Reply to Anonymous Referee #1

This study starts with a comprehensive delineation of an elevated foehn-induced O_3 air pollution event in Beijing. Such a delineation includes the spatial-temporal distribution of surface O_3 in Beijing, the synoptic background, the evolution of vertical air structure, the backward trajectory analysis, cross-section progression, and climatological status. The manuscript is clearly structured and well-written, with figures that are clear and easy to interpret. I would recommend its publication at ACP with the following issues addressed.

Reply: Thank you so much for your positive feedback. We have carefully considered your suggestions and comments and have made corresponding revisions and clarifications accordingly.

1、The authors pointed out the distinct impacts of shallow and elevated foehn on O3 air pollution. Could the authors please add somewhere an illustration of the different progression and structure between shallow and elevated foehn?

Reply: Thank you for this constructive comment. In the revised manuscript, we have expanded the discussion on the distinct impacts of shallow and elevated foehn on air pollution. We have included statistics on MDA8O_3 and $PM_{2.5}$ pollution during summertime elevated foehn events identified in this study, along with a comparison with shallow foehn events reported in Li et al. (2025) (Table S1). For comparison, we also plotted composite afternoon boundary layer temperature profiles, boundary/residual layer heights, and afternoon boundary layer wind speed profiles before, during, and after 90 shallow foehn events in Beijing, as identified by Li et al. (2025) (Fig. S5).

Table S1. Statistics of MDA8O_3 and $PM_{2.5}$ pollution for summertime elevated foehn events identify in this study, and their comparison with shallow foehn events identified in Li et al (2025).

	Average concentration on post-foehn days (μg m^{-3})	Average increasing rate relative to pre-foehn days (%)	Pollution-worsened rate in all cases (%)
Statistics for summertime elevated foehn events (54 cases)			
MDA8O_3	168.3	32.4	86.7 (46 in 53 cases)
$PM_{2.5}$	32.2	31.5	69.8 (37 in 53 cases)
Statistics for summertime shallow foehn events (90 cases)			
MDA8O_3	142.9	7.6	55.2 (48 in 87 cases)
$PM_{2.5}$	27.7	-2.5	55.2 (48 in 87 cases)

Note: Pollution data were missing for one day in the elevated foehn events and for three days in the shallow foehn events. The summertime shallow foehn events were identified over the period 2015–2020, which differs from the elevated foehn events identified over 2015–2024.

The comparison indicates that elevated foehn exacerbates not only O_3 pollution but also $PM_{2.5}$ pollution, making it a more reliable meteorological precursor for air pollution warnings than shallow foehn. While shallow foehn induces a weak low-level jet that cleanses air pollution, elevated foehn worsens air quality through three primary mechanisms: (1) increasing boundary layer temperature, thereby enhancing photochemical formation; (2) reducing residual/boundary layer height, thereby inhibiting vertical diffusion of pollutants; and (3) slowing boundary layer winds, thereby suppressing horizontal dispersion. **Lines: 447-458.**

In light of the above mechanisms, we added a conceptual diagram in the revised manuscript (Fig. 13) to illustrate the differing pollution mechanisms associated with shallow versus elevated foehn.

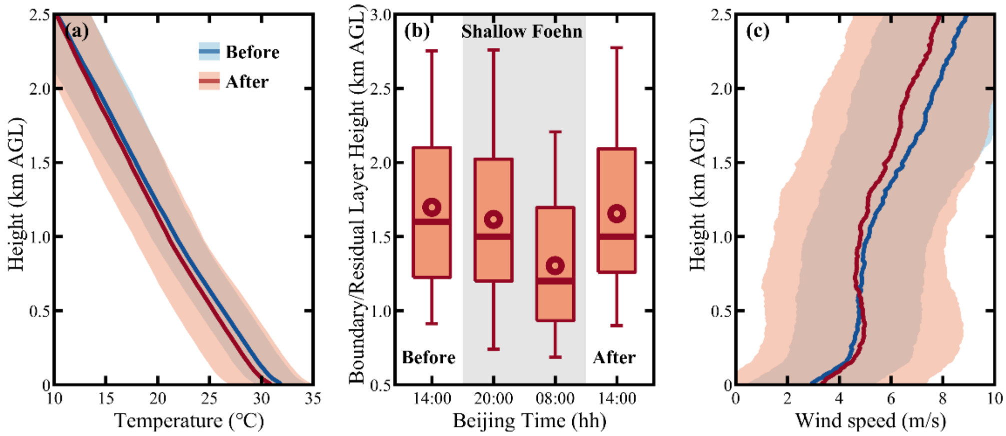

Figure S5. Composite of (a) afternoon boundary layer temperature profiles, (b) boundary/residual layer height, and (c) afternoon boundary layer wind speed profiles before, during, and after 90 shallow foehn events in Beijing, as identified by Li et al (2025). In (a) and (c), solid lines represent the mean profiles and shaded areas indicate the standard deviation. In (b), box-and-whisker plots display the 5th, 25th, 50th, 75th, and 95th percentiles; dots denote the means.

