25st August 2026

Dear Editor

Thank you again for handling our manuscript "An underappreciated cyclonic-like circulation drives high summer ozone in North China Plain" (egusphere-2026-3245).

We sincerely appreciate the very helpful comments/suggestions from the two reviewers, and all of the comments have been accounted for in our revisions. A point-by-point response (our responses in blue) follows this letter. The changes in the main text are also tracked in red.

Thank you for your consideration.

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Sincerely yours,
On behalf of all co-authors

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.

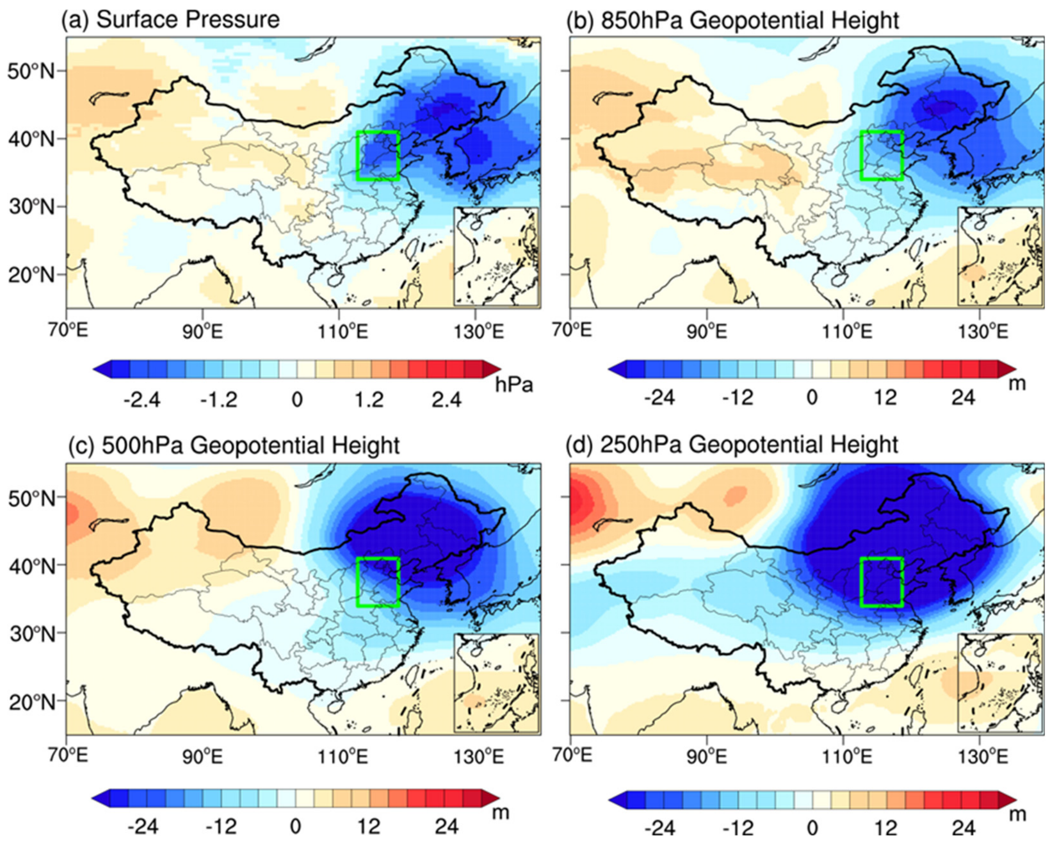

Figure R1. Spatial patterns of anomalous (a) surface pressure and geopotential height at (b) 850 hPa, (c) 500 hPa, and (d) 250 hPa under cyclonic-like circulation. The green rectangles denote the NCP.

