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Meteorological conditions drive divergent responses of co-occurring $PM_{2.5}$ and O_3 pollution to emission reductions and role of aerosol feedback in Beijing–Tianjin–Hebei-Shandong

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Abstract

Co-occurring $PM_{2.5}$ and O_3 pollution (Double High Pollution, DHP) presents a growing air quality concern, yet its response to emission controls under different meteorological conditions is poorly quantified. Previous studies have focused on synoptic-scale or single meteorological variable with limited consideration of aerosol-meteorology feedback. This study investigated the DHP response to NOx–VOC emission reductions and the role of aerosol-meteorology feedback in Beijing–Tianjin–Hebei-Shandong in July 2020 using the WRF-Chem model. DHP occurred under warm (23–31°C), moderately humid (45–80%), and shallow boundary layer (0.5–1.1 km) conditions. These typical meteorological conditions were classified into five types: Convective, Stable, WarmHumid, DryHot, and Moderate based on boundary layer height, temperature and humidity. $PM_{2.5}$ was highest under Stable and WarmHumid (~46 μg m^{-3}) and lowest under DryHot (~40 μg m^{-3}); O_3 was highest under DryHot and Moderate (~83–84 ppb) and lowest under WarmHumid (~76 ppb). O_3 responded most strongly to emission controls under WarmHumid (-25.2% at 50%/50% NOx/VOC) and weakest under DryHot (-23.3%) with stronger NO_x sensitivity under WarmHumid and Convective; $PM_{2.5}$ reductions were largest under Stable and WarmHumid (-20.9% and -20.6%) and smallest under DryHot (-15.2%). Aerosol feedback enhanced $PM_{2.5}$ reduction most under Stable and WarmHumid but weakened O_3 reduction under Stable when NO_x cuts were large without VOC co-reduction, driven by the most lasting PBLH increase and strong OH amplification. These results demonstrate that meteorological condition-specific strategies, particularly coordinated NOx–VOC control under stagnant and humid conditions, are essential for effective DHP mitigation.

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1 Introduction

Fine particulate matter ($PM_{2.5}$) concentration has decreased significantly across China over the past decades, particularly after the Air Pollution Prevention and Control Action Plan took effect in 2013. Nevertheless, surface ozone (O_3) concentration has increased in several regions, adding complexity to the co-control of $PM_{2.5}$ and O_3 (Zhang et al., 2019; Liu et al., 2023b; Wang et al., 2023). Recent nationwide evidence based on observations from 1092 sites (2015–2023) showed a clear trend evolution of co-occurring $PM_{2.5}$ and O_3 pollution (hereafter referred to double-high pollution, DHP) in China: the frequency of DHP first declined from 2015 to 2021 and then rebounded during 2021–2023 and North China remained the most affected area (Wang et al., 2025a). It implies that control strategies focused primarily on particulate matter is no longer sufficient to achieve coordinated $PM_{2.5}$ and O_3 reductions or to avoid rebound risks in one pollutant while reducing the other (Lu et al., 2020; Zhao et al., 2021).

Both $PM_{2.5}$ and O_3 concentration are strongly affected by thermodynamic conditions, boundary-layer development, humidity, and regional transport (Zong et al., 2021; Qian and Liao, 2025). Previous studies have shown that DHP was typically associated with two kinds of meteorological backgrounds. One was characterized by stagnant high-pressure systems, weak near-surface winds, and limited ventilation, together with strong solar radiation and high temperature that enhanced daytime photochemistry (Ma et al., 2023; Wang et al., 2025b; Zhan et al., 2024). The other involved the coupling of regional transport with humid and shallow boundary layer conditions which promoted secondary aerosol formation while maintaining a sufficiently oxidizing environment for elevated O_3 (Luo et al., 2022; Dai et al., 2024; Liu et al., 2026). However, some studies have shown that, even under the same large-scale circulation patterns, differences in local boundary layer, temperature, and humidity still led to two- to three-fold differences in pollutant concentrations (Zong et al., 2021). Therefore, detailed meteorological condition classification is necessary for understanding the meteorological dependence of DHP and its response to emission control.

The difficulty of synergistic control arises largely from the nonlinear response of O_3 to its precursors, nitrogen oxides (NO_x) and volatile organic compounds (VOCs). Depending on local chemical sensitivity, O_3 formation may be NO_x-limited, VOC-limited, or transitional, so the same emission reduction strategy can produce very different outcomes across regions and meteorological conditions (Lu et al., 2018; Ivatt et al., 2022; Wang et al., 2023). Previous studies have examined how precursor emission reductions affect DHP. Using a deep-learning based emission-concentration response surface model, Ding et al. (2022) showed that coordinated NO_x/VOC control was generally more effective than single-precursor control for $PM_{2.5}$/O_3 co-mitigation, and that delayed VOC abatement substantially weakened the overall clean-air benefits. Based on GEOS-Chem sensitivity simulations for urban and non-urban areas of Beijing-Tianjin-Hebei (BTH) and Yangtze River Delta (YRD), Dai et al. (2024) demonstrated that synergistic NO_x/VOC reductions markedly decreased DHP days, with VOC reductions contributing more in urban areas and NO_x reductions playing a stronger role in non-urban areas. Some studied showed that under VOC-limited conditions, isolated NO_x reductions may even increase O_3 and the benefit of coordinated precursor control may be partly offset by the O_3 enhancing effect induced by declining $PM_{2.5}$ and weakened aerosol suppression (Ren et al., 2022; Liu et al., 2023b; Yang et al., 2024). The reduction efficiency was also affected by meteorological conditions: based on observations, reanalysis data, and

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GEOS-Chem model over BTH, Qian and Liao (2025) demonstrated that O_3 reduction efficiency was more sensitive to temperature whereas $PM_{2.5}$ reduction efficiency was more sensitive to humidity.

Beyond precursor emission sensitivity, aerosol-meteorology feedback which includes aerosol-radiation interaction (ARI) and aerosol-cloud interaction (ACI) (Satheesh and Krishnamoorthy, 2005; Lohmann and Feichter, 2005) also affects DHP. As offline atmospheric chemistry models treat meteorology as fixed, they cannot separate the concentration change caused directly by emission perturbations from induced indirectly through aerosol-meteorology feedback. Online coupled models resolve this two-way coupling, yet many such studies still considered ARI only. Over the North China Plain during the COVID-19 lockdown, Zhu et al. (2021) found that ARI enhanced the emission-induced $PM_{2.5}$ decrease by 2.7 μg m^{-3} and the O_3 increase by 0.8 ppbv beyond the baseline changes of -16.3 μg m^{-3} for $PM_{2.5}$ and 10.2 ppbv for O_3 with WRF-Chem model. Yang et al. (2024) showed that weakened ARI under sustained clean air measures enhanced photolysis and thereby exacerbated O_3 pollution, offsetting part of the expected co-control benefit over eastern China using coupled WRF-Chem simulations. Li et al. (2026) revealed pronounced seasonality in the O_3 response to ARI and heterogeneous chemistry with winter O_3 rising by 6.7%–10.7% whereas summer O_3 declining by 2.9%–6.7% under future mitigation scenarios in eastern China. Zhao et al. (2026b) demonstrated that ARI and ACI together reduced surface shortwave radiation, especially under moist and cloudy conditions, depressing O_3 while increasing $PM_{2.5}$ which implied future $PM_{2.5}$ reductions may weaken this O_3 suppression and heighten rebound risk.

However, how emission reductions affect DHP under refined local meteorological conditions remains unclear. Most previous studies focused on large scale synoptic classifications or individual meteorological variables, which do not directly link to the chemical environment governing precursors reactions. In addition, the role of aerosol-meteorology feedback in affecting control effectiveness under different meteorological conditions is poorly understood, as most previous coupled studies considered ARI only and did not evaluate how this feedback effects vary with boundary layer and thermal moisture conditions. To fill these gaps, this study investigates DHP responses to emission reductions in Beijing–Tianjin–Hebei–Shandong (BTHS), a hotspot of summertime DHP, in July 2020. Specifically, the typical meteorological conditions of DHP were identified and classified into different types based on combined boundary layer, temperature and humidity conditions rather than large scale synoptic categories or a single meteorological element, thereby capturing the interactions that actually control local chemistry and aerosol feedback. Then, two-dimensional NO_x–VOC emission-reduction response matrices were constructed using the online-coupled WRF-Chem model to evaluate O_3 and $PM_{2.5}$ responses and aerosol feedback contribution under each meteorological condition type. The response was also linked to key meteorological and chemical indicators to elucidate the underlying mechanisms.

Section 2 describes the model configuration, experimental design, and observation datasets. Results and discussion including identification of DHP, meteorological condition classification, model validation, pollutant response to emission reduction and the role of aerosol-meteorological feedback are presented in Section 3. The key findings and conclusions are summarized in Section 4.

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2. Materials and methods

2.1 Model configurations and emissions

The Weather Research and Forecasting model coupled with Chemistry (WRF-Chem) (Grell et al., 2005) was used to simulate interaction between atmospheric chemical processes and meteorological fields. The USTC (University of Science and Technology of China) version of WRF-Chem adopted in this study incorporates several enhancements over the standard release including biogenic volatile organic compound emissions coupled to the land surface module, diagnosis of aerosol radiative forcing components, aerosol-snow interactions, and refined treatment of aerosol mixing within the planetary boundary layer (PBL) (Zhao et al., 2013, 2014, 2016; Zhang et al., 2021; Yang et al., 2025). The modeling domain covered 140 (west-east) × 120 (south-north) grid points at 27 km horizontal resolution and centered at 32°N, 115°E with BTHS marked by the blue lines (Fig. S1). Vertically, 29 sigma layers stretched from the surface to 50 hPa, 14 of which below 2 km altitude to resolve PBL structure.

Gas-phase photochemistry followed the Carbon Bond Mechanism Z (CBM-Z; Zaveri and Peters, 1999) and aerosol processes were treated with the four-bin Model for Simulating Aerosol Interactions and Chemistry (MOSAIC), including nucleation, condensation, gas-particle partitioning, and aqueous-phase chemistry (Zaveri et al., 2008). The physics parameterizations comprised the Morrison double-moment microphysics scheme (Morrison and Gettelman, 2008), Noah land surface model (Chen and Dudhia, 2001), RRTMG longwave and shortwave radiation scheme (Iacono et al., 2008), revised MM5 Monin-Obukhov surface layer scheme (Foken, 2006), Mellor-Yamada-Janjić PBL scheme (Janjić, 1994), Grell-Freitas ensemble cumulus scheme (Freitas et al., 2018), fast-J photolysis scheme (Wild et al., 2000), and a single-layer urban canopy model (Kusaka et al., 2001; Kusaka and Kimura, 2004).

Meteorological initial and boundary conditions were derived from the ERA5 reanalysis of 0.25° × 0.25° (https://cds.climate.copernicus.eu/cdsapp#!/dataset/10.24381/cds.adbb2d47). Chemical lateral and initial conditions came from the Community Atmosphere Model with Chemistry (CAM-Chem; https://www2.acom.ucar.edu/gcm/cam-chem-output). Anthropogenic emissions over China were from the MEIC inventory (http://meicmodel.org.cn; Li et al., 2017a, 2017b; Geng et al., 2024) for 2020 at 0.25° × 0.25° supplemented by the Regional Emission Inventory in Asia (REAS; https://www.nies.go.jp/REAS/) outside mainland China at the same resolution. The species included SO_2, CO, NO_x, NH_3, NMVOCs, BC, OC, PM_{10} and $PM_{2.5}$. Biomass burning emissions were from the Fire INventory from NCAR (FINN) at 1 km and 1 h resolution (Wiedinmyer et al., 2011). Biogenic emissions were calculated online using the Model of Emissions of Gases and Aerosols from Nature version 2.1 (MEGAN v2.1; Guenther et al., 2006). Dust and sea-salt emissions were calculated online by the WRF-Chem, driven by predicted meteorological fields (Gong et al., 1997; Zhao et al., 2013).

