Response to Reviewer #1

This is a quite complete study about the ozone concentrations in the North China Plain under cyclonic and anticyclonic circulations and orographic effects play a main role. Observations were obtained from a network that includes 39 urban stations. Summertime observations (June-August) were considered during 2017-2022. Simulations with the GEOS-Chem model were conducted during June of 2017-2022. Moreover, 5 June 2022 was selected by way of example. Since the paper is quite elaborated, only some minor changes are required for establishing the paper restrictions.

We thank the reviewer for the positive evaluation and comment on this manuscript. The manuscript has been revised accordingly. Please find our response in blue.

1. Firstly, the authors should indicate if cyclonic circulation is thermally induced. A comparison with similar situations around the world would increase the potential readers.

We thank the reviewer for raising this important point. Based on our analysis, the cyclonic-like circulation is not thermally induced but is instead a synoptic-scale baroclinic cyclone. To clarify this point, we examined the surface pressure field and geopotential height fields at 850 hPa, 500 hPa, and 250 hPa (Fig. R1), and compared the locations of the warm core (Fig. R2) and the cyclone center.

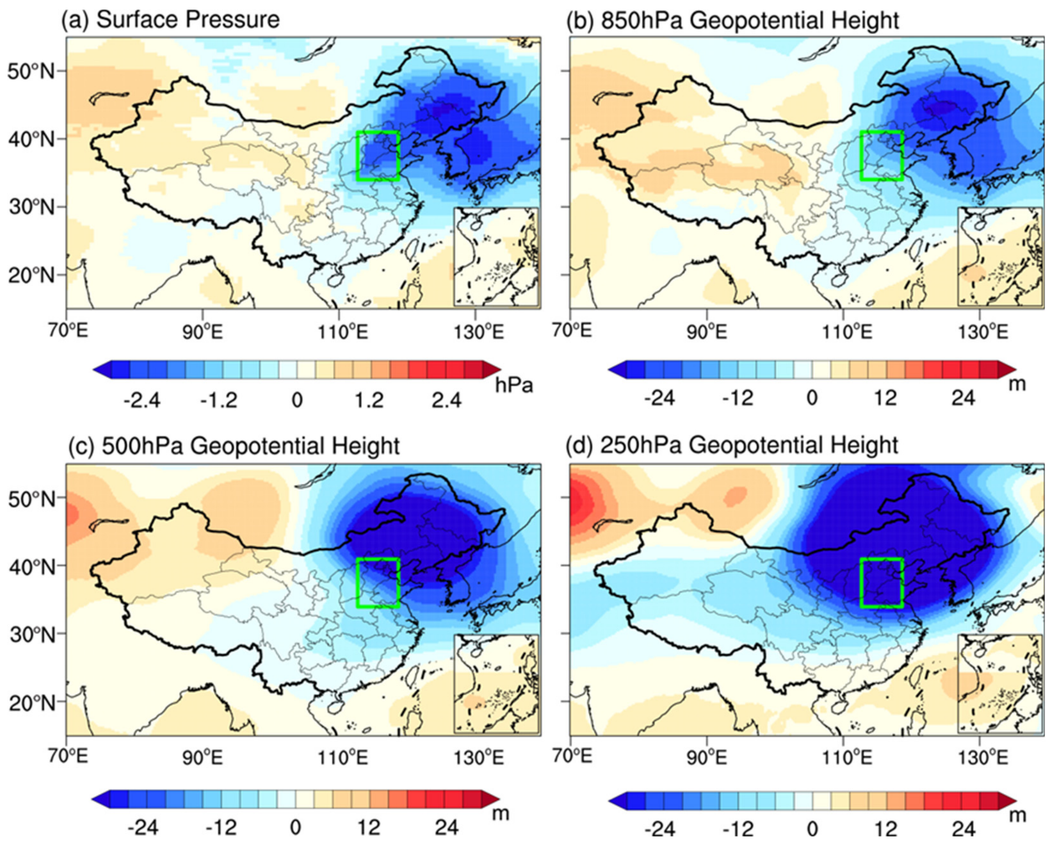

Figure R1. Spatial patterns of anomalous (a) surface pressure and geopotential height at (b) 850 hPa, (c) 500 hPa, and (d) 250 hPa under cyclonic-like circulation. The green rectangles denote the NCP.