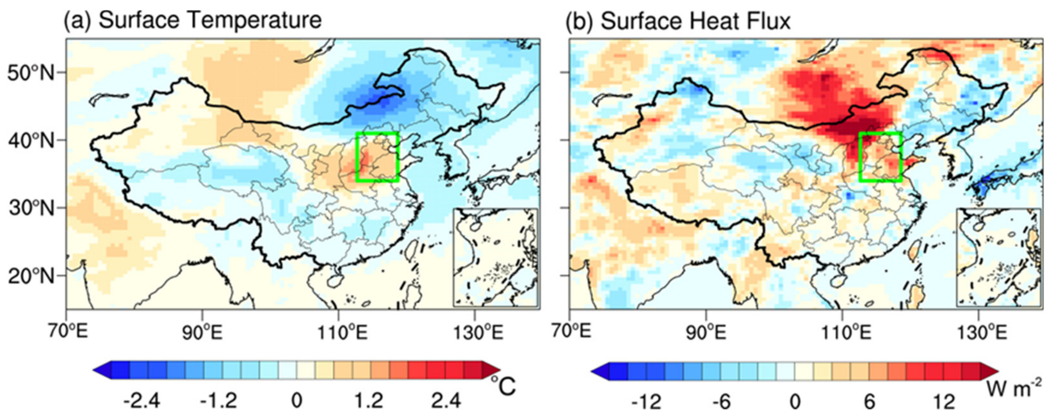

Figure R2. Spatial patterns of anomalous (a) 2-m temperature and (b) surface sensible heat flux under cyclonic-like circulation. The green rectangles denote the NCP.

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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Response to Reviewer #2

Qiao et al identified a new cyclonic-like circulation (CC) pattern that enhanced the summertime ozone in North China. This finding contrasts with the traditional perspective that high ozone occurs under anticyclonic circulation (AC), but authors provide sound evidence and represent a very clean and convincing foehn-related mechanism. The manuscript is written well and easy to follow. I would recommend it to be published in ACP, while the following concerns need to be addressed.

Thank you very much for your constructive comments. We have addressed the comments carefully and please find our response in blue.

1. The meteorological field data is solely from MERRA2, while it is questionable whether the global re-analyzed data can reliably capture the topographic effects? Could authors incorporate other independent observational data, e.g. data from ground-level sites or soundings, to have a robust calibration on the foehn mechanism?

Response: To verify that the global reanalysis data (MERRA2) can reliably capture the topographic effects associated with the foehn mechanism, we performed additional validation using an independent, higher-resolution reanalysis dataset (ERA5; 0.1° × 0.1°) and ground-level meteorological observations over the NCP.