2.2 Observation data

Model performance was assessed against surface observations for July 2020. Hourly temperature, relative humidity, and wind speed data from 147 meteorological stations in BTH (77 sites) and Shandong province (70 sites) were obtained from the National Meteorological Information Center of the China Meteorological Administration (CMA, http://www.nmic.cn/) to evaluate simulated 2 m temperature (T2), 2 m relative humidity (RH2), 10 m wind speed (WS10) and 10 m wind direction (WD10). Hourly near-surface $PM_{2.5}$ and O_3 concentrations from 479 air quality monitoring sites (23 sites in BTH and 46 sites

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in Shandong province) were obtained from the China National Environmental Monitoring Centre (CNEMC, https://www.cnemc.cn/) to evaluate the simulated $PM_{2.5}$ and O_3 concentrations. Maximum Daily 8-hour Average O_3 (MDA8 O_3) was computed from hourly data using an 8-h running mean and taking the daily maximum. Following the Chinese air quality standard GB 3095-2012, an 8 h block was retained only if at least 6 of the 8 hourly records were valid. The daily MDA8 value was then calculated only when more than 14 valid 8 h moving averages were available during the daytime window (08:00–24:00 LST). The locations of all the stations are presented in Fig. S1. The 1-km gridded population density dataset of China (Xu, 2017) were used to classify the BTHS into urban (population density > 1500 persons km^{-2}), suburban (500–1500 persons km^{-2}), and rural (<500 persons km^{-2}) areas.

2.3 Numerical experiments

To investigate the response of $PM_{2.5}$ and O_3 to precursor emission reductions and the impact of aerosol-meteorology feedback, two parallel sets of numerical experiments were conducted for July 2020 with a 5 days spin-up time (Table 1). The first experiment set (EXP_W) accounted for the full interaction between aerosols and meteorology including both ARI and ACI. The second experiment set (EXP_WO) excluded both ARI and ACI. By comparing EXP_WO and EXP_W, the contribution of aerosol-meteorology feedback to the air pollutant changes can be isolated. For each set of experiments, it contained 36 simulation scenarios: one baseline scenario (EXP_W_BASE/EXP_WO_BASE) without emission reduction and 35 sensitivity scenarios which represented combinations of NO_x and VOCs emission reductions ranging from 0% to 50% with a 10% interval. Scenarios were named as EXP_W_NO(x)_VOC(y)/EXP_WO_NO(x)_VOC(y), where x and y denote the percentage reductions of NO_x and VOC, respectively. For instance, EXP_W_NO10_VOC10/EXP_WO_NO10_VOC10 denotes 10% reductions in both NO_x and VOC emissions with/without aerosol-meteorology feedback, while EXP_W_NO30_VOC0/EXP_WO_NO30_VOC0 denotes a 30% NO_2 reduction and no VOC reduction with/without aerosol-meteorology feedback. The response of $PM_{2.5}(O_3)$ concentrations to the emission reductions with/without aerosol-meteorology feedback were obtained by subtracting EXP_W_NO(x)_VOC(y)/EXP_WO_NO(x)_VOC(y) from EXP_W_BASE/EXP_WO_BASE, which can be named as $\Delta PM_{2.5}(O_3)/\Delta_{wo}PM_{2.5}(O_3)$. Therefore, subtracting $\Delta_{wo}PM_{2.5}(O_3)$ from $\Delta PM_{2.5}(O_3)$ yielded the impact of aerosol-meteorology feedback on $PM_{2.5}(O_3)$ concentration changes after emission reduction which can be named as $\Delta_{aer}PM_{2.5}(O_3)$. ARI was disabled by removing aerosols effects on radiation in the RRTMG scheme, and ACI was disabled by prescribing a fixed cloud droplet number concentration (CDNC) of 10 cm^{-3} in the Morrison double-moment cloud microphysics scheme (Zhao et al., 2017; Zhang et al., 2018; Xiong et al., 2022; Zhao et al., 2026b), a value consistent with satellite observations of clean marine liquid clouds (Bennartz, 2007; Zeng et al., 2014).

3. Results and discussion

3.1 Model evaluation

The simulated meteorology and air quality against surface observations in BTHS are evaluated for 1–30 July 2020 in this section. Figure 1 presents the time series comparison of T2, RH2, WS10, WD10, and planetary boundary layer height (PBLH) while Fig. 2 shows the spatial distributions and time series comparison of $PM_{2.5}$ and MDA8 O_3. Statistics are provided in Table 2, including the mean observed and modeled values (AVGO and AVGM), correlation coefficient (R), mean bias (MB), normalized mean bias

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(NMB) and root mean square error (RMSE).

Overall, the model captures the temporal variability of near surface meteorology. In Fig. 1a and 1b, the simulated T2 in BTH and Shandong province reproduces the observed day-to-day evolution and diurnal cycle with R of 0.91 and 0.92, respectively, and exhibits only a small overestimation (NMB around 3%). Similarly, RH2 is well correlated with observations in BTH and Shandong province (R = 0.91 and 0.92) in Fig. 1c and 1d, indicating that the model reasonably represents the timing of moist and dry periods. A slight underestimation is present (NMB = -9.17% and -7.17%), which may influence aerosol hygroscopic growth and heterogeneous chemistry. In contrast, near-surface winds show larger discrepancies. Figure 1e and 1f show that WS10 is overestimated throughout the period with R of 0.80 and 0.83 and MB of 0.68 and 0.80 m s^{-1} in BTH and Shandong province. The high correlation suggests that the simulation captures much of the variability in wind strength, but the systematic positive bias indicates overly strong mechanical mixing and excessive boundary-layer ventilation in the model. In Fig. 1g and 1h, WD10 is also well simulated with R of 0.69 and 0.85 with a positive bias (NMB = 20.05% and 7.20%) implying that transport pathways are reasonably represented. For PBLH, the model accurately captures its temporal evolution, with R of 0.95 and 0.94 against ERA5 reanalysis (Fig. 1i and 1j) demonstrating the model's ability to reproduce the dynamic variation of the planetary boundary layer. The NMB are 37.45% and 34.17% for BTH and Shandong province, respectively, indicating a systematic overestimation by the model during the simulation period.

For $PM_{2.5}$, the model simulation demonstrates good performance at the regional scale. In Fig. 2a, the modeled $PM_{2.5}$ field is consistent with the observed distribution (R = 0.72) indicating that the model captures the overall burden of fine particles during this month, with higher concentrations over the North China Plain and lower concentration toward surrounding cleaner regions. The time series in Fig. 2c and 2e suggests that the model generally follows observed day-to-day variability and several pollution episodes with R of 0.64 and 0.56 and NMB of -8.05% and -3.98%, though differences remain in peak intensity and short-term fluctuations. For O_3, in Fig. 2b, 2d and 2f, the model captures both spatial gradients (R = 0.85) and the temporal evolution (R = 0.81 and 0.82) of MDA8 O_3, reflecting a good representation of the timing of photochemical production and synoptic modulation. However, the model simulation shows an underestimation in MDA8 O_3 for BTH and Shandong province (NMB = -21.94% and -33.22%). The time series reveals that the model underestimates nighttime O_3 concentrations, which is a widely documented bias in chemical transport models (Li and Rappenglueck, 2018; Travis and Jacob, 2019; Liu et al., 2021). This nighttime O_3 low bias is primarily attributed to excessive O_3 titration by NO within the shallow nocturnal boundary layer, where the model typically underestimates the nocturnal PBL height, leading to overestimated NO_x concentrations and consequently excessive chemical destruction of O_3 (Zhao et al., 2019; Liu et al., 2021). Generally, the model simulation provides a solid foundation for regional analyses, with strong performance in temperature and humidity and spatial-temporal patterns of $PM_{2.5}$ and O_3.

3.2 Identification of DHP samples and their typical meteorological conditions

DHP samples of BTHS were identified using WRF-Chem model simulations during July 2020. Earlier investigations typically adopted Class II thresholds Chinese National Ambient Air Quality Standard (GB 3095-2012) namely 75 μg m^{-3} for 24-h $PM_{2.5}$ and 160 μg m^{-3} for MDA8 O_3 as the criteria

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for compound pollution. Given that atmospheric concentrations in China have fallen markedly in recent years, those thresholds no longer reflect current pollution levels or the stricter goals of contemporary air quality management (Ma et al., 2023; He et al., 2024; Liu et al., 2025). We therefore applied the more stringent Class I limits (35 μg m^{-3} for daily $PM_{2.5}$ and 100 μg m^{-3} for MDA8 O_3) to screen model grids. The screening procedure comprised four steps. First, daily mean $PM_{2.5}$ and MDA8 O_3 were calculated from hourly WRF-Chem outputs for all model grids over China's land area. Grid-day samples meeting the Class I criteria were retained as candidate DHP samples. The spatial distribution of simulated DHP days is compared with observations in Fig. S2, which indicates that the model results are in generally good agreement with the observations in BTHS. Therefore, this consistency demonstrates that using simulated results to identify DHP samples is reliable. All subsequent filtering was conducted within the BTHS area, which is the study region of this paper.

Second, to minimize the influence of wet removal and precipitation-related processes, we excluded grid-day samples in BTHS with daily rain-hours ≥3 h (hourly precipitation increment > 0.1 mm). Third, to ensure statistical robustness, model grids in BTHS with no more than 9 DHP days (less than 30% days of 1–30 July 2020) during the study period were excluded. Fourth, only days with more than 20 DHP samples within the BTHS were retained. This absolute count threshold was adopted instead of a percentage criterion (e.g., >50% of sites, as used by Zong et al., 2021, for observational networks with ~10–30 stations) because the model grid contains several hundred cells in BTHS, making a percentage threshold excessively restrictive. The threshold of 20 grid cells corresponds approximately to the number of stations exceeding the 50% criterion in prior observational studies (Zong et al., 2021). After the four-step screening, a total of 1510 DHP samples were retained, covering 113 unique model grids in BTHS.

