Reply to Reviewer Comments

This study employs machine learning to evaluate the impact of firework displays on $PM_{2.5}$ pollution during the Chinese Spring Festival. Overall, the manuscript is well-structured and concisely written. The findings offer valuable insights for the scientific management of $PM_{2.5}$ pollution in China. Revisions are needed before consideration for publication.

Comment #1:

P2, L41: "often marked by a decline in nitrogen oxide levels and a sharp increase in $PM_{2.5}$ concentrations". This statement requires supporting references.

Response:

We have added appropriate references to support this statement.

Previous studies have consistently reported a pronounced reduction in nitrogen oxides during the Chinese Spring Festival due to decreased traffic and industrial activities. For example, Li et al. (2021) showed substantial declines in tropospheric NO_2 columns (31.8%-44.5%) across Chinese megacities associated with large-scale population migration and reduced vehicular emissions. In contrast, $PM_{2.5}$ responses during this period are more complex. Dai et al. (2021a) demonstrated that although NO_2 concentrations decreased significantly during the Spring Festival and the coincident COVID-19 lockdown, $PM_{2.5}$ exhibited heterogeneous changes driven by shifts in emission sources, including enhanced firework-related emissions. In addition, the review by Wu et al. (2022) summarized that air quality during the Spring Festival is influenced by competing effects, including reduced anthropogenic emissions and enhanced emissions from fireworks and residential fuel use, leading to heterogeneous $PM_{2.5}$ responses across regions and periods.

Based on these findings, the manuscript has been revised to state that:

"During this period, a distinct 'holiday effect' is observed in air quality variations, often marked by a decline in nitrogen oxide (NOx) levels and complex changes in $PM_{2.5}$

concentrations" (P2, L42–L44), with supporting references added (Li et al., 2021; Dai et al., 2021a; Wu et al., 2022).

Refs:

Li, D., Wu, Q., Wang, H., Xiao, H., Xu, Q., Wang, L., Feng, J., Yang, X., Cheng, H., and Wang, L.: The Spring Festival Effect: The change in NO_2 column concentration in China caused by the migration of human activities, Atmospheric Pollution Research, 12, 101232, https://doi.org/10.1016/j.apr.2021.101232, 2021.

Dai, Q., Hou, L., Liu, B., Zhang, Y., Song, C., Shi, Z., Hopke, P. K., and Feng, Y.: Spring Festival and COVID-19 lockdown: disentangling PM sources in major Chinese cities, Geophys. Res. Lett., 48, https://doi.org/10.1029/2021GL093403, 2021a.

Wu, G., Tian, W., Zhang, L., and Yang, H.: The Chinese spring festival impact on air quality in China: A critical review, International Journal of Environmental Research and Public Health, 19, 9074, https://doi.org/10.3390/ijerph19159074, 2022.

Comment #2:

P3, L74-81: (1) Please specify the instrumentation used for measuring chemical compositions, along with their limits of detection, accuracy, and precision. (2) Regarding the calculation of SOC: The OC/EC minimum ratio method assumes stable emission sources over a period, which is clearly not applicable to the drastic emission changes during the Spring Festival. The authors should re-evaluate the validity of this method.

Response:

We have revised the manuscript accordingly:

(1) Instrumentation, limits of detection, accuracy, and precision.

We have updated the Methods section to explicitly report the analytical instrumentation and methods used for $PM_{2.5}$ chemical composition measurements. Elemental species were measured using an iCAP 7000 Series ICP-OES spectrometer (Thermo Scientific, USA). Carbonaceous components (OC/EC) were analyzed using a DRI 2001A

thermal/optical OC/EC analyzer following the IMPROVE_A protocol. Water-soluble ions were determined by ion chromatography (IC). In addition, the method detection limits (MDLs) and uncertainty/precision terms (error fractions) for all measured species are now summarized in Table S2, and these values are also those used as PMF model inputs. To address analytical accuracy, we added a table note stating that instrument calibration and routine QA/QC procedures (multi-point calibration using standards, field/laboratory blanks, and replicate analyses) were performed to ensure data quality (Section 2.1, lines 82-91).

(2) We agree that the minimum OC/EC ratio (EC-tracer) approach assumes relatively stable primary emission characteristics over the period used to determine $(OC/EC)_{min}$, and that abrupt source changes during the Spring Festival may increase uncertainty in SOC estimates. We therefore re-evaluated this assumption by examining the period dependence of $(OC/EC)_{min}$: the 10th-percentile OC/EC ratio was calculated separately for the periods before and after Lunar New Year's Eve (pre-eve: 3.10; post-eve: 3.13; full period: 3.11). Based on this check, we added clarifying text in the Methods section noting that the EC-tracer-based SOC is included as an input variable in the PMF analysis to represent the secondary organic component; nevertheless, potential non-stationarity of primary emissions during the Spring Festival may introduce additional uncertainty, and SOC-related results for this period are interpreted with caution.
We thank the reviewer again for these helpful suggestions.