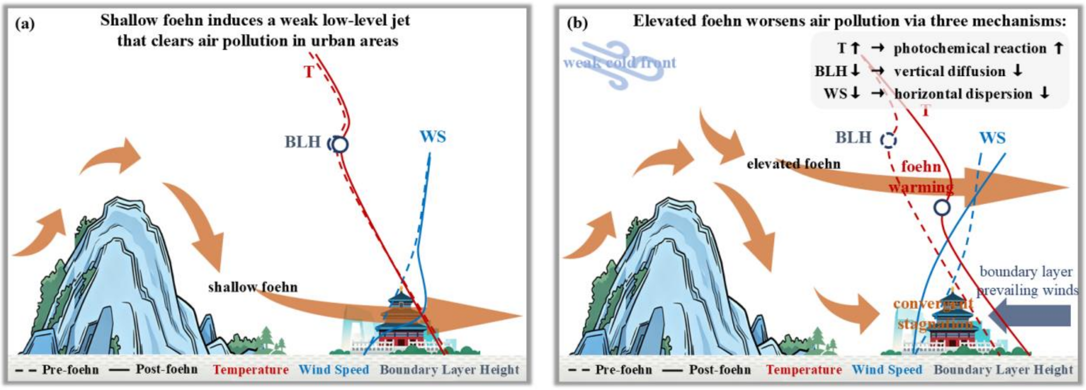

Figure 13. Conceptual diagram illustrating the differing pollution mechanisms associated with shallow versus elevated foehn.

2、One factor for post-foehn O_3 pollution is increased temperature. The author also mentioned in some places in the manuscript that foehn could decrease $PM_{2.5}$. Therefore, I presume that foehn has different or even opposite impacts on O_3 and $PM_{2.5}$, since the former is more sensitive to temperature while the latter is more affected by diffusion and transport processes. Could the authors please add some clarifications about the possible different impacts of foehn on $PM_{2.5}$ and O_3?

Reply: Thank you for this comment. In our original manuscript, we actually compared the worsening effect of elevated foehn on O_3 pollution with the cleaning effect of shallow foehn on $PM_{2.5}$ pollution. However, when the respective effects of elevated foehn on O_3 and $PM_{2.5}$ are considered on the same scale, both actually show a pollution-worsening effect. In contrast to O_3, $PM_{2.5}$ may be less sensitive to temperature increases, which explains its slightly lower pollution-worsened rate in elevated foehn cases (69.8%). When compared with shallow foehn, elevated foehn exhibits a very weak pollution-worsening effect for both O_3 and $PM_{2.5}$. In other words, it is the foehn type that plays a decisive role, rather than the type of pollutant. In the revised manuscript, we clarified these mechanisms with the addition of Table S1 and Fig. S5. **Lines: 447-458.**

3、So the foehn is a more localized meteorological impact on O_3, as compared to synoptic-scale meteorology. The authors mentioned in the end to explore the contribution of elevated foehn to O_3 generation under different synoptic backgrounds. Could the authors here illustrate more of this point for the events introduced in this paper? This could be important since there are numerous publications showing the importance of synoptic-scale weather on regional O_3 pollution in the NCP region.

Reply: Thank you for this excellent comment. We expanded this point as follows.

"To date, numerous circulation classification-based studies have highlighted the importance of synoptic-scale weather on regional O_3 pollution in the NCP region (Dong et al., 2020; Han et al., 2020; Liao et al., 2024; Liu et al., 2019). However, day-to-day circulation classifications actually overlook sub-daily meteorological processes, such as the nocturnal elevated foehn identified in this study. A very recent study (Xu et al., 2026) indicated that ground-based foehns on the eastern Taihang Mountains preferentially occur under stable atmospheric stratification, with a surface high over the windward side and a low over the leeward side, together with an upper-level cold trough at 500 hPa and pronounced subsidence at 850 hPa on the leeward side on the eastern foothills of the Taihang Mountains. However, this study did not extend its findings to the field of air pollution, nor did it clarify whether the aforementioned synoptic conditions are also conducive to the occurrence of elevated foehn. Overall, a better coupling of synoptic-scale circulation patterns and local-scale elevated foehn processes will further deepen our understanding of meteorological mechanisms underlying O_3 pollution". **Lines: 511-521.**

Reply to Anonymous Referee #2

Overview:

Liao et al. conducts a detailed case study, accompanied by a longitudinal observational assessment, of lofted foehn impacts on surface ozone through boundary layer modifications in Beijing during the summer. In doing so, the authors utilize various observational datasets including ground-monitoring and lidar ozone measurements, radar wind profiles, and radiosondes. The authors focus on ozone and winds before and after a single lofted foehn event (occurring overnight on August 29) that doesn't result in surface warming as typical foehn events. The authors also assess back trajectories and conduct WRF-chem simulations to confirm elevated foehn impacts on residual layer warming. Finally, a climatological analysis of radiosonde data from 2015 – 2024 reveals that elevated foehn winds caused 87% of identified nocturnal residual layer warming (n = 63, 6.85% of summer nights) with elevated surface ozone concentrations the next day after every one of the events. The work mainly concludes elevated foehn increase surface ozone concentrations through three mechanisms: 1) increasing boundary layer temperature leading to increased ozone production; 2) reduction of residual/boundary layer height causing a subsequent decrease in ozone vertical diffusion; and 3) slowing boundary layer winds resulting in reduction of horizontal dispersion.