Then, the variations in $PM_{2.5}$ and O_3 under temperature, humidity and PBLH bins and the typical meteorological condition of DHP are examined, focusing on the contrast between all samples and DHP samples (Fig. 3). Figure 3a and 3b show that for T2, DHP does not occur at all time ranges, but mainly occurs within 23°C to 31°C. For all samples, the median $PM_{2.5}$ at the low T2 bin (17–23°C) is ~20 μg m^{-3}, rising to ~35–40 μg m^{-3} at 25–29°C with a peak of ~40 μg m^{-3} at ~27°C, and then declining to ~20 μg m^{-3} at the warm bin (~33°C), indicating a non-linear response. For DHP samples, $PM_{2.5}$ is systematically higher, with median values of ~38 μg m^{-3} at 23–25°C, ~43 μg m^{-3} at 27–29°C, and declining to ~40 μg m^{-3} at ~31°C. MDA8 O_3 increases with T2 (Fig. 3b): for all samples, its median value rises from ~60 ppb at 17–23°C to ~76–80 ppb at 27–31°C, reaching ~85 ppb at 33°C. MDA8 O_3 of DHP samples ranges from ~69–81 ppb for the 23–31°C range, with a peak of ~81 ppb at ~29°C. In Fig. S3, both O_x (O_3 + NO_2) and OH similarly increase with T2 for all samples and DHP samples, and O_x in DHP samples is generally higher than that in all samples, especially in the mid-to-high T2 bins, indicating that warm conditions are associated with enhanced oxidant levels for DHP samples. Therefore, warm conditions simultaneously favor elevated O_3 and $PM_{2.5}$, and enhanced oxidant capacity for DHP samples, although the absolute O_3 levels are slightly lower than that in all samples at the highest temperatures due to the DHP selection criteria which require both $PM_{2.5}$ > 35 μg m^{-3} and MDA8 O_3 > 100 ppb.

Figure 3c and 3d show that for RH2, DHP mainly occurs for the range from 45% to 80%°C. Considering different RH bins, for all samples, the median $PM_{2.5}$ is ~19–20 μg m^{-3} at low RH (~25–45%),

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increases to ~34–48 μg m^{-3} at RH of ~50–75%, and decreases to ~15–20 μg m^{-3} at very high RH (~80–95%), showing a broad peak at moderate-to-high humidity rather than a sharp decline. For the DHP samples, $PM_{2.5}$ is systematically higher, peaking at ~48–50 μg m^{-3} around RH of 70–75%. MDA8 O_3 shows a clear decrease with increasing RH (Fig. 3d): for all samples, the median value is ~78–86 ppb at low RH (25–60%) and decreases to ~60 ppb at RH ≥80%, reflecting the suppression of photochemistry under humid conditions. For the DHP samples, the median MDA8 O_3 remains higher than all samples in most RH bins, peaking at ~84 ppb at RH ~55% and declining to ~68–73 ppb at RH ≥70%. Both O_x and OH also decrease with increasing RH for all samples and DHP samples (Fig. S3), while DHP samples exhibit higher O_x and comparable or slightly higher OH than all samples at moderate RH (55–75%), evidencing that DHP preferentially occurs in a moderate humidity window where aerosol formation is enhanced but photochemical O_3 is not yet strongly suppressed.

DHP also occurs within a specific PBLH range from 0.5–1.1 km (Figs. 3e and 3f). For all samples, $PM_{2.5}$ generally decreases with PBLH: the median value is ~30 μg m^{-3} at low PBLH bin(< 0.9 km), and then decreases to ~19 μg m^{-3} at higher PBLH (~1.1–1.5 km). DHP samples exhibit higher $PM_{2.5}$ concentrations in all PBLH bins, along with a more pronounced decreasing trend as PBLH increases. MDA8 O_3 shows a positive dependence on PBLH (Fig. 3f): for all samples, median O_3 increases from ~60 ppb under low PBLH (~0.3 km) to ~74 ppb at moderate PBLH (~0.5–0.9 km) and further to ~80 ppb under Convective (PBLH ~1.1–1.5 km), indicating enhanced entrainment of O_3-rich air from aloft and stronger photochemical production in deeper boundary layers. For DHP samples, MDA8 O_3 remains relatively uniform (~80 ppb) in most PBLH bins (0.3–1.1 km). Similarly, O_x and OH generally increase with PBLH for all samples (Fig. S3), while remaining relatively stable for PBLH bins of 0.3–1.1 km for DHP samples, suggesting suppression of oxidant levels for DHP samples. This pattern reflects the competing effects of boundary layer mixing: while low PBLH concentrates $PM_{2.5}$, it also traps NO_x near the surface, enhancing NO titration of O_3 and reducing entrainment of O_3-rich air from aloft, whereas higher PBLH allows sufficient mixing for photochemical O_3 production and entrainment (Zong et al., 2021).

3.3 Meteorological condition classification and characteristics of DHP under the classification

The meteorological condition of each DHP sample is classified into different types based on boundary layer, temperature and humidity conditions derived from model simulations rather than relying solely on large scale synoptic categories or on a single meteorological element. The detailed classification procedure is described as follows. Samples with PBLH above the monthly 90th percentile were classified as Convective which means unstable and well-mixed, whereas those with PBLH below the monthly 10th percentile were classified as Stable which means stable and weakly mixed. Remaining samples with intermediate PBLH was classified using daily mean T2 and RH2. Three subtypes were defined: WarmHumid (T2 ≥ 25 °C and RH2 ≥ 65%), DryHot (T2 ≥ 25 °C and RH2 < 60%), and Moderate (all remaining samples). The binned meteorological relationships in Section 3.2 provide the reference for the threshold of T2 and RH2. The T2 threshold of 25 °C corresponds to a sharp increase in both $PM_{2.5}$ and MDA8 O_3 in Figs. 3a and 3b, marking the onset of conditions favorable for vigorous photochemical and secondary aerosol production. For RH thresholds, the binned RH relationships with $PM_{2.5}$ and MDA8 O_3 under DHP (Fig. 3c, d) reveal a clear inflection near 60% RH: $PM_{2.5}$ median concentrations remain low

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and stable below 60%, begin a steady rise through 60–65%, and accelerate further above 65%. Concurrently, MDA8 O_3 peaks at 55–60% RH, then declines steadily after 65% RH. The OH radical concentration follows a similar pattern, peaking at 60% RH and decreasing after 65% RH (Fig. S3d), confirming the gradual suppression of photochemical activity as humidity increases. Zang et al. (2019) directly classified days using daily-mean RH ≥ 60% as wet days. The DryHot category thus captures conditions where gas-phase photochemistry dominates. At 65% RH, $PM_{2.5}$ has risen measurably and O_3 has declined consistently, indicating that aqueous-phase chemistry has become sufficiently influential to warrant a distinct category. The interval between 60% and 65% RH represents a transitional regime where the relative importance of gas-phase versus aqueous-phase chemistry shifts progressively; samples falling within this range under warm conditions are therefore classified as Moderate. The resulting classification yields a balanced distribution: WarmHumid (~40%) and Moderate (~25.5%) are the two most prevalent categories, reflecting the frequent occurrence of elevated humidity during summertime DHP in the BTHS; DryHot (~16%) represents the contrasting photochemistry dominated regime; Stable (~12.7%) and Convective (~5.8%) conditions constitute the remaining minority categories. All five types retain sufficient sample sizes for robust statistical analysis (87–604 samples).

To validate and interpret the classification, Figure S4 shows the boxplots of daily meteorological variables (T2, RH, PBLH, and WS10) by the five types. As the classification defines WarmHumid, DryHot, and Moderate primarily by temperature and humidity thresholds, these three types exhibit narrow ranges in RH (Fig. S4b). Their T2 distributions are also relatively compact (Fig. S4a). Although Convective and Stable can be sharply distinguished by PBLH (Fig. S4c) with much wider ranges in T2 and RH (Fig. S4a and S4b), there is also distinct difference of T2 and RH2 between the two types: T2 is relatively high in Convective and low in Stable while RH2 is relatively high in Stable and low in Convective. The PBLH difference among WarmHumid, DryHot, and Moderate is relatively small. WS10 differences (Fig. S4d) are weaker than those in T2, RH, or PBLH with the largest WS10 in WarmHumid and DryHot. Overall, the five types effectively separate distinct ventilation and thermodynamic environments in DHP samples.

Figure 4 presents the boxplots of daily mean $PM_{2.5}$ and MDA8 O_3 by meteorological condition type. In Fig. 4a, $PM_{2.5}$ shows strong meteorological condition dependence: Stable has the highest median (~46 μg m^{-3}) and the largest spread (IQR ~40–56 μg m^{-3}, with upper whiskers extending above ~70 μg m^{-3}), followed by WarmHumid (median ~46 μg m^{-3}, IQR ~40–53 μg m^{-3}). Convective and Moderate are intermediate (medians ~42 μg m^{-3}), and DryHot is the lowest (median ~40 μg m^{-3}) with the tightest distribution (IQR ~37–44 μg m^{-3}). In Fig. 4b, MDA8 O_3 remains elevated in all types (medians ~76–84 ppb), consistently above the all samples median (~79 ppb). DryHot and Moderate show the highest O_3 (medians ~83–84 ppb), while WarmHumid is the lowest (~76 ppb).

These patterns are supported by the oxidants, precursors, and $PM_{2.5}$ composition variations for different meteorological condition types (Figs. S5 and S6). The high $PM_{2.5}$ under Stable reflects pollutant accumulation within a shallow boundary layer, as evidenced by elevated NO_2 and CO, while the lowest OH and relatively low O_x indicate suppressed photochemistry. The elevated $PM_{2.5}$ under WarmHumid is consistent with enhanced aqueous-phase secondary aerosol formation with the lowest HNO_3, suggesting efficient gas-to-particle conversion of HNO_3 into NH_4NO_3. This is further confirmed by the $PM_{2.5}$

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composition (Fig. S6): NO_3^- is the dominant secondary inorganic component with the highest median under WarmHumid and the lowest under DryHot; NH_4^+ follows the same pattern, while SO_4^{2-}, EC, and OC show relatively small variations across types. In contrast, DryHot favors the strongest photochemical O_3 production, with the highest O_x, NO_2, and HNO_3 indicating active daytime photochemistry and abundant precursors, yet the lowest $PM_{2.5}$ due to the absence of aqueous-phase enhancement, high temperature volatilization of NH_4NO_3, and deeper boundary layer dilution. The afternoon (12:00–16:00 LST) formaldehyde-to-NO_2 ratio (FNR) ranges from 0.76 to 0.93 (median) (Fig. S5e), placing the DHP samples in the transitional regime between VOC-limited and NO_x-limited conditions (FNR ≈ 0.6–1.8; Tonnesen and Dennis, 2000; Folorunsho et al., 2025), with Convective and WarmHumid showing the highest FNR and Stable and DryHot the lowest. Together, these results demonstrate that $PM_{2.5}$ is more sensitive to different meteorological conditions with highest value under stable and humid conditions that favor accumulation and aqueous chemistry. In contrast, O_3 stays persistently elevated under all types, with DryHot favoring the strongest photochemical production.

Based on the above discussion, the characteristics of DHP differ substantially among different meteorological conditions. WarmHumid shows the most pronounced secondary inorganic aerosol enhancement, driven by efficient gas-to-particle conversion under humid conditions as evidenced by the lowest HNO_3. Stable similarly favors particulate accumulation because of shallow boundary layers and suppressed ventilation, resulting in the highest $PM_{2.5}$ median and the widest spread, with the lowest OH indicating suppressed photochemical activity. In contrast, DryHot and Moderate are characterized by lower $PM_{2.5}$ yet the highest O_3 and O_x, with DryHot also exhibiting the highest NO_2 and HNO_3, indicating that strong thermal forcing and active photochemistry enhance ozone production while deeper mixing and high-temperature volatilization of NH_4NO_3 limit particle increase. Convective shows the low $PM_{2.5}$ with moderate O_3, suggesting that efficient ventilation dominates its pollution characteristics. Overall, these results demonstrate that DHP is not controlled by a single meteorological element but arises from the combined influences of boundary-layer mixing, temperature, humidity, and aqueous-phase versus gas-phase chemical pathways.

