

1 **RESPONSE TO REVIEWERS**

2 Thank you for your valuable time, effort and insightful comments. We have attended all
3 suggestions and revised the MS accordingly. The author's response below and revised parts
4 in MS are shown in blue typeface. We do hope that the referees and the Editor would find
5 the revised MS more interesting and recommend a publication in *Atmospheric Chemistry and*
6 *Physics* very soon.

7

8 **Response to Reviewer #5**

9 Gopikrishnan et al. use GEOS-Chem simulations to investigate photochemical surface ozone
10 formation in India for 2018 and 2022. They found that substantial variations in PM10 and
11 aerosol surface area, as well as changing meteorology, influence the surface ozone formation.
12 While the topic is relevant to ACP, the manuscript is poorly presented because the data
13 discussion is not well linked to the included literature findings, the process-level discussion is
14 lacking, and the abbreviations are misused. The manuscript will require major revisions
15 before it can be considered for publication. I highly recommend that the authors consider
16 what information GEOS-Chem can provide, what underlies the variations in simulations across
17 regions, and which processes are included in GEOS-Chem. The current presentation in the
18 manuscript does not demonstrate a good understanding of GEOS-Chem from the authors.

19 Thank You for the comments. Please see the specific response for each comments below:

20 **Major Comments:**

21 1. Line 88: Why PM10 but not PM2.5? Reasonings should be provided to illustrate why the
22 impact of PM10 is important on surface O3 pollution.

23 Done, we have now included the justification for this in **lines 89—98**.

24 *PM₁₀ affects surface ozone formation mainly by enhancing aerosol optical depth and surface*
25 *area, which reduces the photolysis rates of NO₂ and O₃ and decreases the concentrations of*
26 *OH and HO₂ radicals, resulting in reduced net photochemical ozone production (Liu et al.,*
27 *2024). To characterise the aerosol-driven ozone inhibition, we explicitly account for the*
28 *surface area contributions from secondary organic aerosol, mineral dust, sea salt, black*
29 *carbon, and primary organic carbon. As mineral dust and sea salt predominantly reside in the*
30 *coarse fraction of PM₁₀, this framework captures aerosol–ozone interactions that are not fully*
31 *represented by PM_{2.5} alone (Bian and Zender, 2003; Bonasoni et al., 2004; George et al., 2017;*
32 *Alves et al., 2018). Furthermore, given that national air-quality initiatives in India, such as the*
33 *National Clean Air Programme, target a 20–30% reduction in PM₁₀ relative to 2018 levels, this*
34 *analysis also assesses the potential implications of PM₁₀ mitigation for surface ozone pollution*
35 *(NCAP, 2023).*

36 **References**

37 *Liu, M., Wang, X. and Wang, Y., 2024. Interactions between aerosols and surface ozone in arid*
38 *and semi-arid regions of China. Environmental Monitoring and Assessment, 196(4), p.390.*
39 <https://doi.org/10.1007/s10661-024-12555-9>

40 *NCAP, 2023. National Clean Air Programme (NCAP) to improve air quality in 131 cities by*
41 *engaging all stakeholders.*
42 <https://www.pib.gov.in/PressReleaselframePage.aspx?PRID=1909910®=3&lang=2>

43 *Bian, H. and Zender, C.S., 2003. Mineral dust and global tropospheric chemistry: Relative roles*
44 *of photolysis and heterogeneous uptake. Journal of Geophysical Research: Atmospheres,*
45 *108(D21). <https://doi.org/10.1029/2002JD003143>*

46 *Bonasoni, P., Cristofanelli, P., Calzolari, F., Bonafe, U., Evangelisti, F., Stohl, A., Zauli Sajani, S.,*
47 *Van Dingenen, R., Colombo, T. and Balkanski, Y., 2004. Aerosol-ozone correlations during dust*
48 *transport episodes. Atmospheric Chemistry and Physics, 4(5), pp.1201-1215.*
49 <https://doi.org/10.5194/acp-4-1201-2004>

50 *Alves, C.A., Evtuygina, M., Vicente, A.M.P., Vicente, E.D., Nunes, T.V., Silva, P.M.A., Duarte,*
51 *M.A.C., Pio, C.A., Amato, F. and Querol, X., 2018. Chemical profiling of PM10 from urban road*
52 *dust. Science of the Total Environment, 634, pp.41-51.*
53 <https://doi.org/10.1016/j.scitotenv.2018.03.338>

54 *George, K.V., Patil, D.D., Anil, M.N., Kamal, N., Alappat, B.J. and Kumar, P., 2017. Evaluation*
55 *of coarse and fine particles in diverse Indian environments. Environmental Science and*
56 *Pollution Research, 24(4), pp.3363-3374. <https://doi.org/10.1007/s11356-016-8049-3>*

57 2. Unit for O₃: It is more common to express the unit for O₃ with ppb rather than µg/m³.