Comment #3:

P3, L88: Why was ERA5 reanalysis data used instead of locally measured meteorological data? Please justify this choice.

Response:

We used the ECMWF ERA5 hourly reanalysis meteorological data with the following reasons:

(1) Completeness and physical consistency of predictors. Our model requires not only

standard near-surface variables but also key predictors that are typically unavailable or not routinely reported by local surface stations, such as boundary-layer height and surface solar radiation. These variables are essential for representing vertical mixing potential and photochemical conditions. ERA5 provides a physically self-consistent and spatiotemporally continuous set of meteorological variables through a unified data assimilation system, ensuring internally consistent model inputs.

(2) Spatial representativeness for regional-scale analysis. This study aims to characterize pollution processes and $PM_{2.5}$ behavior at the city and regional scales. Point observations can be strongly influenced by local micro-terrain and urban canopy effects and may not represent the area-average forcing relevant for regional transport and dispersion. The gridded ERA5 fields (0.25° × 0.25°) are better suited to capturing the synoptic and regional meteorological conditions driving the counterfactual predictions.

(3) Continuity and availability. ERA5 avoids gaps due to station outages or discontinuous records and provides an uninterrupted hourly time series required for stable machine-learning training and inference.

To evaluate the representativeness of ERA5 during the study period (20 December 2023-16 February 2024), we compared hourly ERA5 data from the grid cell centered over downtown Hangzhou with observations at the Hangzhou Xiaoshan International Airport station (approximately 20 km away). The comparison shows very small mean biases for temperature (≈ 0.36 °C) and wind speed (≈ 0.40 m/s), indicating that ERA5 captures the regional meteorological background with high fidelity. While inherent discrepancies exist between a 0.25° reanalysis grid average and point measurements due to spatial smoothing and local microclimates, ERA5's ability to represent synoptic-scale transitions and atmospheric dynamics is well documented (Hersbach et al., 2020) and provides a robust basis for our regional-scale modeling framework. We have clarified this in the revised manuscript in Text S2, representativeness of ERA5 meteorological data.

Ref:

Hersbach, H., Bell, B., Berrisford, P., Hirahara, S., Horányi, A., Muñoz-Sabater, J., Nicolas, J.,

Peubey, C., Radu, R., and Schepers, D.: The ERA5 global reanalysis, Quarterly journal of the royal meteorological society, 146, 1999-2049, https://doi.org/10.1002/qj.3803, 2020.

Comment 4:

P 6-7, Line 180-181: Fireworks also release substantial amounts of potassium.

Wang Ying et al. The air pollution cased by the burning of fireworks during the lantern festival in Beijing, Atmospheric Environment, 417-431, 41, 2007.

Wang Wenhua et al. Chemical composition and morphology of $PM_{2.5}$ in a rural valley during Chinese New's Eve: Impact of firework/firecracker display, Atmospheric Environment, 120225, 318, 2024.

Response:

As suggested, we have incorporated these references into the revised manuscript to support the identification of the firework source factor. These references, covering both a study in urban Beijing (Wang et al., 2007) and the findings in a rural valley (Wang et al., 2024), significantly strengthen our discussion on the enrichment of potassium (K^+) during the firework event in Hangzhou by providing evidence across different environmental settings.

Comment 5:

P8, L214: The authors report that fireworks contributed ~70% to $PM_{2.5}$, which is an exceptionally high figure. How does this compare with previous studies? Were these fireworks discharged in the immediate vicinity of the monitoring sites? Furthermore, are firework bans implemented in this city?

Response:

We acknowledge that a ~70% contribution of fireworks to $PM_{2.5}$ is unusually high when viewed in a general context. However, we believe that this estimate is physically plausible for an extreme, short-lived pollution episode. Specifically, the reported value represents an average contribution of 76.8% over the 24-hour New Year's Eve haze

event, rather than a long-term or seasonal mean. The following lines of evidence support this interpretation.

(1) Comparison with previous studies.