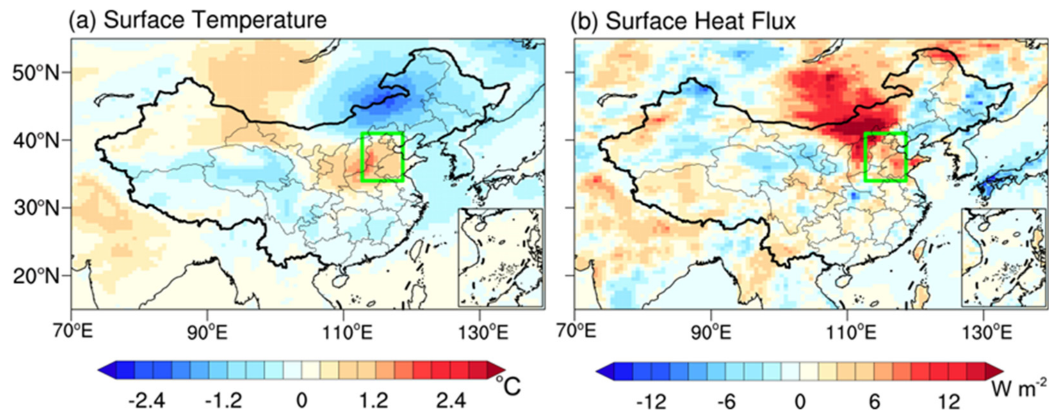

Figure R2. Spatial patterns of anomalous (a) 2-m temperature and (b) surface sensible heat flux under cyclonic-like circulation. The green rectangles denote the NCP.

As shown in Fig. R1, the cyclonic-like circulation becomes progressively more pronounced with height, with a well-developed upper-level trough and enhanced cyclonic circulation at 250–500 hPa. Such a vertical structure is characteristic of a synoptic-scale baroclinic cyclone rather than a thermally induced low-pressure system. In addition, we examined the spatial distributions of 2-m air temperature and surface sensible heat flux (Fig. R2). No warm-core structure is evident around the cyclone center over northeastern China, further confirming that the cyclonic-like circulation is not thermally driven.

Following the reviewer's suggestion, we have clarified the factors driving the cyclonic-like circulation and discussed analogous situations in other regions worldwide in the revised manuscript at Lines 378-386: "The cyclonic-like circulation identified in this study represents a mid-latitude synoptic-scale baroclinic system rather than a locally thermally driven circulation. Similar synoptic systems occur across other mid-latitude regions, including Europe, North America, and Japan (Shibata et al., 2010; Colle et al., 2015; Catto, 2016). Previous studies have reported foehn development under such cyclonic conditions when airflow crosses the Alpine in Europe, the Appalachian Mountains in northeastern North America, and Backbone Mountain Range in Japan (Seaman and Michelson, 2000; Zängl et al., 2007; Kusaka et al., 2021). Therefore, the cyclonic-like circulation and the associated physical and chemical processes have broader implications for understanding ozone pollution and developing effective emission control strategies worldwide and warrant further attention."

2. Ozone concentrations are different in urban and rural environments. In consequence, maps showing the ozone spatial distribution present this contrast where cities highlight as ozone sinks due to the precursor levels, whereas ozone concentrations are higher at rural sites. This contrast is not observed in the presented maps. Perhaps the model resolution does not allow the definition of cities. In addition, only cities are used in this study, where precursors play a main role. A comment about the ozone concentrations at rural sites would increase the paper value.

We acknowledge that this study does not explicitly examine urban–rural differences in ozone concentrations, because the air quality monitoring stations operated by China's Ministry of Ecology and Environment (MEE) are located predominantly in urban areas, and the model resolution is designed to resolve regional-scale ozone variability rather than fine-scale urban–rural differences. Nevertheless, the focus of this study is to investigate how synoptic-scale circulation modulates regional ozone pollution. Such circulation exerts its influence over a broad spatial scale and can lead to synchronous ozone enhancement across both urban and rural areas, rather than being confined to individual locations. Therefore, although our observational analysis relies primarily on urban monitoring sites, the circulation-induced ozone enhancement identified here is likely to extend to the surrounding rural areas as well.