58 While the mixing ratio (ppb) is a standard convention in global atmospheric modeling, this
59 study expresses surface ozone concentrations in µg/m³ to maintain consistency with the
60 National Ambient Air Quality Standards (NAAQS) established by the Government of India. The
61 Central Pollution Control Board (CPCB) mandates ozone monitoring and reporting in mass
62 concentration units (100 µg/m³ for 8-hour averages and 180 µg/m³ for 1-hour averages),
63 making this unit more relevant for regional policy assessment and health-risk communication
64 within the Indian context (CPCB 2013; NCAP, 2023). Additionally, the conversion between
65 ppbv and µg/m³ is a very simple factor of nearly exactly 2 for O₃ at typical surface
66 temperature and pressure, so readers can do this simple math in their head.

67 *NCAP, 2023. National Clean Air Programme (NCAP) to improve air quality in 131 cities by*
68 *engaging all stakeholders.*
69 <https://www.pib.gov.in/PressReleaselframePage.aspx?PRID=1909910®=3&lang=2>

70 CPCB, 2013:

71 <https://cpcb.nic.in/openpdf.php?id=UHVibGljYXRpb25GaWxlLzk5OV8xNzM1NjlyNTA0X2>
72 [1lZGlhcGhvdG8xNjkzMC5wZGY=](https://cpcb.nic.in/openpdf.php?id=UHVibGljYXRpb25GaWxlLzk5OV8xNzM1NjlyNTA0X2)

73 3. Abbreviations of regions: I would suggest avoiding the use of the abbreviations for regions.
74 I have to go back to section 2.1 many times to check what they are when reviewing the
75 manuscript.

76 Done. We have now expanded the names of the regions in the revised MS, for e.g., in **lines**
77 **280, 295, 305, 314.**

78 4. Figure 2: It is not easy to spot the difference between observations and model estimates,
79 regarding the claim in Lines 270-271. I would suggest calculating the differences between
80 observations and model estimates for sites and summarizing them in a table or figure. Please
81 also check that the colour scheme is colour-blind friendly.

82 The differences between modelled and observed surface ozone and PM₁₀ are shown in
83 **Figures S4 and S5** for major Indian cities, supporting the statements in Lines 270–271. The
84 manuscript refers the reader to those figures for exact numbers, in **lines 223–246.**

85 5. Section 3.1.1: The current discussion on the differences between observation and model
86 estimates is problematic. For each region, the authors cite only papers in the discussion. There
87 is no real discussion about whether there is a systematic reason causing such differences. It
88 would be better if the authors could look at how GEOS-Chem performed in other regions.

89 The discussion on observation versus model comparison builds upon not only literature, but
90 actual analysis from our manuscript, specifically in **Figure 2** and **Figures S4 and S5**, and a
91 discussion in **section 2.2**. To make this clearer, we have added references to these figures in
92 the **Section 3.1.1**. Comparisons between observations and model simulations demonstrate
93 good agreement according to our analysis. While the GEOS-Chem model has been extensively
94 evaluated in previous studies, a comprehensive validation of its overall performance in “other
95 regions” is well beyond the scope of this work, which is focused on India. Regarding systematic
96 reasons for biases, we have added the following sentences:

97 *The bias in the NW region may partly arise from uncertainties in dust emission*
98 *parameterisations and coarse-resolution representation of wind-driven dust mobilisation in*
99 *GEOS-Chem (Saxena and Pandey, 2018). Biases in the IGP region are likely linked to*
100 *uncertainties in anthropogenic emission inventories, particularly for primary PM, NO_x and VOC*
101 *emissions in India, which are often underreported or lack temporal and sectoral detail (Smith*
102 *et al., 2001; Ge et al., 2024; Tripathi et al., 2025). In addition, simplifications in secondary*
103 *aerosol formation pathways can further contribute to PM underestimation (Lane et al., 2008).*
104 *In the Hilly Regions, Stratosphere to Troposphere Transport is an important cause of error in*
105 *model calculations. Nevertheless, GEOS-Chem uses the UCX chemical mechanism to reduce*
106 *this error (Eastham et al., 2014). This positive bias in PI likely arises from uncertainties in NO_x*
107 *and VOC emission inventories over PI and an underrepresentation of coastal ozone loss*

108 *processes, including marine deposition and halogen chemistry, in CTMs (Li et al., 2019;*
109 *Lakshmi et al., 2024; Galbally and Roy, 1980; Lavanyaa et al., 2023; Nilaya et al., 2024).*

110 6. Lines 309-327: Could you elaborate on how the BC scavenges ozone and how the
111 accumulation of PM suppresses the planetary boundary layer and enhances pollutant
112 trapping? Were these processes included in your model run?