3.4 Responses of DHP to emission reductions under different meteorological conditions

In this section, the response of DHP to emission reductions under different meteorological conditions and associated sensitivity diagnostics are discussed. Figure 5 shows the percentage response of MDA8 O_3 and $PM_{2.5}$ to NO_x and VOC reductions under five meteorological condition types. For O_3, all types exhibit asymmetric isopleths where NOx reductions produce larger decreases than equivalent VOC reductions, but the degree of asymmetry varies substantially. Convective and WarmHumid show strong NO_x dominance: under 50% NOx-only reduction, O_3 decreases by 17.4% and 18.2%, respectively, compared to only 10.2% and 12.1% under 50% VOC-only reduction, yielding a NO_x advantage of 6–7 percentage points. This is consistent with their higher afternoon FNR (Fig. S5), placing them closer to the NO_x-sensitive side of the transitional regime. In contrast, Stable, DryHot, and Moderate show nearly symmetric responses at moderate reduction levels: under 50% NO_x-only reduction, O_3 decreases by 16.0%, 15.6%, and 16.3%, respectively, versus 13.5%, 12.7%, and 13.5% under 50% VOC-only reduction, with the NO_x advantage narrowing to only 2–3 percentage points. At weak control (≤20% reduction), the pattern reverses in these three types with VOC-only reductions (-5.0%, -4.7%, and -4.9%,

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respectively) slightly larger than NOx-only reductions (-4.4%, -4.3%, and -4.5%), indicating a more VOC-sensitive baseline. Under joint 50%/50% control, the O_3 response converges across types (-23.3% to -25.2%), as the nonlinear amplification of NOx sensitivity compensates for the weaker baseline NO_x response in the more VOC-sensitive types. WarmHumid consistently shows the strongest O_3 response for all reduction levels (e.g., -25.2% at joint 50%/50%), while DryHot shows the weakest (e.g., -23.3% at joint 50%/50%). For $PM_{2.5}$, the response is overwhelmingly dominated by NO_x reductions under all types (VOC-only reductions produce only 1–2% decreases, which is attribute to the known underestimation of secondary organic aerosol (SOA) in WRF-Chem with the MOSAIC aerosol scheme (Zhao et al., 2026a), with WarmHumid and Stable showing the strongest $PM_{2.5}$ response (-21.4% and -21.2% at 50% NO_x reduction), and DryHot showing the weakest (-15.2%). The absolute response (Fig. S7) shows the same pattern.

It is important to note that the overall NO_x-sensitivity of O_3 for different meteorological condition is largely attributable to the spatial distribution of DHP samples. 64.4% of the DHP samples are located in suburban areas and 28.6% in rural areas, with only 7.0% in urban areas. This suburban and rural dominance is for all types: suburban and rural samples together account for 90.8% (Convective), 89.7% (DryHot), 92.2% (Moderate), 92.7% (Stable), and 95.4% (WarmHumid) of the DHP samples. As shown in Fig. S8 and S9, rural and suburban samples exhibit stronger O_3 sensitivity to NO_x reductions than to VOC reductions, whereas urban samples display the opposite pattern with greater VOC sensitivity. Therefore, the apparent NO_x-dominance reflects the overwhelming contribution of suburban and rural samples, which mask the VOC-limited regime that prevails in urban areas. Notably, this urban VOC-limited characteristic is not specific to DHP episodes: the response matrices for all samples (Fig. S10 and S11) show the same regional pattern, with urban areas consistently exhibiting stronger O_3 sensitivity to VOC reductions than to NO_x reductions.

The O_3 gradient diagnostics further clarify these differences (Fig. 6). The gradients measure how much the pollutant concentration changes per additional percentage point of emission reduction ($\partial\Delta O_3/\partial NO_x$ or $\partial\Delta O_3/\partial VOC$), computed by differentiating the absolute-response matrices with respect to the reduction level at 10-percentage-point intervals (0, 10, 20, 30, 40, 50%). For example, at the 10% NO_x reduction level, $\partial O_3/\partial NO_x$ is calculated as (ΔO_3 at 20% NO_x reduction − ΔO_3 at 0% NO_x reduction) / 20%, yielding the marginal O_3 change per percent of NO_x reduction at that point. All panels display negative values, indicating that emission reductions effectively lower O_3. At weak emission control (≤10% reduction), Convective and WarmHumid show stronger O_3 benefit from NO_x reduction than from VOC reduction ($|\partial\Delta O_3/\partial NO_x|/|\partial\Delta O_3/\partial VOC| \approx 1.15–1.28$) while Stable, DryHot, and Moderate show the opposite, with VOC reductions more effective ($|\partial\Delta O_3/\partial NO_x|/|\partial\Delta O_3/\partial VOC| \approx 0.81–0.85$), consistent with Fig. 5. As NO_x reduction deepens, the two sensitivities diverge nonlinearly but asymmetrically: $\partial\Delta O_3/\partial NO_x$ intensifies by a factor of ~2.0–2.4 (roughly doubling by 50% NO_x reduction) while $\partial\Delta O_3/\partial VOC$ weakens to ~0.5–0.6 of its initial value. Along the VOC-only path, $\partial\Delta O_3/\partial VOC$ also intensifies but only by a factor of ~1.2–1.3, while $\partial\Delta O_3/\partial NO_x$ weakens to ~0.4–0.7 of its initial value. Therefore, the effectiveness of NO_x reduction accelerates far more strongly than that of VOC. Consequently, even under Stable, DryHot, and Moderate where VOC reductions are initially more effective, NO_x reductions overtake them once the control level exceeds ~20%, showing NO_x dominated

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total O_3 response under all types in Fig. 5. For $PM_{2.5}$ (Fig. S12), $\partial\Delta PM_{2.5}/\partial NO_x$ dominates $\partial\Delta PM_{2.5}/\partial VOC$ by an order of magnitude under all types and for all reduction levels, confirming that $PM_{2.5}$ responds almost exclusively to NO_x control.

Figure 7 further links the responses shown in Fig. 5 and 6 to the underlying chemical states. Each panel includes all 36 emission-reduction scenarios (6 NO_x reduction levels × 6 VOC reduction levels) for each meteorological condition type, with the zero-reduction baseline highlighted by yellow-filled markers. The axes represent the absolute value of chemical state diagnosed for each scenario, while the point color denotes the change in O_3 or $PM_{2.5}$ relative to the baseline. Figure 7a shows the O_3 response mapped onto the $\log_{10}(OH)$ and FNR space, indicating that all types primarily lie in the transitional regime but with different shifts in chemical sensitivity. WarmHumid and Convective occupy the higher FNR of this space, implying a stronger tendency toward NO_x-limited O_3 production; this directly supports Fig. 5, where these two types show a greater sensitivity to NO_x reductions than to VOC reductions. In contrast, Stable, DryHot, and Moderate are concentrated at lower FNR, closer to the VOC-influenced edge of the transitional regime, consistent with Fig. 5 showing near-symmetric NO_x–VOC effectiveness and a slight VOC advantage under weak controls. OH mainly modulates the overall photochemical intensity, whereas the separation among types is better explained by FNR. Figure 7b shows O_3 response in the $\log_{10}(HNO_3)$ and NO_2 space, reflecting the strength of NO_x oxidation and termination (e.g., $NO_2 + OH \rightarrow HNO_3$) and thus how O_3 responds to NO_x perturbations. WarmHumid and Convective exhibit trajectories that emphasize O_3 reductions along decreasing NO_2 and HNO_3, consistent with the stronger NO_x-driven reductions reported in Fig. 5. By comparison, Stable, DryHot, and Moderate occupy relatively NO_x-rich portions of this space (higher NO_2 and/or higher HNO_3), matching the more symmetric behavior in Fig. 5.

Figure 7c shows the $PM_{2.5}$ response in the NH_3/HNO_3 and NO_2 space, demonstrating that $PM_{2.5}$ changes are controlled primarily through the nitrate formation pathway under all types. $PM_{2.5}$ responds strongly as the NH_3–HNO_3 balance shifts under NO_x reduction under WarmHumid and Stable indicating higher nitrate aerosol formation efficiency, which is also consistent with Fig. 5 where these two types show the largest $PM_{2.5}$ decreases under NO_x reductions. DryHot shows weaker $PM_{2.5}$ sensitivity within the same chemical coordinate system, consistent with Fig. 5, indicating that hot conditions reduce the effectiveness of translating HNO_3 changes into particulate mass via unfavorable ammonium nitrate partitioning. Convective and Moderate generally fall between these extremes, consistent with their intermediate $PM_{2.5}$ response ranking in Fig. 5. Figure 7d shows $PM_{2.5}$ response in the NH_3/HNO_3 and NO_3^- space and directly confirms that NO_3^- is the dominant driver of $PM_{2.5}$ reductions. Under all types, stronger $PM_{2.5}$ decreases co-occur with lower NO_3^-, but the coupling strength differs: WarmHumid and Stable show a clearer alignment between declining NO_3^- and more negative $PM_{2.5}$ response, consistent with their stronger NO_x-driven $PM_{2.5}$ sensitivity in Fig. 5, whereas DryHot exhibits a weaker effective coupling, consistent with its weak $PM_{2.5}$ response.

Figure 8 illustrates the diurnal variation of the chemical responses. For O_3 (Fig. 8a), all meteorological condition types exhibit a similar diurnal pattern characterized by weak nighttime changes, rapidly increasing reductions after sunrise, and maximum decreases during late morning and afternoon when photochemical production is most active. The strongest daytime O_3 reductions occur under

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WarmHumid, whereas the other types show comparatively weaker responses. This behavior is consistent with the FNR response (Fig. 8b), where WarmHumid shows the largest positive FNR response, indicating that emission reductions push the chemical regime further toward the NO_x-sensitive side. These diurnal patterns are consistent with Fig. 5, where WarmHumid exhibits the strongest O_3 response and the largest asymmetry between NO_x and VOC controls.

In contrast, $PM_{2.5}$ responses (Fig. 8c) are strongest during nighttime and early morning and weaken substantially during daytime. The contrast among different meteorological condition is more pronounced than for O_3, with WarmHumid and Stable exhibiting the largest reductions and DryHot the weakest throughout most of the day. This behavior is closely linked to the NH_3/HNO_3 response (Fig. 8d), which shows the largest positive changes under WarmHumid and Stable during nighttime and early morning, indicating that emission reductions substantially increase the NH_3/HNO_3 ratio and thus enhance the sensitivity of nitrate formation to HNO_3 removal. Conversely, the smaller NH_3/HNO_3 response under DryHot is consistent with less favorable conditions for particulate nitrate formation, leading to weaker $PM_{2.5}$ reductions.

The p10–p90 ranges further reveal that the influence of emission-reduction levels varies throughout the day. For O_3, the spread increases markedly during the daytime reduction period, indicating enhanced sensitivity of O_3 responses to emission controls under active photochemical conditions. In contrast, the largest spread in $PM_{2.5}$ and NH_3/HNO_3 response occurs during nighttime and early morning, suggesting that the effectiveness of emission reductions on nitrate-related processes is more affected by reduction scenario during periods when partitioning and accumulation processes dominate. Notably, for O_3 the inter-scenario variability clearly exceeds the inter-type differences, whereas for $PM_{2.5}$ the inter-type differences are comparable to or even larger than the inter-scenario variability, highlighting that O_3 responses are controlled primarily by reduction intensity, while $PM_{2.5}$ responses are additionally modulated by meteorological condition.