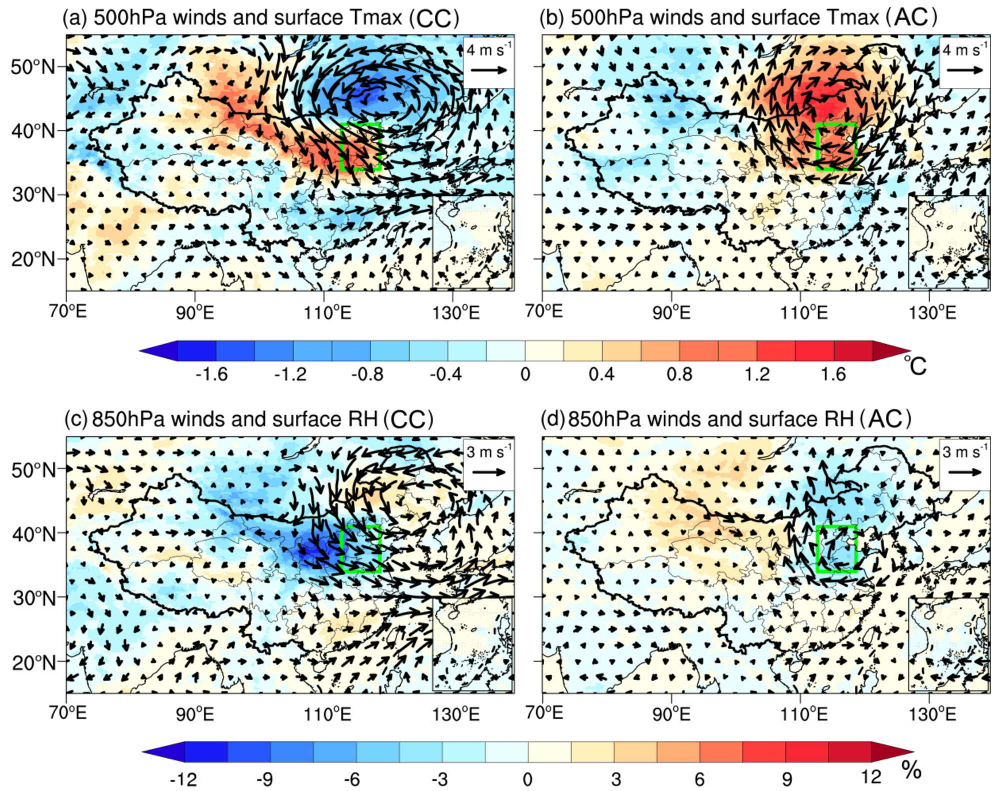


Figure R1. (a, b) Anomalous 500 hPa winds (vectors) and surface maximum temperature (filled colors) under cyclonic-like circulation (CC) and anticyclonic circulation (AC). (c, d) Anomalous 850 hPa winds (vectors) and surface relative humidity (filled colors) under CC and AC conditions.

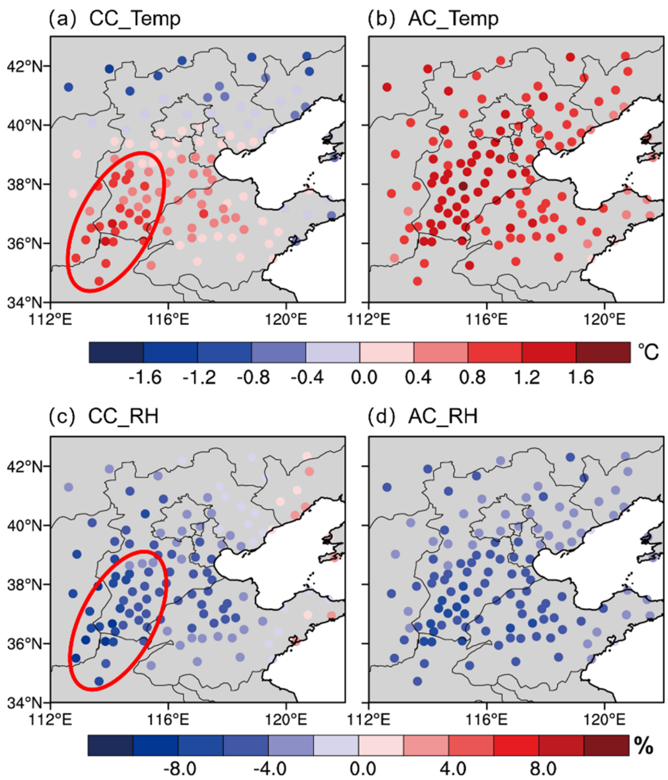


Figure R2. Anomalies in observed (a, b) 2-m temperature and (c, d) relative humidity under cyclonic-like circulation (left) and anticyclonic circulation (right). The red circles highlight the pronounced warming and drying over the adjacent plains of the Taihang Mountains under cyclonic-like circulation.

