Response to Reviewer #2

General Comments

The paper employed WRF-Chem to simulate PM2.5 formation in the North China Plain (NCP) during a lockdown period (January 21y 21 – February 16ry 16, 2020) under three scenarios: baseline, SEN_METEO, and SEN_EMIS. The SEN_METEO case replaced baseline meteorology with 2015-2019 mean climatology, while SEN_EMIS used baseline meteorology but substituted emissions with a no-lockdown scenario. By comparing their results, the study explores the impacts of meteorology and emission reductions on PM2.5 levels. Results indicate that, in the northern NCP, meteorological conditions had a stronger influence on PM2.5 levels than emission reductions, whereas, in the southern NCP, the benefits of emission reductions were more significant.

Thank you for recognizing the critical components of our study. Your constructive feedback will significantly strengthen our manuscript. We respond to your 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：

Overall, this study presents a solid approach with a well-evaluated model, but I have several concerns that need to be addressed before recommending this paper for publication:

Major.1 *The title used "insights from 6-year simulations," but the manuscript appears to focus on one-month simulations for Jan-Feb 2020. It would be helpful to clarify the source of this "6-year" claim.*

Thank you for your constructive feedback. The phrase "insights from six-year simulations" in the original title was intended to highlight the climatological averages from 2015 to 2019, which provide a critical baseline for understanding the $PM_{2.5}$ dynamics during the one-month COVID-19 lockdown period. To address this and ensure clarity, we have revised the title and added detailed explanations throughout the manuscript.

[*Title*]:

"Impacts of meteorology and emission reductions on haze pollution during the Lockdown in the North China Plain"

[Lines 189 in *Sect 2.2*]:

In the METEO case, we applied the same emission inventory as the BASE case but with averaged meteorological conditions from 2015 to 2019. These mean meteorological fields were derived by averaging key meteorological variables (**Text S2**).

[*Text S2*]:

Text S2 Mean meteorology from 2015 to 2019

This study's mean meteorology field data was derived by averaging key meteorological variables (e.g., temperature, wind speed, relative humidity, and pressure) from 2015 to 2019. Given that the vertical levels in the NCEP FNL data varied across different years, we did not average the original data directly. Instead, we processed the data using the WRF Preprocessing System (WPS) to ensure consistency. Specifically, we ran WPS yearly to generate the met_em* files containing processed meteorological variables at uniform vertical levels and grid resolution. We then averaged these met_em* files across the six years at each grid point and pressure level, which helped preserve the atmospheric variables' vertical structure and physical coherence. This approach maintained a realistic representation of the atmospheric state by accounting for the multi-year variability while ensuring that the averaged fields were consistent with the WRF-Chem grid resolution. As the WPS processing already matched the data to the model's spatial resolution, no additional interpolation was required, thus ensuring the physical and spatial consistency of the averaged climatological fields used in the WRF-Chem simulations. This multi-year climatological averaging was designed to capture the typical variations in initial and boundary meteorological conditions. This approach provided a robust and representative baseline for multiple years, effectively minimizing the influence of anomalies or extreme weather events characteristic of any individual year.

Major.2 *In section 3.5, the discussion on "combined effects of meteorology and emission reduction" seems to involve a simple addition of the individual impacts of emissions and meteorology. This approach could be misleading. I suggest either comparing the magnitudes of these impacts separately or, if discussing combined* *effects, perform a simulation that perturbs both emissions and meteorology simultaneously. Alternatively, you could have a separate section discussing how emission impacts vary under different meteorological conditions (EP1 vs. EP2 vs. non-haze episodes), as this question inherently addresses the coupled effects of emissions and meteorology.*

Thank you for your valuable suggestion. In response, we added a new simulation that simultaneously perturbs emissions and meteorological conditions (EMIS_METEO case). We also evaluated the combined and interactive effects of these factors more comprehensively. The data and analysis have been accordingly updated.

[Lines 183 in *Sect 2.2*]:

The other three groups are sensitivity simulations, which include the emission condition-sensitive simulation (EMIS), the meteorology condition-sensitive simulation (METEO), and the combined emission and meteorology condition-sensitive simulation (EMIS_METEO). 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**). In the METEO case, we applied the same emission inventory as the BASE case but with averaged meteorological conditions from 2015 to 2019. These mean meteorological fields were derived by averaging key meteorological variables (**Text S2**). For the EMIS_METEO case, we used the emission inventory from the EMIS case and the mean meteorological conditions from the METEO case.

The comparison between the BASE and EMIS cases allowed us to evaluate the impact of sudden reductions in anthropogenic emissions on $PM_{2.5}$ levels. The comparison between the BASE and METEO cases provided a stable reference point by reducing the influence of anomalies or fluctuations in meteorological conditions from any year, enabling a comprehensive evaluation of the effects of meteorological factors on $PM_{2.5}$ levels. Finally, comparing the BASE and EMIS_METEO cases enabled a thorough assessment of the combined impact of emission reductions and meteorological conditions on $PM_{2.5}$ levels. Additionally, we analyzed the coupled effects between emission reductions and meteorological factors using a factor separation approach (**Text S3**).