3.5 Aerosol-induced change of pollutant response to emission reductions

To isolate the aerosol-induced change of the effectiveness of emission control for both O_3 and $PM_{2.5}$, as described in section 2.3, the aerosol-induced change of the response ($\Delta_{aer}X$) is calculated as the difference between the ΔX and $\Delta_{wo}X$. A negative value indicates that aerosols enhance the emission reduction effect (i.e., the concentration decline is larger when aerosols are present), while a positive value indicates that aerosols weaken it. The absolute changes of response are shown in Fig. S13 and the percentage changes of response are shown in Fig. 9.

For MDA8 O_3 (Fig. 9a–e), Δ_{aer}MDA8 O_3 is generally negative under Convective, WarmHumid, DryHot, and Moderate, indicating that aerosol slightly enhance the effectiveness of emission reductions. The magnitude of this enhancement is relatively small, typically less than 1% in relative terms and reaching up to -0.41 to -0.58 ppb in absolute terms (Fig. S13), as these are regional mean values averaged over the entire sample. In contrast, under Stable, Δ_{aer}MDA8 O_3 becomes positive when NO_x reductions are large and VOC reductions are small (up to 0.6% with absolute value of 0.43 ppb; Fig. S13), suggesting that aerosol feedbacks can weaken the O_3 reduction under stagnant atmospheric conditions. This behavior likely reflects complex interactions among aerosols, photochemistry, and boundary layer processes where reduced photolysis and elevated NO titration offset the emission-driven O_3 decline. However, as the VOC

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emission reduction ratio increases, the positive Δ_{aer}MDA8 O_3 diminishes and eventually turns negative (reaching -0.8% with the absolute value of -0.63 ppb at VOC-only scenario; Fig. S13), indicating that the weakening effect under Stable can be overcome by sufficient VOC reduction. For $PM_{2.5}$ (Fig. 9f–j), $\Delta_{aer}PM_{2.5}$ remains consistently negative under all types and emission control scenarios, demonstrating that aerosol generally enhance $PM_{2.5}$ reduction effectiveness. The enhancement becomes stronger as NO_x reductions increase and is particularly pronounced under Stable and WarmHumid, where the relative enhancement reaches -4.3% to -4.8% and the absolute enhancement reaches -2.08 to -2.10 μg m^{-3} at 50% NO_x reduction (Fig. S13). These results indicate that aerosol amplifies the response of $PM_{2.5}$ to precursor emission controls. The effect is weaker under Convective (-3.1%, -1.30 μg m^{-3}), DryHot (-2.3%, -0.94 μg m^{-3}), and Moderate (-2.9%, -1.23 μg m^{-3}) but remains consistently beneficial for $PM_{2.5}$ reduction. Overall, the response matrices show that aerosol generally enhances the effectiveness of emission control measures, especially for $PM_{2.5}$. For O_3, however, the influence of aerosol feedbacks is different for different meteorological conditions: they typically enhance O_3 reductions under Convective, WarmHumid, DryHot, and Moderate, but weaken the O_3 response under Stable.

Figure 10 decomposes the aerosol-induced changes into diurnal profiles of pollutant response and the related meteorological and chemical elements (T2, PBLH, OH, and FNR) for different meteorological condition. The hourly decomposition reveals that the instantaneous aerosol effects are substantially larger than the daily averages, with distinct diurnal phases that provide insight into how meteorological condition modulates the aerosol–radiation–chemistry coupling. Aerosol feedback weakens O_3 reduction effectiveness ($\Delta_{aer}O_3 > 0$, Fig. 10a) while enhancing $PM_{2.5}$ reduction effectiveness ($\Delta_{aer}PM_{2.5} < 0$, Fig. 10b) under all types, but both the magnitude and sign exhibit strong diurnal variation. For O_3, the aerosol weakening is concentrated in the morning (hours 8–10) and evening (hours 18–20), with a sign reversal during the afternoon (hours 12–16). Under Stable, the morning weakening reaches a median of 0.69 ppb (1.7%), with the strongest scenario reaching 1.85 ppb (4.5%), and the evening weakening reaches +0.53 ppb (1.2%, up to 1.14 ppb/2.7%). In contrast, the afternoon aerosol effect on O_3 is near zero under Stable (-0.01 ppb) and slightly negative under the other types (-0.28 to -0.33 ppb, -0.3% to -0.4%), indicating a modest enhancement of O_3 reduction during peak photochemical hours. The morning weakening is weakest under DryHot (0.15 ppb, 0.3%) and strongest under Stable (0.69 ppb, 1.7%). The scenario spread is large: under Stable, the P10–P90 range spans 0.07 to 1.51 ppb in the morning and -0.14 to 1.00 ppb in the evening, indicating that while the direction of aerosol weakening is robust, its magnitude depends strongly on the emission reduction pathway. For $PM_{2.5}$, the aerosol enhancement is concentrated in the morning (hours 7–10), with a median of -1.46 μg m^{-3} (-2.8%) under Stable, -1.74 μg m^{-3} (-3.8%) under WarmHumid, -1.34 μg m^{-3} (-3.3%) under Convective, -1.22 μg m^{-3} (-2.7%) under Moderate, and -1.02 μg m^{-3} (-2.4%) under DryHot. The strongest scenarios reach -2.66 to -2.89 μg m^{-3} (-5.1% to -6.4%) under Stable and WarmHumid. During the afternoon (hours 12–16), the $PM_{2.5}$ enhancement weakens substantially but persists under Stable (-1.06 μg m^{-3}, -3.7%) and WarmHumid (-0.86 μg m^{-3}, -3.2%), while diminishing to --0.12 μg m^{-3} (-0.7%) under Convective and -0.07 μg m^{-3} (-0.4%) under DryHot. This persistent afternoon $PM_{2.5}$ enhancement under Stable and WarmHumid is a key distinction from the other types.

The aerosol-induced increase of temperature ($\Delta_{aer}T2 > 0$, Fig. 10c) is sustained for all 24 hours under

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Stable and WarmHumid (peak 0.08 K and 0.05 K at hour 9, with P10–P90 of 0.01 to 0.15 K and -0.01 to 0.11 K, respectively) but weaker under DryHot. This indicates that when aerosol feedback is weakened under emission control, the enhanced solar radiation raises surface temperature more, which in turn increases sensible heat flux and promotes boundary layer development. Accordingly, Δ_{aer}PBLH is predominantly positive (Fig. 10d), reflecting that the removal of aerosol suppression leads to a higher PBLH and thus stronger dispersion. Under Stable, positive Δ_{aer}PBLH spans 19 out of 24 hours with a broad daytime value of 14–18 m (hours 9–14), and the P10 remains positive at hour 10 (1.5 m), indicating that the aerosol-induced increase of PBLH is robust across scenarios. Under Convective, the positive Δ_{aer}PBLH is concentrated around morning boundary layer development (peak 39 m at hour 9) but with a wider spread (P10–P90: -1.2 to 16.0 m at hour 10), reflecting greater scenario dependence. The extended duration of PBLH increase under Stable directly sustains the persistent afternoon $PM_{2.5}$ enhancement.

Figure 10e shows that when aerosol feedback is weakened, increased solar radiation enhances OH production with the largest increase of Δ_{aer}OH under Stable. The OH spread is the largest among all variables indicating that the OH amplification is highly scenario-dependent, with some emission pathways even producing negative Δ_{aer}OH. The FNR response (Fig. 10f) is predominantly negative, with the strongest change under Stable, but the spread frequently crosses zero across scenarios, indicating that the direction of FNR response is scenario-dependent while the median remains negative. The magnitude of FNR changes is very small suggesting that aerosol affects O_3 reduction effectiveness primarily through the OH changes rather than through substantial shifts in the NO_x- versus VOC-limited regime.

Generally, under Stable, the combination of the longest PBLH sensitivity duration (19 h, with P10 remaining positive), strongest OH amplification (4.1×10^5 molec cm^{-3} over 18 h) maximizes both the weakening of O_3 reduction and the enhancement of $PM_{2.5}$ reduction. Under WarmHumid, the $PM_{2.5}$ enhancement is comparable to Stable due to humidity driven heterogeneous chemistry, but the O_3 weakening is much weaker, reflecting a decoupling between the radiative and chemical pathways under moist conditions. Under DryHot, efficient turbulent mixing and low humidity minimize all feedback pathways and narrow the scenario spread, yielding the weakest responses.

4 Conclusions

This study investigated the response of co-occurring $PM_{2.5}$ and O_3 pollution (DHP; daily $PM_{2.5} > 35$ μg m^{-3} and MDA8 $O_3 > 100$ μg m^{-3}) to precursor reductions under typical meteorological conditions and the role of aerosol feedback in modulating this response using WRF-Chem with 36 NO_x–VOC emission-reduction scenarios (0–50% each) and paired simulations with and without aerosol-meteorology feedback for July 2020 over BTHS.

DHP samples were characterized by warm temperature (T2 ~ 23–31°C), moderate-to-high humidity (RH ~ 45–80%), and low PBLH (0.5–1.1 km), with concurrent increases of 8–12 μg m^{-3} in $PM_{2.5}$ and 8–15 ppb in MDA8 O_3 relative to all samples. These characteristics are consistent with previous findings linking co-pollution to stagnant and humid conditions (Ma et al., 2023; Luo et al., 2022; Dai et al., 2024; Liu et al., 2026). Based on boundary layer, temperature and humidity conditions, the meteorological conditions of DHP samples are classified into five types: Convective (deep PBLH, low RH2), Stable (shallow PBLH, low T2), WarmHumid (high RH2, moderate T2), DryHot (high T2, low RH2), and Moderate (intermediate T2 and RH2). Unlike previous synoptic-scale classifications (Zong et al., 2021;

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Wang et al., 2025b; Zhan et al., 2024) or single meteorological element (Qian et al., 2025), this approach directly captured local boundary layer and thermodynamic conditions. As Zong et al. (2021) noted, local differences under the same circulation patterns can cause two- to three-fold concentration variations; our classification addressed this by partitioning meteorological conditions into physically distinct regimes governing DHP formation.

The pollutant characteristics were different under different meteorological conditions. Stable and WarmHumid showed the highest $PM_{2.5}$ (median ~46 μg m^{-3}), driven by shallow boundary layer accumulation and humid gas-to-particle conversion, respectively, while DryHot showed the lowest (~40 μg m^{-3}) due to unfavorable NH_4NO_3 partitioning. NO_3^- drives the $PM_{2.5}$ contrast. For O_3, DryHot and Moderate showed the highest concentrations (~83–84 ppb) through active photochemistry, while WarmHumid was lowest (~76 ppb).

O_3 and $PM_{2.5}$ responses to emission controls were also distinctly different under different meteorological conditions. For O_3, WarmHumid consistently showed the strongest O_3 response at all reduction levels, while DryHot showed the weakest. WarmHumid and Convective also showed stronger NO_x sensitivity (NO_x-only exceeds VOC-only by 6–7 percentage point at 50% reduction) due to higher FNR, while Stable, DryHot, and Moderate showed near-symmetric responses with VOC slightly more effective at ≤20% reduction. Beyond ~20% NO_x reduction, nonlinear amplification caused NO_x control to overtake VOC control under all types, extending Ding et al. (2022) by showing the crossover point depends on meteorological condition. For $PM_{2.5}$, NO_x reductions dominated through the nitrate pathway, with WarmHumid and Stable showing the strongest response (-21.4% and -21.2% at 50% NO_x) and DryHot the weakest (-15.2%).