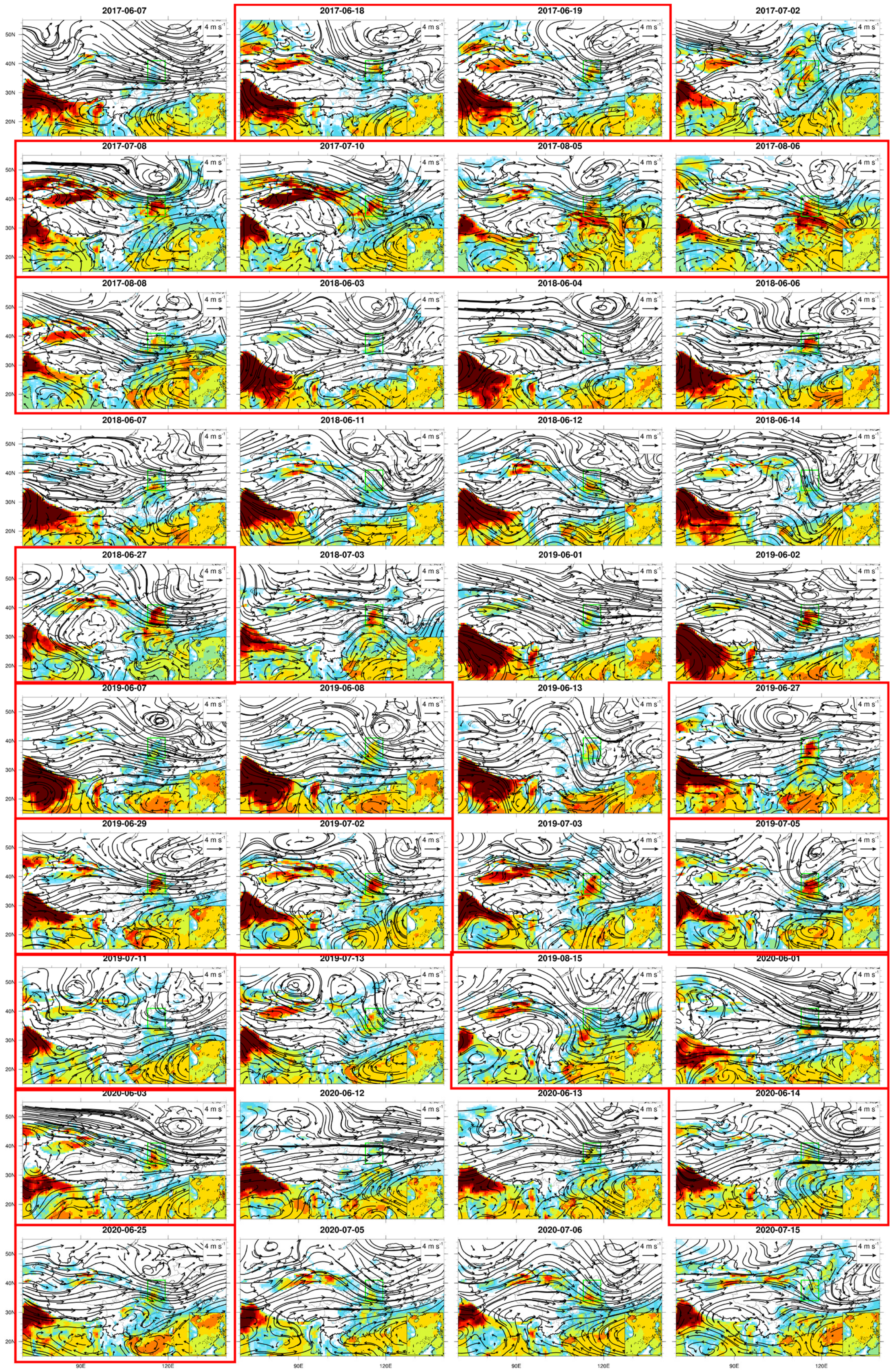
As shown in Fig. R1, ERA5 dataset reproduces the same spatial patterns as MERRA2 dataset. Under cyclonic circulation, both datasets exhibit pronounced anomalous warming and reduced relative humidity along the eastern foothills of the Taihang Mountains, consistent with the expected signature of foehn warming. Moreover, the surface meteorological observations capture the same characteristics (Fig. R2). During cyclonic-like circulation, ground-level sites located on the leeward side of the Taihang Mountains show substantially larger positive temperature anomalies and stronger negative relative humidity anomalies than stations over the central and eastern plain. In contrast, under anticyclonic circulation, both ERA5 and the surface observations show spatially homogeneous warming and drying across the NCP, in good agreement with the MERRA2 results. The consistent results obtained from the independent ERA5 reanalysis and the ground-level sites observations provide strong evidence that MERRA2 reliably captures the topographic effects associated with the Taihang Mountains and therefore provides a robust basis for interpreting the foehn mechanism discussed in this study.

Following the reviewer's suggestion, we have added the surface observational evidence to the Supplementary Information as the new Fig. S4 and have highlighted this consistency in the revised manuscript at Lines 194-195: "Surface meteorological observations exhibit similar spatial characteristics (Fig. S4), providing independent observational support for the MERRA-2 results."

2. The classification of different circulations seems oversimplified. Authors only used the averaged north-westerly winds across a transect to identify the CC, and assumed the remaining ozone polluted days are controlled by AC. To what extent that the transect wind can represent the circulations over North China? Can authors provide more detailed evidences, e.g. the absolute wind fields on individual days, to justify this classification?

Response: We thank the reviewer for this insightful comment. We adopted the transect-averaged northwesterly wind as an index because predominant northwesterly flow over the NCP is a typical feature of cyclonic-like circulation (CC) and represents a key dynamical condition for foehn development that promotes ozone enhancement over the western NCP. This index has also been used to identify CC in previous studies (Chen and Lu (2016)).