Major comments:

The paper effectively uses observations to characterize foehn influence on the nocturnal residual layer and traces those impacts through to the following day's convective boundary layer. The associated layer changes (increased temperature, reduced boundary layer height, and weaker winds) are well documented in both observations and model simulations. However, the physical justifications for mechanisms 1 and 3 warrant further support and considerations of nuances.

Reply: Thank you very much for your positive comments. We have carefully considered your suggestions, and made corresponding revisions and clarifications accordingly.

Regarding mechanism 1, the authors use changes in ozone, which is a function of production and loss, both of which can be independently impacted by temperature. While elevated temperatures are known to enhance ozone production, temperature also modulates chemical loss pathways and this is not addressed. Reduced PAN transport into the study region (due reduction in vertical mixing as mentioned in mechanism 2), could suppress ozone loss and independently contribute to the observed surface ozone increases. The current attribution of higher ozone concentrations solely to enhanced production is incomplete. The paper would benefit from discussion of temperature-sensitive loss processes, or at minimum acknowledgement of them as a potential contributing factor.

Reply: Thank you for your thoughtful comment. We agree that the discussion of temperature-sensitive processes was one-side in our original manuscript. In the revised version, we expanded our analysis and discussion to address this point as follows.

"As observed, the afternoon boundary layer temperature on 30 August showed a significant increase compared to the previous afternoon, and this higher temperature further promotes photochemical O_3 production by accelerating photochemical reaction rates and enhancing emissions of volatile organic compounds and soil nitric oxide (Gu et al., 2020; Wu et al., 2024). Thus, in addition to promoting daytime O_3 accumulation by reducing the boundary layer height, residual layer warming also enhances daytime photochemical O_3 production. Moreover, these changes in boundary layer thermal properties can facilitate O_3 accumulation by lowering O_3 loss. For instance, the lowered CBLH can reduce the transport of PAN (peroxyacetyl nitrate, a NO_x reservoir in the upper atmosphere) into urban Beijing (a NO_x-saturated zone), which may suppress O_3 loss from NO titration and independently contribute to the observed O_3 increases (Flowerday and Hansen, 2026)." **Lines: 231-239.**

Mechanism 3 is more directly supported by the observations, though a brief clarification would strengthen it specifically, whether the reduced boundary layer winds are an elevated foehn-driven signal or a signature of the converging synoptic systems (specified on page 6) within which the foehn occurs.

Reply: Thank you for this constructive comment. It is difficult to define this point, as the elevated foehn identified in this study is also a local manifestation of converging synoptic systems. Our observations indicated that the post-foehn convergent stagnation (i.e, the reduced boundary layer winds) results from the confrontation between the emerging northwestern foehn winds and the prevailing southwestern winds within the boundary layer. We thought that relatively strong boundary-layer southwesterly winds serve as a necessary prerequisite for the occurrence of elevated foehn in summer Beijing, as they inhibit the intrusion of shallow foehn toward plain areas and, in turn, force the foehn to develop upward. During this "inhibit" process, the confrontation between the opposite-direction winds lead to reduced boundary layer winds and elevated foehn aloft in tandem.

We clarified this point in **Lines: 435-442.**

Specific comments:

Figure 7c seems to have the middle hollow marker (~06, 2024-08-30) cut off. Also, please include time zone (e.g. local time vs UTC) as well as for other time relevant plots (e.g. Fig 6).

Reply: Thank you for pointing it out. The software of MATLAB R2016b cut off some markers in their output figures. In the revision, we re-plotted our figures using an updated

MATLAB version (R2020a). Also, we included time zone (i.e., Beijing Time) for relevant plots.

Figure 10b is missing longitude and latitude coordinates.

Reply: We added the longitude and latitude coordinates in Figure 10b.

Figure 11b seems to have a cut off marker in the fourth box-whisker.

Reply: We re-plotted this figure using an updated MATLAB version.

For all site-relevant figures, it would be helpful to delineate the specified sites (CXT, SDZ, and YQ); e.g. Figure 3b and c and Figure 12.

Reply: Thank you for your suggestions. We marked the specified sites in relevant plots, e.g., Figure 3b and c and Figure 12.