Aerosol feedback generally enhanced $PM_{2.5}$ reduction but weakened O_3 reduction, with both effects different under different meteorological conditions. For $PM_{2.5}$, the enhancement was strongest under Stable and WarmHumid (-4.3% to -4.8% at 50% NO_x) and weakest under DryHot (-2.3%), consistent with Zhu et al. (2021) but extending to meteorological condition difference. For O_3, aerosol feedback slightly enhanced reduction under Convective, WarmHumid, DryHot, and Moderate (< 1%), but weakened it under Stable when NO_x reductions were large without VOC co-reduction (up to +0.6%), consistent with Yang et al. (2024) who showed weakened ARI exacerbates O_3, but our results further revealed this effect is concentrated under stagnant conditions and can be overcome by sufficient VOC co-reduction. Diurnally, the O_3 weakening peaked in morning and evening (0.69 ppb under Stable at hour 9) while the afternoon effect was near zero or slightly negative; the $PM_{2.5}$ enhancement peaked in morning (-1.74 μg m^{-3} under WarmHumid) and persisted into afternoon under Stable and WarmHumid. Under Stable, persistent PBLH increase (19 h) and strong OH amplification sustained both the largest $PM_{2.5}$ enhancement and O_3 weakening; under WarmHumid, humidity driven heterogeneous chemistry yielded comparable $PM_{2.5}$ enhancement but weaker O_3 weakening; under DryHot, efficient mixing and low humidity minimized all feedback. These results extended Li et al. (2026) and Zhao et al. (2026b) by demonstrating that aerosol feedback varied substantially for different meteorological condition even within the same season.

Several limitations should be noted. First, the analysis covers a single month (July 2020); while the five meteorological conditions types are physically distinct, they may not capture the full spectrum of

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conditions conducive to DHP in other seasons or years. Second, the MOSAIC aerosol scheme is known to underestimate SOA, which weakens the simulated $PM_{2.5}$ response to VOC reductions; the $PM_{2.5}$ response should therefore be interpreted as conservative estimates. Third, the DHP thresholds reflect the air quality changes after the Action Plan took effect and may require adjustment as concentrations continue to decline.

These findings indicate important implications for atmospheric chemistry understanding and air quality management. From a scientific perspective, the results demonstrate that the effectiveness of emission controls and aerosol feedback on pollutant reductions are not fixed but vary systematically with local boundary layer, thermal, and moisture conditions. This dependence helps explain why identical emission reduction policies can yield different outcomes across episodes and locations. For management, the results suggest dynamic and meteorological condition specific control strategies: coordinated NOx–VOC reduction is most beneficial under Stable and WarmHumid when $PM_{2.5}$ is most responsive and aerosol feedback most strongly modulates O_3 reduction. Under Stable, sufficient VOC co-reduction can overcome aerosol-induced O_3 weakening. Under DryHot and Moderate, deeper combined precursor reductions are needed because control efficiency is weaker and aerosol-feedback effects are limited. In urban areas, additional VOC control remains necessary to avoid possible O_3 increases under VOC-limited chemistry. Incorporating meteorological classification into emission control strategies can enhance the effectiveness and efficiency of DHP mitigation.

Code and data availability

The updated USTC version of WRF-Chem can be downloaded from https://doi.org/10.5281/zenodo.15702248 or can be obtained from the corresponding author upon request. The Multi-resolution Emission Inventory for China (MEIC) at 0.25° x 0.25° resolution for 2020 is available at http://meicmodel.org.cn (last access: 11 June 2026). ERA5 reanalysis data is available from the Copernicus Climate Data Store (https://cds.climate.copernicus.eu/). Other raw data can be provided by the corresponding authors upon request.

Author contributions

YG, YZ, and MZ designed the study. YG, and YZ conducted model simulations. YG and MZ carried out the analysis and visualized the results, with YZ and ZY contributing to the investigation. The manuscript draft was written by YG. All authors discussed the results and edited the paper.

Competing interests

The authors declare that they have no conflict of interest.

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Table 1 Summary of WRF-Chem numerical experimental design.

Experiment Group	Emission Scenarios	Aerosol-meteorology interaction	Description
EXP_W	Baseline and 35 Sensitivity Matrix (36 scenarios)	On	with full aerosol-meteorology interaction
EXP_WO	Baseline and 35 Sensitivity Matrix (36 scenarios)	Off	without aerosol-meteorology interaction

Note: The Sensitivity Matrix includes 35 scenarios with varying NO_x and VOCs reduction rates (0% to 50% with 10% interval), plus the Baseline (0% reduction).

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Table 2 Statistics of comparisons between observed and simulated (EXP_W_BASE) hourly 2m temperature (T2, °C), 2m relative humidity (RH2, %), 10m wind speed (WS10, m s^{-1}), 10m wind direction (WD10, °), planetary boundary layer height (PBLH, m), $PM_{2.5}$ (μg m^{-3}), and O_3 (μg m^{-3}) averaged at the observational sites of Beijing-Tianjin-Hebei (BTH) and Shandong Province (SD) from 1–30 July 2020 (local time).

Variable	region	[a]N	[c]AVGO	[c]AVGM	[b]R	[d]MB	[d]NMB	[e]RMSE
T2	BTH	712	25.03	25.90	0.91	0.87	3.47	1.89
	SD	712	25.03	25.83	0.92	0.80	3.21	1.69
RH2	BTH	712	72.07	65.46	0.91	-6.61	-9.17	9.63
	SD	712	76.06	70.61	0.92	-5.45	-7.17	8.43
WS10	BTH	712	1.82	2.50	0.80	0.68	37.22	0.80
	SD	712	2.15	2.96	0.83	0.80	37.38	1.00
WD10	BTH	712	142.35	162.39	0.69	20.05	14.08	57.68
	SD	712	144.23	151.43	0.85	7.20	4.99	42.40
PBLH	BTH	720	495.58	681.20	0.95	185.62	37.45	280.21
	SD	720	502.60	674.36	0.94	171.76	34.17	306.55
$PM_{2.5}$	BTH	710	36.47	33.53	0.64	-2.94	-8.05	11.09
	SD	712	27.83	26.72	0.56	-1.11	-3.98	9.74
O_3	BTH	710	109.05	85.12	0.81	-23.92	-21.94	40.40
	SD	712	100.83	67.33	0.82	-33.50	-33.22	43.73

[a] *N* is the number of paired samples;

[b] *R* is the correlation coefficient between the observation and model results;

[c] AVGO and AVGM are the average values of observation and model results, sampled at the observation site and time, respectively;

[d] *MB* and *NMB* are the mean biases between the observation and model results, and the normalized mean bias between the observation and model results, respectively;

[e] *RMSE* is the root-mean-square error between observation and model results.

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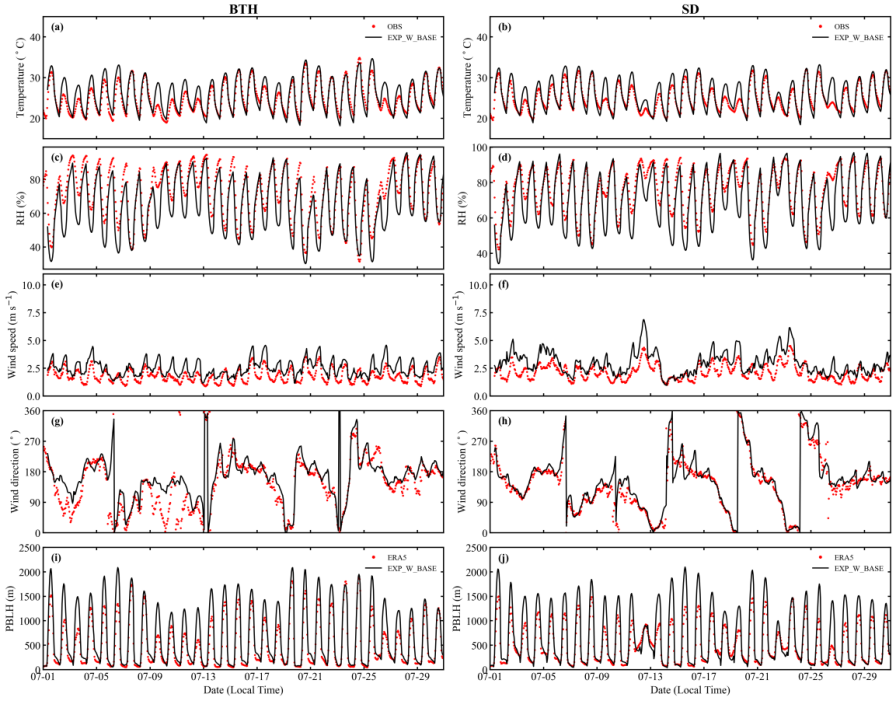

Figure 1 The comparisons between observed and simulated hourly (a) (b) T2 (°C), (c) (d) RH2 (%), (e) (f) WS10 (m s^{-1}), (g) (h) WD10 (°) and (i) (j) PBLH (m) average at the sites in BTH and SD from 1 to 30 July 2020.

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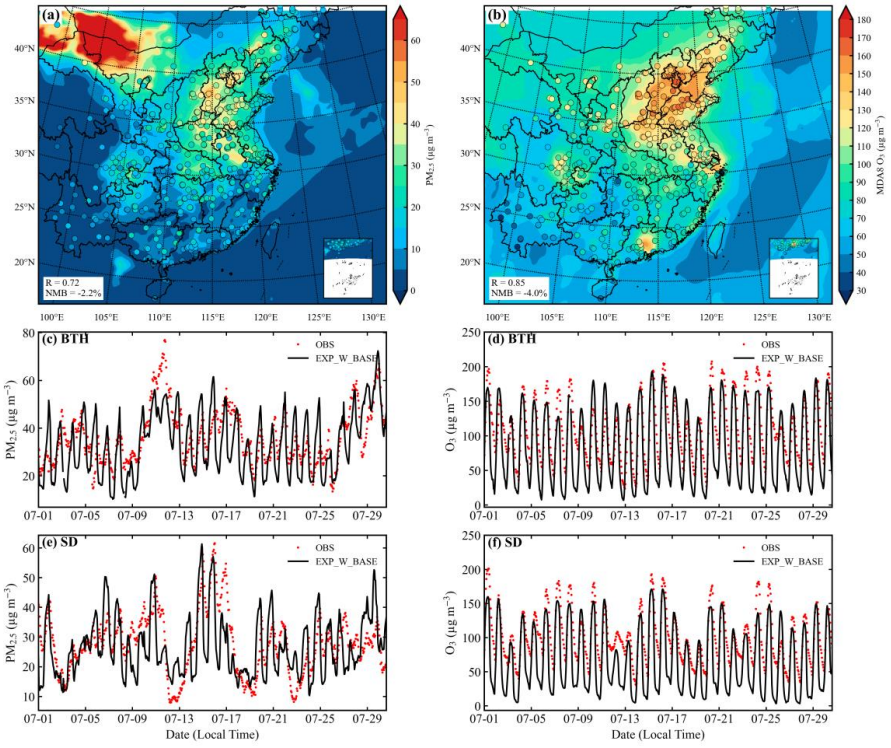

Figure 2 Spatial distribution of simulated mean (a) $PM_{2.5}$ and (b) Maximum Daily 8-hour Average O_3 (MDA8 O_3) surface concentration (μg m^{-3}) with the corresponding observed mean concentration overlaid as colored markers for the period from 1-30 July 2020. The comparisons between observed and simulated hourly (c)(e) $PM_{2.5}$ and (d)(f) O_3 surface concentration average at the sites in BTH and SD from 1 to 30 July 2020.