[Text S3]:

Text S3 Factor separation technique to analyze coupled effects

In nonlinear atmospheric systems, factors often interact in complex ways, making it hard to identify their individual impacts. To address this, we used the factor separation approach (FSA) by Stein and Alpert (1993), which helps separate the direct effects of each factor from their interactions. In this study, we focused on emissions and meteorological changes, aiming to understand both their individual effects and how they interact. The pure contributions from emission reductions and meteorological changes are represented as follows:

$$f'_{EMIS} = f_{EMIS} - f_{BASE} \tag{4}$$

$$f'_{METEO} = f_{METEO} - f_{BASE} \tag{5}$$

When emissions and meteorological conditions are considered, the total impact includes their individual contributions and coupled. The combined effect is expressed as:

$$f_{EMIS\_METEO} = f'_{EMIS} + f'_{METEO} + f'_{EMIS\_METEO} + f_{BASE} \tag{6}$$

To quantify the coupled effects between emissions and meteorological changes, we use the following equation:

$$\begin{aligned} f'_{EMIS\_METEO} &= f_{EMIS\_METEO} - f'_{EMIS} - f'_{METEO} - f_{BASE} \\ &= f_{EMIS\_METEO} - (f_{EMIS} - f_{BASE}) - (f_{METEO} - f_{BASE}) - f_{BASE} \\ &= f_{EMIS\_METEO} - f_{EMIS} - f_{METEO} + f_{BASE} \qquad (7) \end{aligned}$$

This final form helps us understand how the combined effects relate to individual impacts and the baseline. Using the FSA, we can clearly see how emissions and meteorological conditions contribute to changes in the atmosphere.

[Lines 411 in *Sect. 3.5*]:

3.5 Combined and coupled effects of meteorology and emission reduction on $PM_{2.5}$

The combined and coupled effects of meteorological conditions and emission reductions during the COVID-19 lockdown significantly influenced $PM_{2.5}$ concentrations in the NNCP and SNCP. These effects varied depending on the region and the interaction between meteorological factors and reduced emissions, aligning with findings from similar studies in urban areas during lockdowns that emphasize the role of meteorology in modulating pollution levels (Huang et al., 2021).

The results highlight contrasting impacts between the NNCP and SNCP regarding combined effects. In the NNCP, the combined effects of weather conditions and emission reductions led to noticeable increases in $PM_{2.5}$ levels during the study period. These combined effects raised $PM_{2.5}$ concentrations by 10 to 75 μg m^{-3}, especially in the northern regions (**Figure 7a**). Even during non-haze periods, this combined influence caused $PM_{2.5}$ to increase by 10 to 40 μg m^{-3} (**Figure 7b**). The impact was even more significant during haze episodes. For example, during EP2, $PM_{2.5}$ levels increased by exceeding 100 μg m^{-3} (**Figure 7d**), showing that adverse weather conditions, like stagnant winds and low boundary layer heights, negated the benefits of emission reductions. In the SNCP, the combined effects led to significant decreases in $PM_{2.5}$ levels. Throughout the study period, $PM_{2.5}$ concentrations dropped by 30 to 100 μg m^{-3} (**Figure 7a**). The positive impact of emission reductions was most apparent during haze episodes, where the combined effects during EP2 led to reductions exceeding 100 μg m^{-3} in some areas (**Figure 7d**).

The factor separation analysis provided critical insights into the combined effects of emissions and meteorology (**Figure S13**). During non-haze periods(**Figure S13b**), the coupled effects contributed to a $PM_{2.5}$ increase of 5 to 10 μg m^{-3} in the NNCP. Still, they increased to 10 to 50 μg m^{-3} during haze episodes, particularly during EP2 (**Figure S13d**). This indicates that unfavorable meteorological conditions limited the effectiveness of emission reductions in the NNCP. As a result, emission reductions, though beneficial, were insufficient to improve air quality significantly under these conditions. This finding aligns with previous studies showing that areas with adverse weather conditions often struggle to improve air quality despite emission reductions (Feng et al., 2021). Such conditions hinder pollutant dispersion, making it difficult for emission reductions to decrease PM2.5 concentrations significantly (Zheng et al., 2021).

In contrast, the SNCP exhibited more vital coupled effects between meteorology and emission reductions. During haze episodes, this interaction led to an additional 10 to 50 μg m^{-3} reduction in $PM_{2.5}$ levels (**Figure S13c, S13d**). The coupled effects between favorable meteorological conditions and reduced emissions greatly enhanced $PM_{2.5}$ decreases, especially during the EP2 haze episode. This more substantial interaction in the SNCP highlights how favorable meteorology can amplify the impact of emission reductions, leading to more vital improvements in air quality. Previous research has shown that when meteorology supports pollutant dispersion, the benefits of emission reductions are maximized, resulting in significant decreases in pollutant concentrations(Xu et al., 2020b; Zhang et al., 2021).