To address the reviewer's concern, we have displayed the absolute wind fields for all individual days identified by the index (Fig. R3) in the Supplementary Information as the new Fig. S3. In addition, to quantitatively evaluate the reliability of the index, we independently identified cyclonic circulation days through manual inspection of the daily synoptic fields and compared them with the those identified using the transect-based index. The results and related discussion have been added to the revised manuscript at Lines 166-178: "Among the 209 ozone pollution days during the summers of 2017-2022, 60 cyclonic-like circulation days were identified. We examined the absolute wind fields for all individual days identified by the index (Fig. S3) and independently compared them with the cyclonic-like circulation days identified through manual inspection. Of the 60 index-identified cyclonic-like circulation days, 40 coincided with 44 manually identified days, reaching a detection rate of 91%. This high consistency indicates that the transect-averaged northwesterly wind provides a reasonable proxy for identifying the circulation conditions of interest. The remaining 20 days identified by the index were primarily associated with trough-like low-pressure systems rather than well-developed cyclonic circulation. Nevertheless, these days consistently exhibited prevailing northwesterly flow over the NCP and enhanced warming along the foothills of the Taihang Mountains (Fig. S3), suggesting dynamical conditions similar to those of cyclonic circulation with respect to foehn development and the associated ozone response. Therefore, we refer to the circulation identified by the index as cyclonic-like circulation rather than well-developed cyclone."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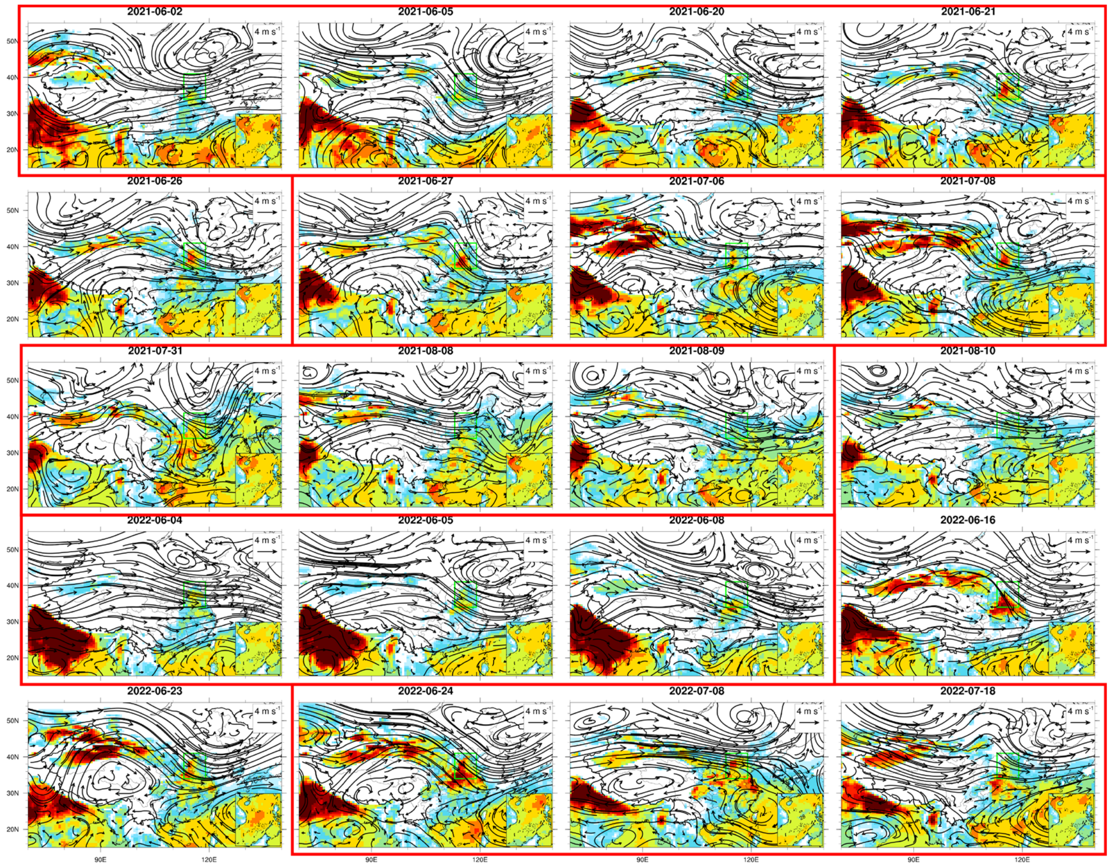

Figure R3. Absolute wind fields for all individual days identified by the cyclonic-like circulation index. Arrows denote absolute wind vectors, and shading represents 2-m air temperature. Red boxes indicate days that coincide with those identified as cyclonic-like circulation days through manual inspection.