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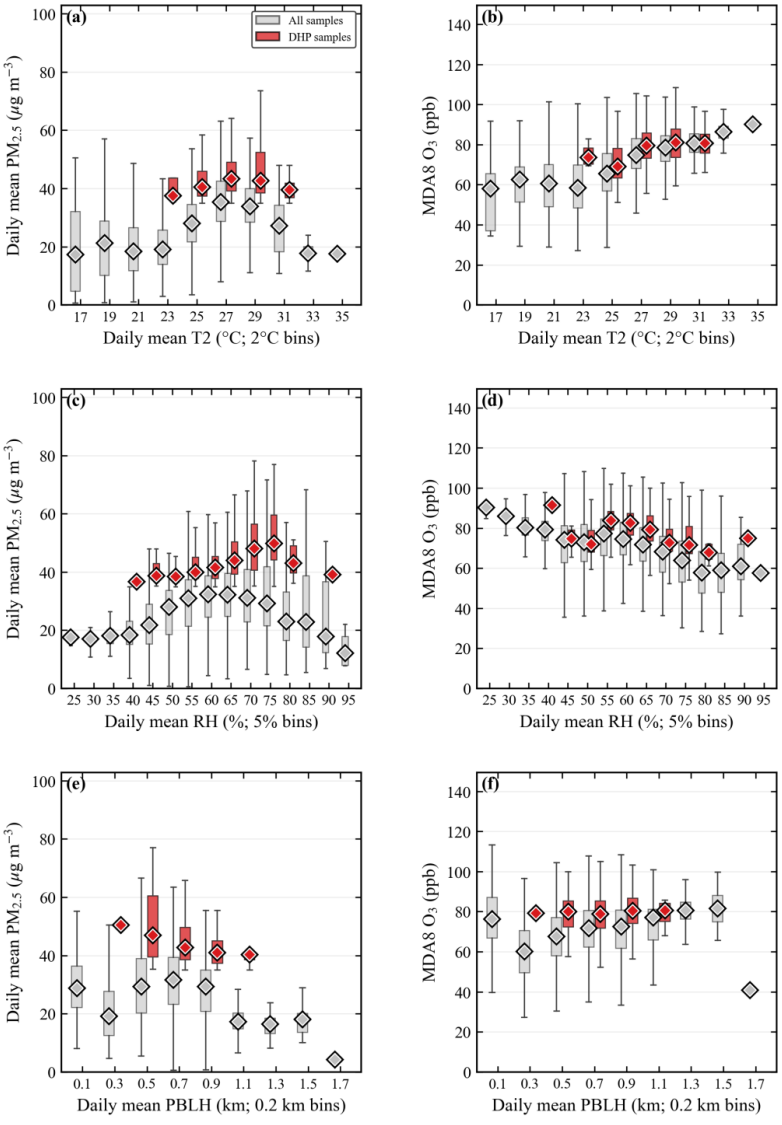

Figure 3 Boxplots of (a), (c), (e) daily mean $PM_{2.5}$ (μg m^{-3}) and (b), (d), (f) MDA8 O_3 (ppb) in each T2, RH2 and PBLH bin of all samples and DHP samples from the EXP_W_BASE experiment. T2 is binned to 2°C intervals, RH2 to 5% intervals and PBLH to 0.2km intervals. In each boxplot, the horizontal line inside the box represents the median, the box spans the interquartile range (25th–75th percentile), and the whiskers extend to the most extreme data points within 1.5 times the interquartile range from the box edges.

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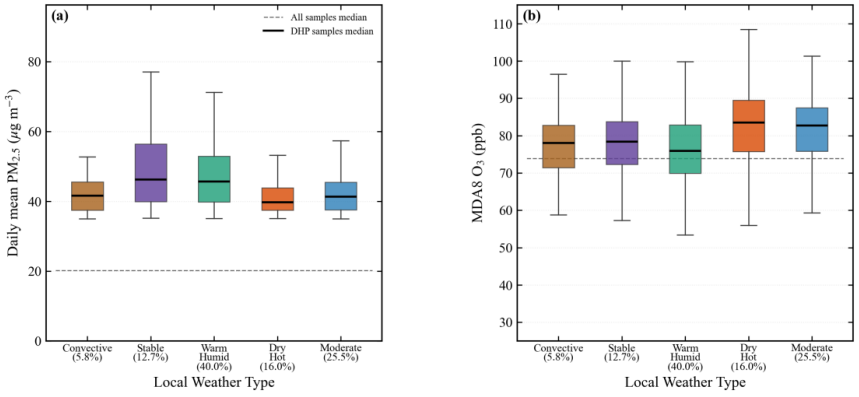

925 **Figure 4** Boxplots of (a) daily mean $PM_{2.5}$ (μg m^{-3}) and (b) MDA8 O_3 (ppb) for different meteorological condition types. The numbers in parentheses beneath each type indicate the proportion in the DHP samples and the gray dashed lines denote the median values for all samples.

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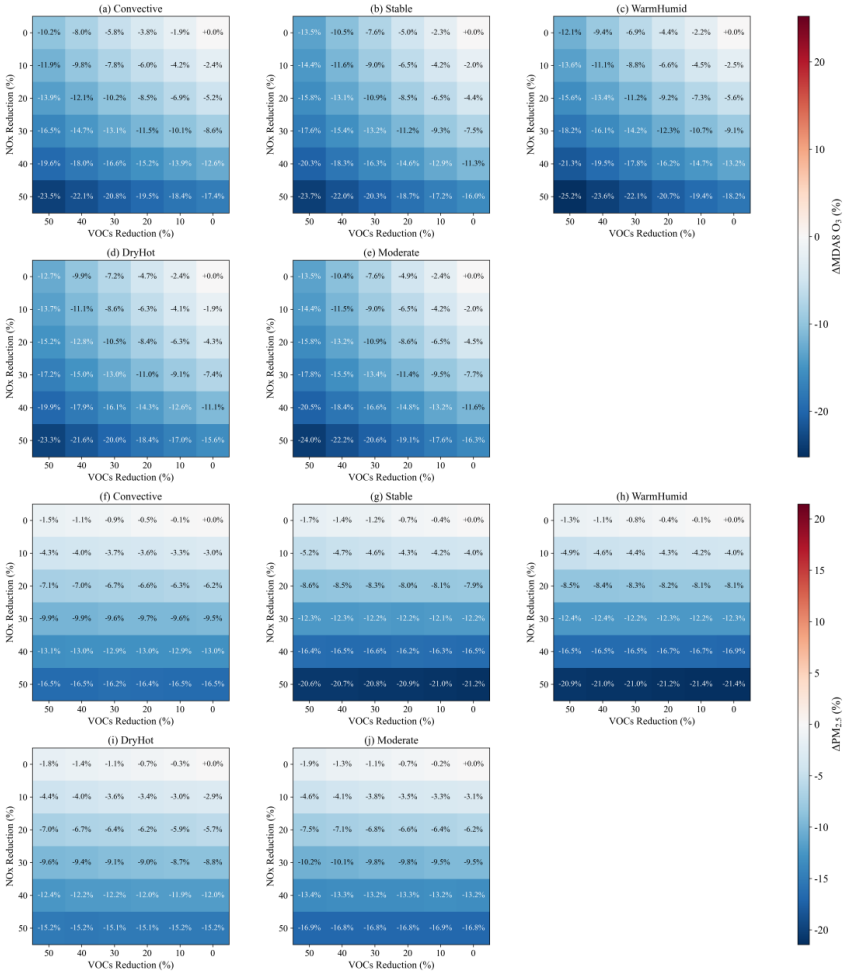

930 **Figure 5** MDA8 O_3 and $PM_{2.5}$ response to NOx and VOC emission reductions for DHP samples classified into different meteorological condition types. The percentage differences in MDA8 O_3 between each reduction scenario and the baseline scenario (ΔMDA8 O_3, %) for (a) Convective, (b) Stable, (c) WarmHumid, (d) DryHot, and (e) Moderate, and the percentage differences in $PM_{2.5}$ between each reduction scenario and the baseline (Δ$PM_{2.5}$, %) for (f) Convective, (g) Stable, (h) WarmHumid, (i) DryHot, and (j) Moderate. Rows and columns denote NOx and VOC
935 reduction levels (%).

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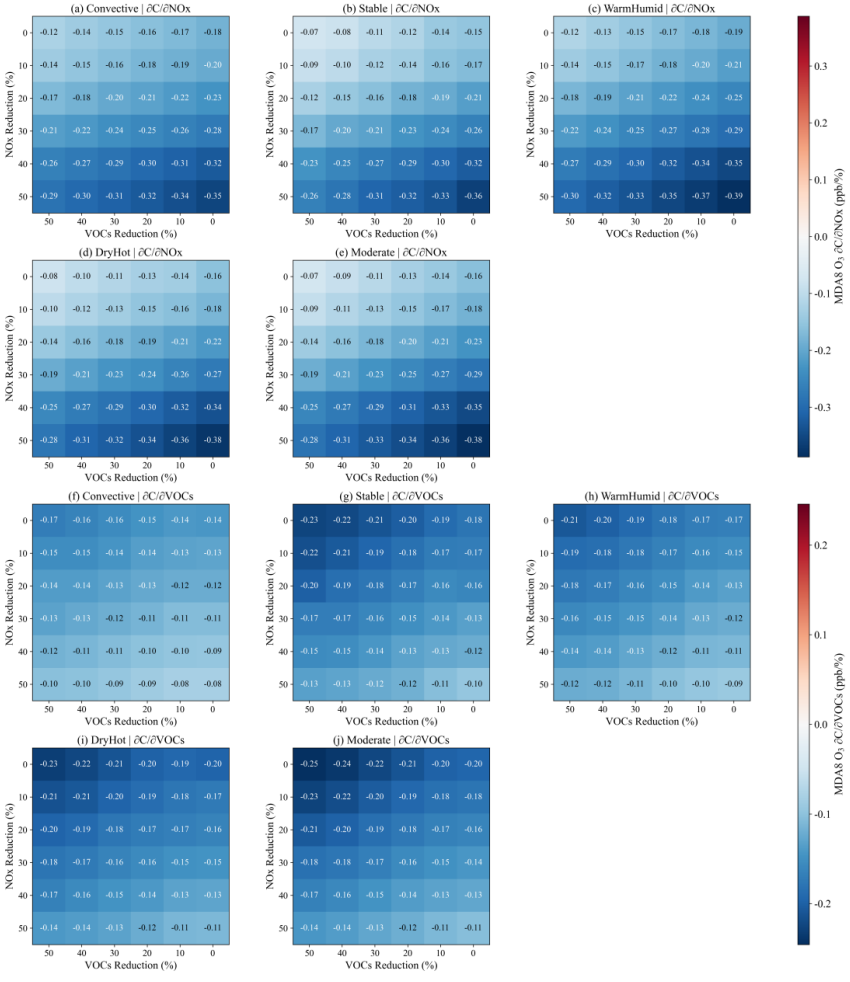

Figure 6 MDA8 O_3 response gradient to NOx and VOC emission reductions for DHP samples classified into different meteorological condition types. ∂(MDA8 O_3)/∂NOx (ppb/%) for (a) Convective, (b) Stable, (c) WarmHumid, (d) DryHot, and (e) Moderate, and ∂(MDA8 O_3)/∂VOCs (ppb/%) for (f) Convective, (g) Stable, (h) WarmHumid, (i) DryHot, and (j) Moderate. The gradients are computed by differentiating the absolute response matrices with respect to the reduction level at 10 percentage point intervals (0, 10, 20, 30, 40, 50%). Rows and columns denote NOx and VOC reduction levels (%).