The station-averaged regional contributions also reveal differences between the NNCP and SNCP during the COVID-19 lockdown (**Figure 8**). In the NNCP, adverse meteorological conditions dominated, driving significant $PM_{2.5}$ increases of 60 to 90 μg m^{-3} during haze episodes. In comparison, emission reductions contributed more modest decreases of 20 to 40 μg m^{-3}. Coupled effects added only 10 to 15 μg m^{-3} in reductions, insufficient to offset the impact of poor weather(**Figure 8a**). Conversely, in the SNCP, emission reductions had a more substantial effect, with $PM_{2.5}$ levels decreasing by 30 to 50 μg m^{-3} during haze episodes, as meteorology and emissions worked synergistically. Coupled effects in the SNCP contributed an additional 15 to 20 μg m^{-3} in reductions, highlighting a more vital interaction between favorable meteorology and emissions controls (**Figure 8b**). Daily contributions support these trends, with the NNCP seeing persistent increases, while the SNCP experienced consistent reductions, especially during EP2, where daily decreases ranged from 40 to 60 μg m^{-3} (**Figure S14**).

[*Figure S13*]

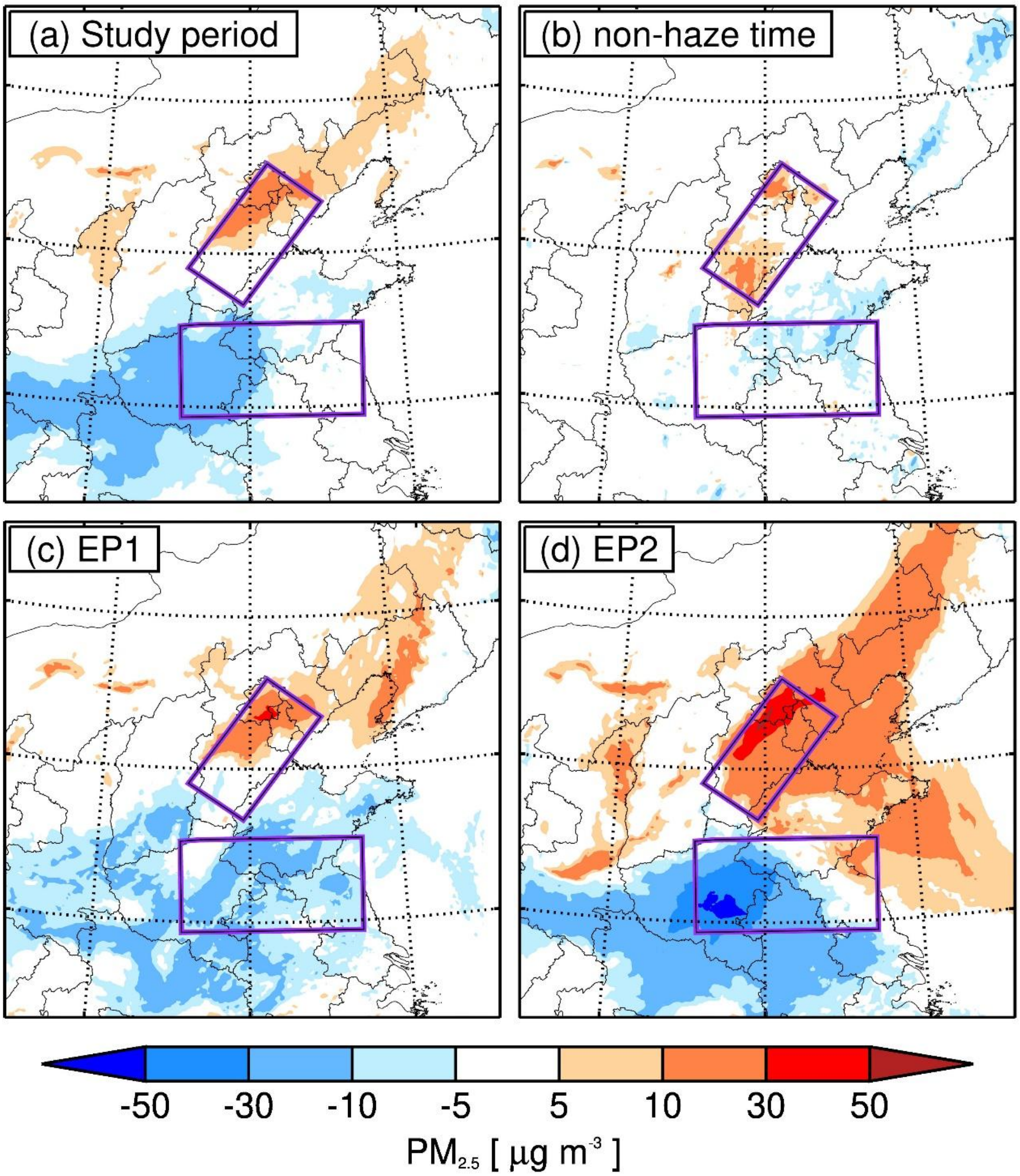

Figure S13. The coupled effects between emission reductions and meteorological factors on $PM_{2.5}$. The color gradient coupled effects averaged from (a) the entire study period, (b) the non-haze period, (c) the EP1 haze period, and (d) the EP2 haze period.

