals, spacing ranging from ~50 m near the surface, ~500 m at 2.5 km above the ground level, and more than 1 km at 14 km above the ground level
Meteorology	
Microphysics scheme	WSM 6-class grapple microphysics scheme (Hong and Lim, 2006)
Boundary layer scheme	MYJ PBL scheme (Janjić, 2002)
Surface layer scheme	Monin-Obukhov surface layer scheme (Janjić, 2002)
Land-surface scheme	Noah land-surface model (Chen and Dudhia, 2001)
Longwave radiation scheme	Goddard (Dudhia, 1989)
Shortwave radiation scheme	Goddard (Dudhia, 1989)
Dry deposition	Wesely (1989)
Wet deposition	CMAQ (Binkowski and Roselle, 2003)
Chemistry	
Gas phase chemistry	SAPRC99 chemical mechanism (Binkowski and Roselle, 2003)
Inorganic aerosols	ISORROPIA version 1.7 (Nenes et al., 1998)

Secondary organic aerosol	Nontraditional VBS parametrization (Li et al., 2011)
Photolysis rates	FTUV radiation transfer model (Tie et al., 2003)
Boundary and initial conditions	
Meteorological	NCEP FNL 6-hr 1° × 1° analysis data
Chemical	CAM-chem 6-hr outputs
Emission inventory	
Anthropogenic	MEIC (Zhang et al. 2009; Li et al., 2017)
Biogenic	MEGAN (Guenther et al., 2006)

Minor.2 *Present percentage reductions in emissions during the lockdown to contextualize the observed* $PM_{2.5}$ *changes, enhancing the understanding of emission effectiveness.*

We revised the manuscript to include specific percentage reductions in emissions during the lockdown. Thank you.

[Lines 185 in *Section 2.2*]:

In the EMIS experiment, we used the anthropogenic emission inventory from the BASE case. Still, we excluded any abrupt decreases associated with anthropogenic emission reductions during the COVID-19 lockdown period 2020, following the provincial emission reduction ratios provided by Huang et al. (2021) (**Table S2**).

[Table S2]:

Table S2 Provincial emission reduction ratios during the COVID-19 lockdown period in 2020 in the study area.

Province \ Species	CO	NO_x	SO_2	VOCs	$PM_{2.5}$	BC	OC
Beijing	22%	45%	26%	45%	18%	46%	8%
Tianjin	21%	38%	20%	41%	14%	22%	6%
Hebei	15%	45%	16%	36%	12%	17%	5%
Anhui	14%	56%	22%	31%	11%	22%	4%
Inner Mongolia	14%	29%	15%	34%	13%	16%	6%
Shaanxi	19%	45%	18%	34%	13%	22%	5%
Hubei	19%	55%	23%	35%	16%	23%	10%

Jilin	16%	39%	23%	34%	13%	18%	5%
Liaoning	21%	40%	28%	36%	16%	28%	8%
Henan	23%	57%	22%	41%	18%	35%	8%
Shandong	23%	50%	25%	39%	19%	35%	9%
Jiangsu	23%	50%	26%	41%	16%	35%	7%
Shanghai	35%	48%	42%	45%	34%	54%	42%

Minor.3 *In section 3.1, the formulas from 1 to 3 are garbled, please correct them.*

Thank you for your comment. We have reviewed and corrected the formulas in Section 3.1. Additionally, these formulas have been moved to the Supplementary Material (Text S1) to improve clarity and organization.

[Lines 128 in *Section 2.1*]:

We validated the final emission inventory using statistical parameters, including normalized mean bias (*NMB*), index of agreement (*IOA*), and correlation coefficient (*r*) (**Text S1**).

[Text S1]:

Text S1 Statistical methods for comparisons

We assessed the model performance using several statistical parameters, including normalized mean bias (*NMB*), index of agreement (*IOA*), and correlation coefficient (*r*), to compare simulations against observational data. The evaluated variables encompass air pollutants such as $PM_{2.5}$, O_3, NO_2, SO_2, and CO concentrations within the NNCP and SNCP regions. $PM_{2.5}$ components, including organic, nitrate, sulfate, and ammonium, are also assessed at the IAP monitoring site. These statistical metrics provide a quantitative measure of how well the model reproduces the observed data, offering insights into its accuracy and reliability in simulating the atmospheric conditions and pollutant levels during the specified period.

$$NMB = \frac{\sum_{i=1}^{N}(P_i - O_i)}{\sum_{i=1}^{N} O_i} \quad (1)$$

$$IOA = 1 - \frac{\sum_{i=1}^{N}(P_i - O_i)^2}{\sum_{i=1}^{N}(|P_i - \overline{O}| + |O_i - \overline{O}|)^2} \quad (2)$$

$$r = \frac{\sum_{i=1}^{N}(P_i - \overline{P})(O_i - \overline{O})}{[\sum_{i=1}^{N}(P_i - \overline{P})^2 \sum_{i=1}^{N}(O_i - \overline{O})^2]^{\frac{1}{2}}} \quad (3)$$

where P_i and O_i represent the calculated and observed variables, respectively. N stands for the total number of predictions for comparison, and $\overline{O}$ and $\overline{P}$ denote the average observations and simulations, respectively. The *IOA* ranges from 0 to 1, where a value of 1 indicates perfect agreement between the predictions and observations. The *r* ranges from -1 to 1, 1 indicating perfect spatial consistency between the observations and predictions.

Minor.4 *Please standardize the subscript for PM2.5 in the manuscript.*

We have reviewed and standardized the subscript for $PM_{2.5}$ throughout the manuscript to ensure consistency. Thank you for your careful attention to detail.

Minor.5 *Coloured or marked text in *.pdf manuscript file is not allowed. Please provide a clean version of *pdf manuscript file (with black text) with the next revision.*

Changed as suggested. Thank you.