Although reported mass fractions vary with location and averaging period, our results are consistent with previous studies documenting extreme enrichment of firework-related aerosols during peak discharge windows. For example, Wang et al. (2007) reported that during the Lantern Festival night in Beijing, fireworks accounted for over 90% of total mineral aerosol and approximately 43% of total carbon in $PM_{2.5}$, accompanied by more than fivefold increases in tracers such as Ba, K, and Mg relative to non-festival periods. More recently, Wang et al. (2024) demonstrated that intensive firework displays can induce abrupt surges in K^+, SO_4^{2-}, and Cl^- concentrations, particularly when emissions are spatially concentrated. Importantly, these high contributions were consistently observed over short peak intervals (hours to one day), rather than over longer averaging periods. In this context, the peak mass concentration of the firework factor resolved in our study (167.2 μg/m^3) falls well within the range implied by these documented tracer-rich aerosol spikes.

(2) Independent chemical evidence from elemental ratios (Section 3.2, lines 244-253).

To ensure that the high contribution was not an artifact of receptor modeling, we performed a detailed analysis of elemental ratios (newly added Section 3.2). During the episode, the K/EC ratio exhibited an abrupt, order-of-magnitude increase, peaking at approximately 13—more than 60 times higher than the background level (~0.2). Meanwhile, the K/Ba ratio transitioned from irregular fluctuations to a stable low-value plateau with a coefficient of variation of ~16%. This distinct and detached chemical signature indicates that the ambient aerosol was physically dominated by a K-rich, EC-poor population characteristic of fireworks emissions, consistent with the morphology and composition reported in previous field and laboratory studies. Taken together, these observations provide independent, physically grounded evidence that reinforces the PMF-resolved firework factor.

(3) Proximity of emissions and policy context.

Fireworks were not legally permitted in the immediate vicinity of the monitoring site

(No. 29 Yanggong Causeway, West Lake Scenic Area). However, during the 2024 Spring Festival, Hangzhou adopted differentiated firework management measures, under which several adjacent districts (e.g., Xiaoshan and Yuhang, located to the south and west of the urban core) allowed limited but intensive firework discharges in designated areas. Under the stagnant meteorological conditions prevailing on New Year's Eve, firework-related aerosols emitted from these nearby permitted zones were rapidly transported into and accumulated within the West Lake basin, where dispersion is constrained by local topography. This interpretation is supported by the explosive midnight $PM_{2.5}$ surge shown in Fig. 2 and is further corroborated by the machine-learning counterfactual analysis (Fig. 3), which identified comparable firework-attributable $PM_{2.5}$ increments across the broader urban area. These results indicate that the elevated contribution observed at the Wolongqiao site reflects a city-wide extreme pollution episode rather than a localized anomaly.

In summary, the reported 76.8% contribution represents a short-lived but intense peak driven by concentrated firework activity in surrounding districts combined with unfavorable dispersion conditions, and is supported by both chemical evidence and independent modeling analyses.

Refs:

Wang, W., Zhou, H., Gao, Y., Shao, L., Zhou, X., Li, X., Wei, D., Xing, J., and Lyu, R.: Chemical composition and morphology of PM2. 5 in a rural valley during Chinese New Year's Eve: Impact of firework/firecracker display, Atmospheric Environment, 318, 120225, https://doi.org/10.1016/j.atmosenv.2023.120225, 2024.

Wang, Y., Zhuang, G., Xu, C., and An, Z.: The air pollution caused by the burning of fireworks during the lantern festival in Beijing, Atmospheric Environment, 41, 417-431, https://doi.org/10.1016/j.atmosenv.2006.07.043, 2007.

Comment #6:

P12-13, L329-335: Figure 5 is well-presented, but the accompanying description and discussion are too superficial. What explains the extreme disparity in firework

contributions across different cities (>80% vs <10%)? Is this linked to local government bans? A more in-depth discussion is warranted.

Response:

We thank the reviewer for this insightful comment regarding the interpretation of Fig. 5 and the need for a more in-depth discussion. In response, we have substantially expanded and reorganized the discussion and incorporated it into the final paragraph of Section 3.5 (lines 421-434).

Specifically, the revised text now explicitly acknowledges the presence of a persistent regional background pollution level across the "2+26" cities and clarifies that the New Year's Eve haze episode represents an acute, event-driven pollution enhancement superimposed on this background. We further discuss the pronounced inter-city variability in estimated firework contributions (>80% versus <10%), attributing it to differences in background $PM_{2.5}$ levels, the relative nature of contribution estimates, and population redistribution during the Spring Festival. In addition, the potential roles of spatially heterogeneous effectiveness of firework prohibition policies (particularly in rural and urban-rural fringe areas) and meteorological conditions are discussed in a cautious and qualitative manner.

These revisions provide a more comprehensive and mechanistic interpretation of Fig. 5 while remaining consistent with the scope and limitations of the available data. We again thank the reviewer for this helpful suggestion.