[*Figure 8*]

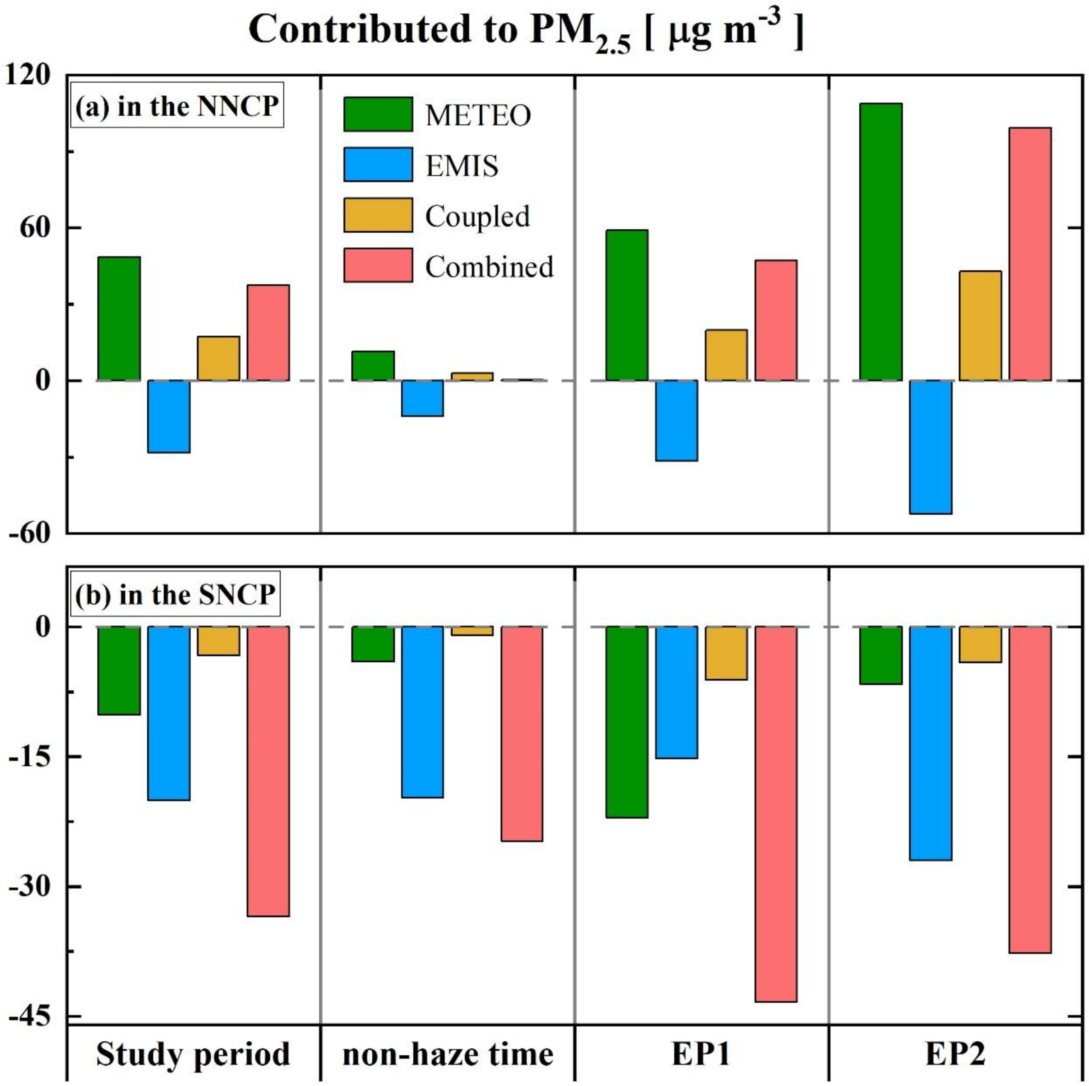

Figure 8. Regional contributions to PM$_{2.5}$ averaged in (a) the NNCP and (b) the SNCP during the entire period, non-haze period, EP1, and EP2. The contributions include meteorological conditions (METEO), abrupt anthropogenic emissions (EMIS) decreases, and coupled and combined effects of METEO and EMIS.