3. If the foehn wind is from mountain area, how do BVOC emissions contribute to the ozone enhancement besides the heating and drying effects? Could authors add one more sensitivity experiment to test it?

Response: Following the reviewer's suggestion, we performed an additional sensitivity experiment in which BVOCs emissions from the Taihang Mountain region were set to zero, while all other model settings remained unchanged, to assess the influence of mountain-emitted BVOCs on ozone pollution over the NCP. We have added discussion on this in the revised manuscript at Lines 356-362: "Given that the northwesterly winds under cyclonic-like circulation pass over the mountainous region, we additionally conducted a sensitivity experiment by setting mountain BVOC emissions to zero to investigate their influence on ozone pollution over the NCP. As shown in Fig. S10, ozone concentrations over the NCP decreased by only 0.75 ppb under this scenario, further demonstrating that ozone pollution is primarily driven by enhanced local photochemical production associated with foehn-induced anomalous warming and drying."

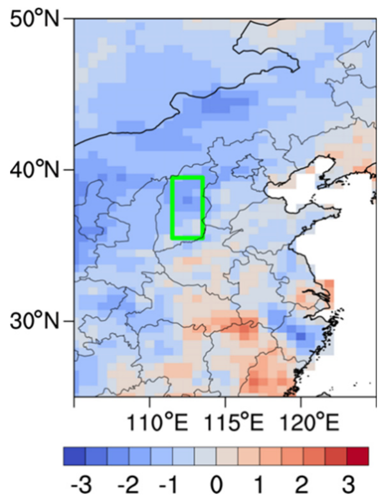

Figure R4. Changes in ozone concentrations resulting from setting BVOC emissions over the mountainous region to zero. The green rectangle indicates the region where MEGAN-derived BVOC emissions were turned off, while all other model settings remained unchanged from the control simulation.

Minor suggestions:

1. Title: as the CC days are still much less than the AC days, it is improper to claim CC ‘drives’ the summer ozone pollution.

Response: Accepted. We have revised the title as “An underappreciated cyclonic-like circulation affects high summer ozone in North China Plain”.

2. Lines 24-26: Please specify the spatial heterogeneity.

Response: The spatial heterogeneity has been explicitly clarified in the revised manuscript at Lines 25–28: “Consequently, the impact of cyclonic-like circulation on ozone pollution exhibits pronounced spatial heterogeneity, with stronger ozone enhancement over the western than the central and eastern NCP, in contrast to the relatively uniform ozone increase across the NCP under anticyclonic circulation.”

3. Line 41-42: It is not clear what the value of 220 ug m^{-3} represents. Does it refer to a regional average or to specific cities? Does it occur on a particular extreme day, or does it represent a monthly mean?

Response: The value of 220 μg m^{-3} refers to the regional monthly mean ozone concentration averaged across 38 cities in the Beijing–Tianjin–Hebei region and surrounding areas in June 2024. We have revised the ambiguous wording in the manuscript at Lines 42-45: “For example, the monthly mean ozone concentration averaged across the 38 cities in the Beijing–Tianjin–Hebei region and surrounding areas even reached 220 μg m^{-3} in June 2024, far exceeding the national air quality standard.”

4. Fig. 1and Fig. S1: Could authors merge them into one figure? Or at least modify the Fig. S1, where the lines with different colours are very unclear and confusing.

Response: We appreciate the reviewer's suggestion. We have revised Fig. S1 to improve its clarity. Specifically, Fig. S1 now retains only the rectangular boxes indicating the emission reduction regions, while the colored lines representing the cross-sections used to identify cyclonic-like circulation have been redrawn in a new Fig. S2.

5. Line 99: Cannot access the link, the same as the data availability statement.

Response: The links in the revised manuscript, including the one in Line 99 and those provided in the Data Availability Statement, have been updated and verified to ensure that they are all accessible.