Following the reviewer's suggestion, we have added a discussion in the revised manuscript at Lines 319-322 regarding the potential impacts of cyclonic-like circulation on ozone pollution in rural sites: "Although only urban sites are analyzed in this study because ozone observation stations operated by MEE are predominantly concentrated in urban areas, the influence of cyclonic-like circulation on ozone pollution in rural areas is expected to be broadly consistent with that observed at urban sites, as this synoptic-scale circulation exerts a coherent regional-scale modulation over the western NCP."

3. Varied periods are employed. For instance, observations cover the summertime, whereas simulations are restricted to June. The authors should comment possible implications of this time disagreement on the obtained results. Moreover, Figure 7 extends for 45 years, whereas 5 June 2022 is highlighted for specific results. The convenience of all these time intervals should be justified.

The different analysis periods adopted in this study are designed to address different scientific objectives.

(1) Observations period versus simulations period. The observational analysis covers the summers (June–August) of 2017–2022 to provide robust statistics on the relationship between cyclonic-like circulation and ozone pollution. In contrast, the numerical simulations are restricted to June because our statistical analysis indicates that the impact of cyclonic-like circulation on ozone pollution is most pronounced during this month. Focusing on June therefore allows us to better isolate and quantify the effects of cyclonic-like circulation.

(2) Representative case analysis. To elucidate the mechanisms through which cyclonic-like circulation influences ozone pollution, we selected a representative pollution episode (5 June 2022) for detailed process analysis. This case study provides an in-depth illustration of the evolution of ozone pollution and its associated meteorological and chemical processes, thereby complementing the statistical analysis based on the multi-year observations.

(3) Long-term analysis (1980–2024). Given the important role of cyclonic-like circulation in regional ozone pollution, we further examined its long-term trend over 1980–2024. This analysis aims to characterize the climatological evolution of cyclonic-like circulation and provide a long-term perspective on its potential

implications for ozone pollution under a changing climate.

We have revised the manuscript to explicitly explain the rationale for these different analysis periods at Lines 139-141 and 281-284.

4. At the end of the paper, the authors present the model response under three types of precursor reductions, such as 10, 30 and 50%. Since such reductions should have a noticeable impact on the human activity due to the affected sources, perhaps potential readers wonder if such reductions are realistic and if expected results agree with those from the model, i.e., if the model was tested under such conditions.

Response: Thanks for this insightful comment. The purpose of conducting precursor emission reduction experiments at different reduction levels is to quantify the nonlinear response of ozone to precursor controls and to provide scientific guidance for designing effective emission control strategies. The selected reduction levels are grounded in actual emission control practices. Anthropogenic VOCs and NO_x emissions decreased by approximately 10% during 2020–2025 under China's 14th five-year plan (Guo et al., 2023; Zhao et al., 2026) and larger reduction levels of 30% and 50% have also been achieved during temporary stringent emission-control events, such as the 2014 APEC meeting in Beijing and the 2016 G20 Summit in Hangzhou (Li et al., 2017; Yang et al., 2018). We therefore designed these reduction scenarios to evaluate ozone responses to precursor emission controls. Similar sensitivity experiments have also been widely adopted in previous studies (Wei et al., 2019; Mao et al., 2022; Zhang et al., 2024).

Chemical transport models are capable of simulating ozone response to rapid changes in precursor emissions under different emission control scenarios because the underlying nonlinear photochemical interactions are explicitly represented in the models. The reliability of model-based emission reduction experiments has been demonstrated by previous studies (Li et al., 2019; Huang et al., 2021). In addition, the COVID-19 lockdown provides a particularly valuable real-world test of this capability, during which substantial and rapid reductions in anthropogenic emissions led to pronounced changes in ozone concentrations that were reasonably reproduced by chemical transport models (Huang et al., 2021).

We have clarified the rationale for the selected emission reduction scenarios and the reliability of the corresponding model results in the revised manuscript at Lines 146-152: "Different emission-reduction levels were designed to quantify the nonlinear response of ozone to precursor controls, based on actual emission-control practices ranging from routine mitigation measures to stringent controls implemented during temporary events (Guo et al.,2023; Zhao et al., 2026; Li et al., 2017; Yang et al., 2018). Such sensitivity simulations have been widely adopted in previous studies, which have demonstrated that chemical transport models can reasonably reproduce ozone responses to substantial changes in anthropogenic emissions (Wei et al., 2019; Li et al., 2019; Huang et al., 2021; Mao et al., 2022; Zhang et al., 2024)."

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