[*Figure S14*]

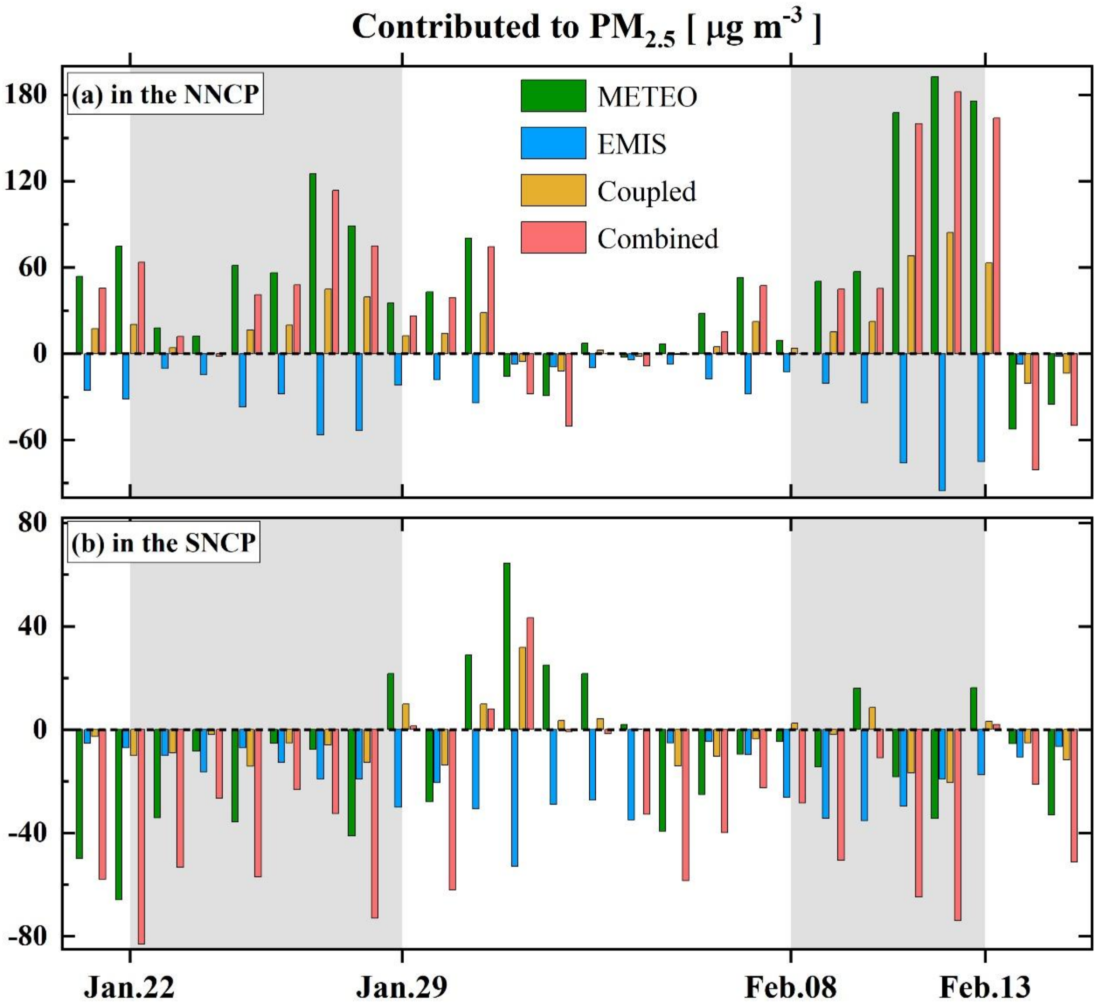

Figure S14. Regional contributions to daily PM$_{2.5}$ averaged in (a) the NNCP and (b) the SNCP. The contributions include meteorological conditions (METEO), abrupt decreases in anthropogenic emissions (EMIS), and synergistic effects of METEO and EMIS.

Major.3 *The study's novelty feels somewhat limited, as numerous previous studies have explored the relationships between emission reductions, meteorology, and air quality during the COVID-19 lockdown, some of which are referenced in this manuscript. The approach and findings do not seem to offer significant new insights or contradictions compared to existing literature. It would be helpful if the authors could more explicitly highlight the innovative aspects of their approach and clarify the novelty of their findings.*

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.4 *The clarity and logical flow of the manuscript could be improved, especially given the multiple sets of comparisons (e.g., SEN_EMIS vs. baseline, SEN_METEO vs. baseline, haze vs. non-haze, NNCP vs. SNCP). At times, these discussions get mixed, making it difficult to follow. For example, section 3.4 compares SEN_EMIS vs. baseline (with the same meteorology) but mentions "decreased atmospheric transport" (line 329), which is confusing – perhaps this refers to EP2 vs. other episodes? If the aim is to explore how emission impacts vary under different meteorological conditions, this should be clearly stated and organized into a separate section/paragraph. This issue appears elsewhere as well, and it would be helpful to clearly signal when switching between comparison sets.*

Thank you for your insightful feedback. We reorganized the Results and Discussion sections to improve the clarity and logical flow of the manuscript, explicitly addressing the need to separate discussions of meteorological and emission impacts. Section 3.4 has been revised to focus solely on the effects of emissions under constant meteorological conditions (EMIS vs. baseline). The reference to "decreased atmospheric transport", which was indeed confusing, has been clarified. This discussion now pertains to the combined and coupled effects between emissions and meteorology and has been moved to *Section 3.5*, where we discuss the newly added EMIS_SEN simulations and their interaction with meteorological conditions.

Specific comments：

Specific.1 *Page 5 line 96: How were the two regions of interest defined? Why are other parts of the NCP not included in your analysis or discussions?*

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.