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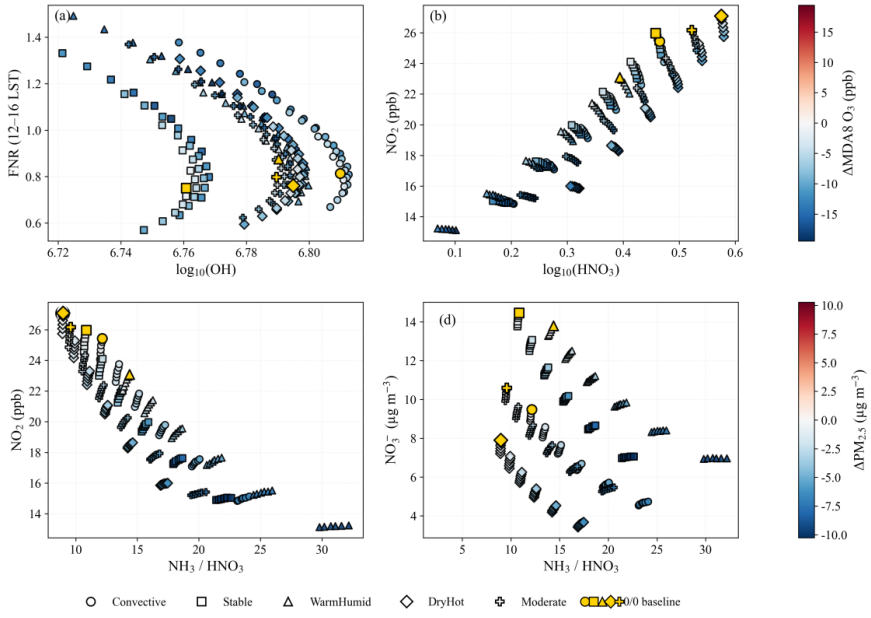

Figrure 7 Chemical state of MDA8 O_3 and $PM_{2.5}$ responses to NOx and VOC emission reductions for DHP samples. Each point represents O_3 and $PM_{2.5}$ responses to one of the 36 emission reduction scenarios for a given meteorological condition type; the baseline response is highlighted by yellow filled markers. The axes show the absolute value of chemical state diagnosed for each scenario, while point color denotes the concentration change relative to the baseline. The O_3 response in relation to (a) $\log_{10}(OH)$ and FNR, and to (b) $\log_{10}(HNO_3)$ and NO_2, respectively. The $PM_{2.5}$ response in relation to (c) NH_3/HNO_3 and NO_2, and to (d) NH_3/HNO_3 and NO_3^-, respectively. OH and HNO_3 are shown on a $\log_{10}$ scale.

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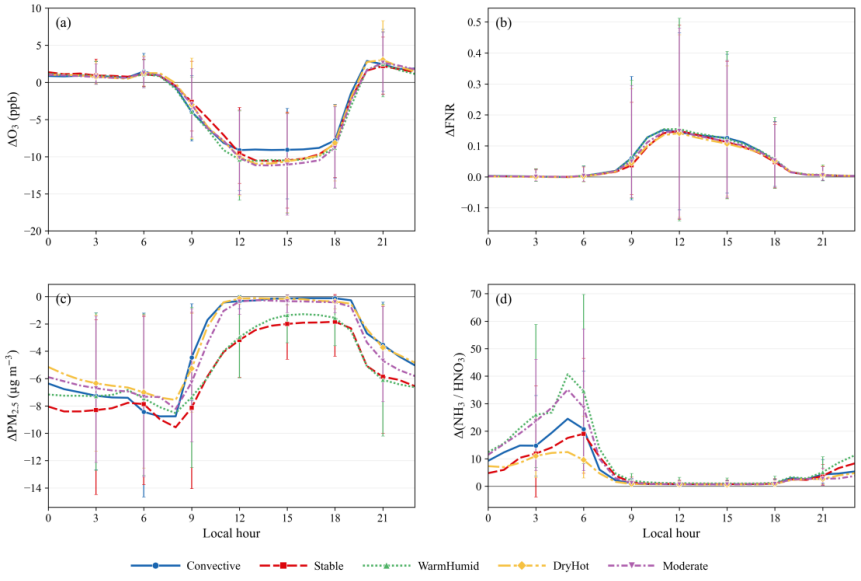

Figure 8 Diurnal variations of the median value of the response of (a) O_3 (ppb), (b) FNR, (c) $PM_{2.5}$ (μg m^{-3}), and (d) NH_3/HNO_3 to NOx and VOC emission reductions. The vertical bars plotted every 3 h indicate the p10-p90 (10th and 90th percentiles) range across emission reduction scenarios.

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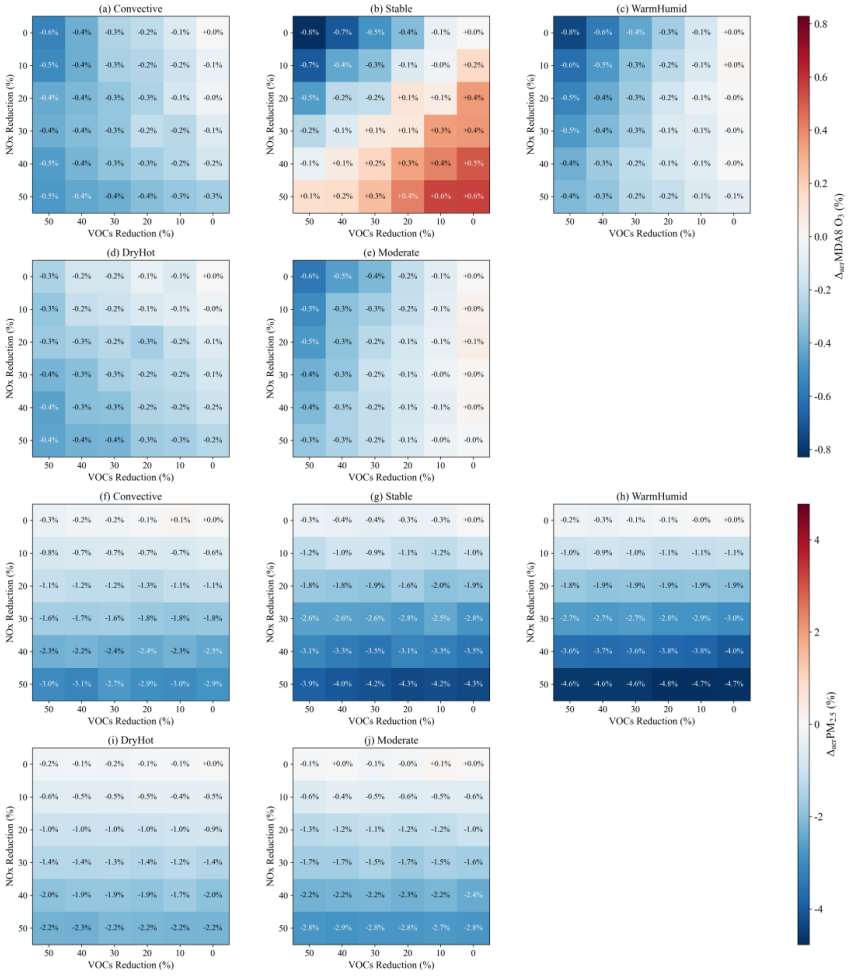

Figure 9 Aerosol-induced percentage change of MDA8 O_3 (Δ_{aer}MDA8 O_3, %) and $PM_{2.5}$ ($\Delta_{aer}PM_{2.5}$, %) responses to NOx and VOC emission reductions for (a) (f) Convective, (b) (g) Stable, (c) (h)WarmHumid, (d) (i) DryHot, and (e) (j) Moderate. Rows and columns denote NOx and VOC reduction levels (%), respectively.

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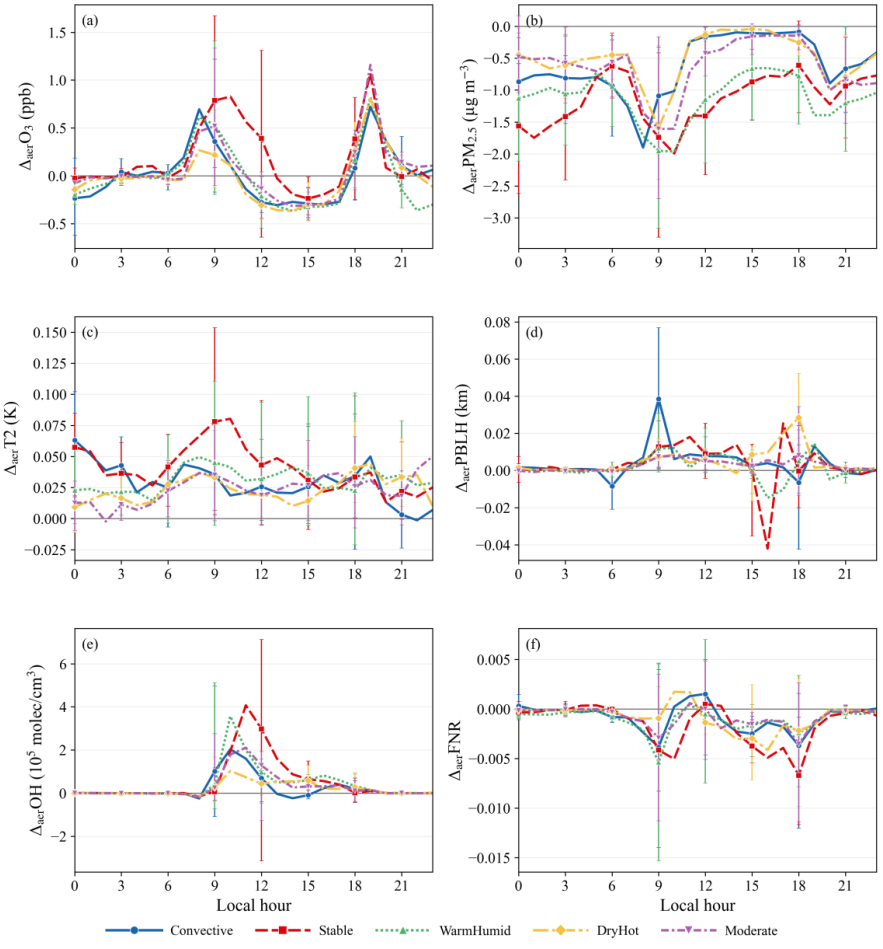

Figure 10 Diurnal profiles of aerosol-induced changes of (a) O_3 (ppb), (b) $PM_{2.5}$ (μg m^{-3}), (c) T_2 (K), (d) PBLH (km), (e) OH (10^5 molec cm^{-3}), and (f) FNR response to NOx and VOC emission reductions denoted as $\Delta_{aer}X$. The vertical bars plotted every 3 h indicate the p10-p90 range across emission reduction scenarios.