6. Fig.4: What do the upper-left numbers indicate? If they represent the averaged ozone concentrations, why is the AC anomaly significantly higher than CC anomaly while their averaged concentrations are similar?

Response: We thank the reviewer for pointing out this error. The numbers in the upper-left corner represent the regional mean ozone concentrations over the NCP. We found that these values were incorrectly labeled in the original figure and have corrected them in the revised manuscript as new Fig. 4. The corrected regional mean ozone concentrations are 90.3 ppb and 92.0 ppb for the cyclonic-like circulation and anticyclonic circulation respectively, while the corresponding ozone anomalies are 14.3 ppb and 16.0 ppb, respectively. The revised figure has been updated.

7. Fig. 5: I suggest to directly name the site groups, such as 'western sites' and 'central and eastern sites', instead of using 'types 1 and type 2'.

Response: Accepted. We have revised the manuscript by replacing "Type 1" and "Type 2" with "western sites" and "central and eastern sites," respectively, in both Fig. 5 and the corresponding text throughout the revised manuscript at Lines 263-265, 267-268, 269-270, and 276-278.

8. Lines 303-305: Please also add the absolute statistical metrics, e.g. mean bias or RMSE.

Response: Accepted. The mean bias (MB), normalized mean bias (NMB), and root-mean-square error (RMSE) between observed and simulated ozone concentrations have been added to the revised manuscript at Line 343-346 and Supplementary Information as new Fig. S9. The MB, NMB, RMSE are −6.3 and −10.9 ppb, −9.4% and −15.5%, and 13.9 and 15.1 ppb under cyclonic and anticyclonic circulation, respectively.

9. Fig. 7: How was the AC trend?

Response: The long-term trend in anticyclonic circulation (AC) during 1980–2024 is shown in Fig. R5, which has been added to the Supplementary Information as new Fig. S8. We have also added the following discussion to the revised manuscript at Lines 331-334: "In contrast, the fraction of anticyclonic circulation days exhibits a significant decreasing trend (Fig. S8). This contrasting trend indicates that cyclonic-like circulation is becoming an increasingly important driver of ozone pollution in the NCP, highlighting the urgency of developing ozone pollution control strategies tailored to this circulation pattern"

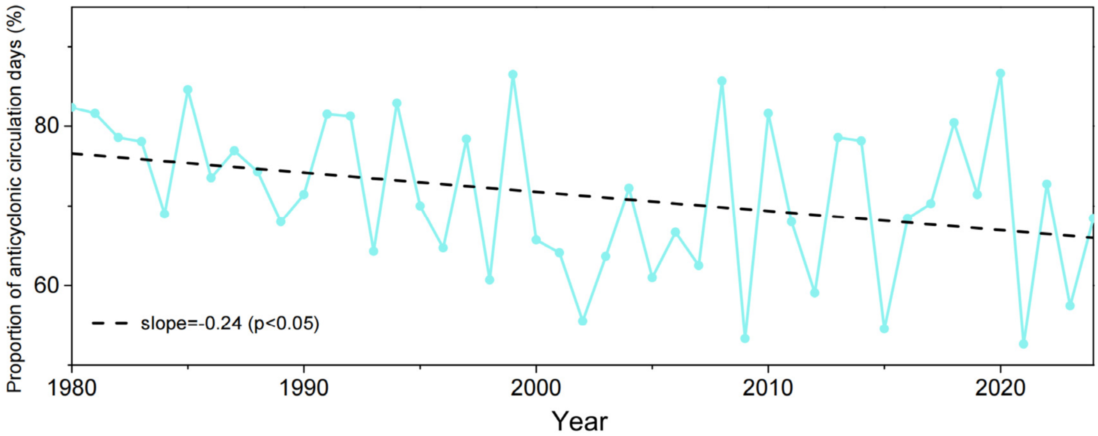

Figure R5. Long-term trends of the proportion of anticyclonic circulation on days with temperatures exceeding 32 °C in the NCP in summer from 1980 to 2024. The dash line indicates the linear fitting trend. The focus on days with temperatures above 32 °C (the average temperature of ozone pollution days) is motivated by the lack of long-term ozone concentration observations. The strong association between high temperatures and ozone pollution allows temperature to serve as a reasonable proxy for assessing long-term changes.