Specific.2 *Page 5 line 109: Please elaborate on the anthropogenic emissions dataset mentioned, "using a bottom-up approach based on near-real-time data." What is the advantage of this dataset? Could you clarify its species and spatiotemporal resolution?*

Thank you for the comment. We have revised the manuscript to provide a more detailed description of the anthropogenic emissions dataset.

[Lines 119 in *Sect. 2.1*]:

We used the Multi-resolution Emission Inventory for China (MEIC), developed by Tsinghua University, with 2016 as the base year (http://meicmodel.org).

This emission inventory includes emissions from power plants, transportation, industry, agriculture, and residential activities, with data available at a monthly time scale and a spatial resolution of 6 km. We updated the MEIC inventory to reflect the total provincial emissions estimated for 2020, using near-real-time estimation (Zheng et al., 2021). While the total emissions for each province were updated, the spatial distribution of emissions within each province still followed the intensity proportions from the 2016 MEIC inventory. Subsequently, we applied a top-down approach to adjust further the emission inventory, iteratively comparing model simulations with observed data to refine the estimates until the simulations closely matched the observations. We validated the final emission inventory using statistical parameters, including normalized mean bias (*NMB*), index of agreement (*IOA*), and correlation coefficient (*r*) (**Text S1**).

Specific.3 *Page 6 line 120: Please specify the WRF-Chem version used.*

We added the WRF-Chem version to the manuscript. Thank you.

[Lines 143 in *Sect. 2.2*]:

We employed a specific version (version 3.5.1) of the WRF-Chem model (Grell et al., 2005).

Specific.4 *Page 6 line 134: You mentioned "6-year simulations" in the title, but this section states the simulations were conducted from January 21 to February 16, 2020. Does this mean they are one-month simulations only?*

Thank you for your constructive feedback. The phrase "insights from six-year simulations" in the original title was intended to highlight the climatological averages from 2015 to 2019, which provide a critical baseline for understanding the $PM_{2.5}$ dynamics during the one-month COVID-19 lockdown period. To address this and ensure clarity, we have revised the title and added detailed explanations throughout the manuscript.

[*Title*]:

"Impacts of meteorology and emission reductions on haze pollution during the Lockdown in the North China Plain"

[Lines 189 in *Sect 2.2*]:

In the METEO case, we applied the same emission inventory as the BASE case but with averaged meteorological conditions from 2015 to 2019. These mean meteorological fields were derived by averaging key meteorological variables (**Text S2**).

[*Text S2*]:

Text S2 Mean meteorology from 2015 to 2019

This study's mean meteorology field data was derived by averaging key meteorological variables (e.g., temperature, wind speed, relative humidity, and pressure) from 2015 to 2019. Given that the vertical levels in the NCEP FNL data varied across different years, we did not average the original data directly. Instead, we processed the data using the WRF Preprocessing System (WPS) to ensure consistency. Specifically, we ran WPS yearly to generate the met_em* files containing processed meteorological variables at uniform vertical levels and grid resolution. We then averaged these met_em* files across the six years at each grid point and pressure level, which helped preserve the atmospheric variables' vertical structure and physical coherence. This approach maintained a realistic representation of the atmospheric state by accounting for the multi-year variability while ensuring that the averaged fields were consistent with the WRF-Chem grid resolution. As the WPS processing already matched the data to the model's spatial resolution, no additional interpolation was required, thus ensuring the physical and spatial consistency of the averaged climatological fields used in the WRF-Chem simulations. This multi-year climatological averaging was designed to capture the typical variations in initial and boundary meteorological conditions. This approach provided a robust and representative baseline for multiple years, effectively minimizing the influence of anomalies or extreme weather events characteristic of any individual year.

Specific.5 *Page 7 line 152: It would be useful to elaborate on how the climatology was averaged. Did you average all meteorological variables directly? If so, how did you ensure the averaged climatology remained physically coherent? Was interpolation done to match the WRF-Chem grid resolution?*

Thank you for your insightful questions. We provided more detailed processing steps, explaining our approach to creating a physically coherent climatology for the simulations.

[Lines 189 in *Sect 2.2*]:

In the METEO case, we applied the same emission inventory as the BASE case but with averaged meteorological conditions from 2015 to 2019. These mean meteorological fields were derived by averaging key meteorological variables (**Text S2**).

[*Text S2*]:

Text S2 Mean meteorology from 2015 to 2019

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Specific.6 *Page 10 line 228: The exact time periods for EP1 and EP2 should be clearly stated here.*

Thank you for your comment. We included the specific dates for each episode in the manuscript.

[Lines 264 in *Sect. 3.2*]:

During the study period, two significant haze episodes were identified: EP1, lasting from January 22 to 29, and EP2, from February 8 to 13.

Specific.7 *Page 10 line 233: Since Figures 5-7 show "non-haze times," it would be helpful to explain the atmospheric conditions during those periods as well.*

Thank you for the insightful suggestion. We added a comprehensive overview of the atmospheric conditions during non-haze periods.

[Lines 329 in *Sect. 3.3*]:

During non-haze periods, weather conditions still significantly impacted $PM_{2.5}$ levels across the region, though the effect was less intense than haze episodes. In the NNCP, stagnant air and low wind speeds led to $PM_{2.5}$ increases of 10 to 30 μg m^{-3} (**Figure 5b**). These weak conditions prevented effective pollutant dispersion, causing pollutants to accumulate, although less than during significant pollution events. This ongoing buildup due to poor weather shows the continued vulnerability of the NNCP to limited ventilation (Feng et al., 2021; Yan et al., 2024). In contrast, in the SNCP, weather conditions helped reduce $PM_{2.5}$ by 10 to 30 μg m^{-3} (**Figure 5b**). This improvement was mainly due to higher PBLH (**Figure S7b**) and stronger winds (**Figure 5b**), which promoted pollutant dispersion. The PBLH rose by 100 to 300 meters, allowing pollutants to spread vertically, leading to lower $PM_{2.5}$ levels at the surface. Favorable winds also helped clear pollutants, enhancing the positive effects of meteorology on air quality. Previous studies have shown that regions with better dispersion conditions can achieve more significant air quality improvements, even with similar emissions, due to more efficient pollutant removal (Xu et al., 2020b; Zhang et al., 2021). These regional differences during non-haze periods show the critical role of weather in influencing air quality. In the NNCP, weak atmospheric circulation limited pollutant dispersion, causing moderate $PM_{2.5}$ increases. In contrast, in the SNCP, more dynamic weather conditions promoted pollutant removal, leading to substantial reductions.

[*References*]

Feng J, Liao H, Li Y, et al. Long-term trends and variations in haze-related weather conditions in north China during 1980–2018 based on emission-weighted stagnation intensity[J]. Atmospheric Environment, 2020, 240: 117830.

Yan, F., Su, H., Cheng, Y., Huang, R., Liao, H., Yang, T., Zhu, Y., Zhang, S., Sheng, L., Kou, W., Zeng, X., Xiang, S., Yao, X., Gao, H., and Gao, Y.: Frequent haze events associated with transport and stagnation over the corridor between the North China Plain and Yangtze River Delta, Atmos. Chem. Phys., 24, 2365–2376, https://doi.org/10.5194/acp-24-2365-2024, 2024.

Xu Y, Xue W, Lei Y, et al. Spatiotemporal variation in the impact of meteorological conditions on PM2. 5 pollution in China from 2000 to 2017[J]. Atmospheric Environment, 2020, 223: 117215.

Zhang, S., Zeng, G., Yang, X., Wu, R., and Yin, Z.: Comparison of the influence of two types of cold surge on haze dispersion in eastern China, Atmos. Chem. Phys., 21, 15185–15197, https://doi.org/10.5194/acp-21-15185-2021, 2021.

Specific.8 *Page 12 line 303: Have you examined the impact of meteorological conditions on biogenic emissions? If so, what role does it play?*

Thank you for the insightful question. During the winter months, biogenic emissions are limited due to lower temperatures, which reduce the release of biogenic volatile organic compounds (BVOCs). Therefore, the overall contribution of biogenic secondary organic aerosols (BSOAs) to PM2.5 concentrations is minimal during this period. We have clarified this point in the revised text and provided supporting data to show that the BSOA contribution is less than 2 μg/m³, representing less than 2% of total PM2.5 concentrations during the study period.

[Lines 368 in *Sect. 3.3*]:

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.

[*References*]

Guenther A B, Jiang X, Heald C L, et al. The Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGAN2. 1): an extended and updated framework for modeling biogenic emissions[J]. Geoscientific Model Development, 2012, 5(6): 1471-1492.

[*Figure S11*]:

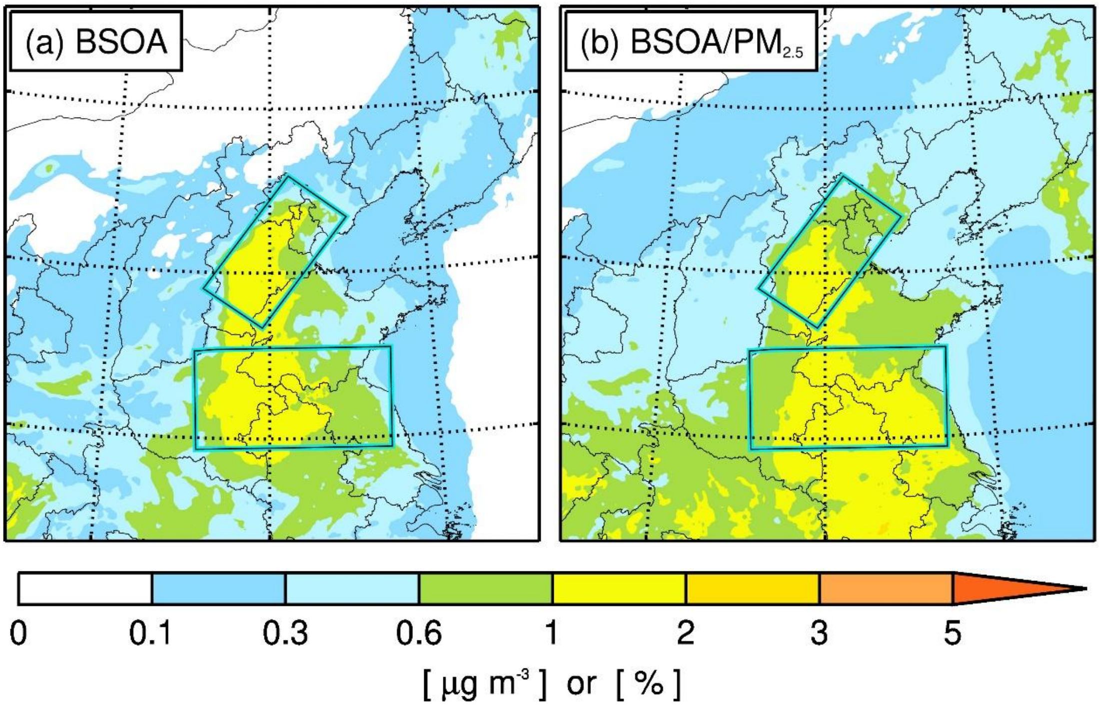

Figure S11. Spatial distribution of (a) near-surface biogenic SOA mass concentration and (b) its contribution as a percentage of $PM_{2.5}$ in the BASE simulations over the study period.

Specific.9 *Figure 4: Clarify what "all time" refers to. Does it mean the one-month period (January 21y 21 to February 16ry 16, 2020) or the 6-year period mentioned in the title?*

Thank you for your valuable observation. We replaced "all time" with "the study period" (January 21 to February 16, 2020). This change has been reflected in the relevant figures (Figs. 4-7 and Figs. S8, S13) to avoid confusion and ensure consistency.

Specific.10 *Figure 5-8: Typically, anomaly values are calculated as [scenario X minus baseline]. If your figures show [baseline minus scenario X], it would be helpful to explicitly mention this in the legend to avoid confusion.*

We explicitly indicated in the figure legends that the values displayed represent [baseline minus scenario X].

Figure 5. The pattern comparisons of the "BASE" simulation minus the "METEO" simulation. The color gradient represents PM2.5 changes averaged from (a) the entire study period, (b) the non-haze period, (c) the EP1 haze period, and (d) the EP2 haze period, along with the simulated surface wind fields.

Figure 6. The pattern comparisons of the "BASE" simulation minus the "EMIS" simulation. The color gradient represents $PM_{2.5}$ changes averaged from (a) the entire study period, (b) the non-haze period, (c) the EP1 haze period, and (d) the EP2 haze period.

Figure 7. The pattern comparisons of the "BASE" simulation minus the "EMIS_METEO" simulation. The color gradient represents coupled effects on $PM_{2.5}$ averaged from (a) the entire study period, (b) the non-haze period, (c) the EP1 haze period, and (d) the EP2 haze period.

Figure S8. The pattern comparisons of the "BASE" simulation minus the "METEO" simulation. The color gradient represents PBLH changes averaged from (a) the entire study period, (b) the non-haze period, (c) the EP1 haze period, and (d) the EP2 haze period.

Figure S13. The coupled effects between emission reductions and meteorological factors on $PM_{2.5}$. The color gradient coupled effects averaged from (a) the entire study period, (b) the non-haze period, (c) the EP1 haze period, and (d) the EP2 haze period.

Specific.11 *Figure 9: Refer to my major comment 2. The calculation of "combined effects" by simply adding meteorological and emission impacts is misleading.*

Thank you for your valuable suggestion. We introduced a new simulation case (EMIS_METEO) that simultaneously perturbs emissions and meteorological conditions. This simulation allows us to assess these two factors' combined and coupled effects comprehensively. The data and analysis have been updated to reflect these changes.

Please refer to our detailed explanation in the response to Major Comment 2, where we elaborate on these updates and their implications for our findings.

Technical corrections:

Technical.1 *Page 3 line 67: "... haze above event" --> "... above haze event"*

Changed as suggested. Thank you.

Technical.2 *Page 4 line 74: Duplicate citations*

We carefully reviewed the manuscript to remove any duplicate references. Thank you.

***Technical.3** Page 5 line 101: “PM2.5, O3, NO2, SO2 and CO” --> “PM2.5, O3, NO2, SO2 and CO”; check subscript formatting throughout the manuscript.*

We carefully reviewed the manuscript to correct any subscript formatting. Thank you.

***Technical.4** Page 6 line 136: Rephrase "consisted of a grid of 300 by 300 points, each spaced at a resolution of 6km" to "consisted of 300 × 300 horizontal grid cells with a 6 km resolution"*

Changed as suggested. Thank you.

***Technical.5** Page 6 line 139: Define the acronym "NCDP FNL" when first introduced*

Changed as suggested. Thank you.

[Lines 168 in *Sect. 2.2*]:

"the National Centers for Environmental Prediction (NCEP) Final (FNL)"