113 Done. While GEOS-Chem robustly captures aerosol-induced photolysis attenuation and
114 radical scavenging (HO₂ uptake), the direct heterogeneous loss of ozone on black carbon
115 surfaces remains a source of model uncertainty as it is not explicitly represented in the
116 standard chemical mechanism (Wang et al., 2022). The process and the uncertainty is now
117 mentioned in **Lines 369—374**.

118 7. Lines 330-351: More discussions are needed on how the change in PM affects the solar
119 radiation. What are the contributions via aerosol direct and indirect effects?

120 Done. We have revised this to discuss how changes in PM₁₀ affect surface solar radiation
121 through aerosol attenuation of actinic flux. PM₁₀ primarily influences ozone via radiative
122 effects by modulating shortwave scattering and absorption, thereby altering photolysis rates.
123 As GEOS-Chem is not a fully coupled general circulation model and relies on input
124 meteorology, it is not simulating the indirect effect of aerosols on cloud formation. This is
125 mentioned in **Lines 382—385**.

126 8. Lines 420-433: When mentioning different aerosol species like biomass burning and dust
127 aerosols, it would be good to include the spatial distributions of their aerosol surface areas
128 like Figures S8 and S9.

129 Done. Black carbon is a major constituent of biomass burning aerosols, and the spatial
130 distribution of changes in aerosol surface area from different aerosol species, including
131 biomass burning and dust, is presented in **Figure S9**.

132 9. Lines 489-491: There is no process-level analysis on how meteorology affects the precursor
133 lifetimes, photolysis rates, and vertical mixing?

134 Done. We now included the roles of photolysis suppression, precursor removal, and
135 boundary-layer dynamics in driving the observed seasonal contrasts of surface ozone (**Lines**
136 **634—639**). A fully quantitative attribution of these processes is beyond the scope of the
137 present study and will be addressed in future work.

138 *During the monsoon, enhanced cloud cover and aerosol–cloud interactions substantially*
139 *reduce photolysis rates, while increased precipitation and convective mixing shorten NO_x and*
140 *VOC lifetimes and promote vertical dilution, particularly over the IGP (Liao et al., 1999; Li et*
141 *al., 2016; Ojha et al., 2022). In contrast, pre-monsoon and post-monsoon conditions over PI*
142 *are characterised by higher solar insolation, deeper boundary layers, and weaker wet*
143 *scavenging, allowing meteorology-driven changes in aerosol loading and chemical regimes to*

144 exert a stronger influence on surface ozone (Badarinath et al., 2022; Keerthi Lakshmi et al.,
145 2024).

146 Li, Z., Lau, W.M., Ramanathan, V., Wu, G., Ding, Y., Manoj, M.G., Liu, J., Qian, Y., Li, J., Zhou,
147 T. and Fan, J., 2016. Aerosol and monsoon climate interactions over Asia. *Reviews of*
148 *geophysics*, 54(4), 866-929. <https://doi.org/10.1002/2015RG000500>

149 Liao, H., Yung, Y.L. and Seinfeld, J.H., 1999. Effects of aerosols on tropospheric photolysis rates
150 in clear and cloudy atmospheres. *Journal of Geophysical Research: Atmospheres*, 104(D19),
151 pp.23697-23707. <https://doi.org/10.1029/1999JD900409>

152 Ojha, N., Girach, I., Soni, M. and Singh, N., 2022. Distribution of reactive trace gases over South
153 Asia: Observations and modeling. In *Asian Atmospheric Pollution* (pp. 147-169). Elsevier.
154 <https://doi.org/10.1016/B978-0-12-816693-2.00022-6>

155 Badarinath, K.V.S., Sharma, A.R., Kharol, S.K. et al. Variations in CO, O₃ and black carbon
156 aerosol mass concentrations associated with planetary boundary layer (PBL) over tropical
157 urban environment in India. *J Atmos Chem* 62, 73–86 (2009). <https://doi.org/10.1007/s10874-009-9137-2>

159 Keerthi Lakshmi, K.A., Nishanth, T., Satheesh Kumar, M.K. and Valsaraj, K.T., 2024. A
160 comprehensive review of surface ozone variations in several indian hotspots. *Atmosphere*,
161 15(7), p.852. <https://doi.org/10.3390/atmos15070852>

162 **Minor Comments:**

163 1. Lines 271-272: How can you come up with the claim “IGP also shows higher PM₁₀ (120–140
164 µg/m³) from industrial, vehicular and agricultural emissions including biomass and crop-
165 residue burning”?

166 Done, we have now included supporting references for this statement in **Lines 293–294**.

167 Devi, N.L., Chandra Yadav, I. and Kumar, A.: Estimation of Particulate Matter (PM₁₀) Over
168 Middle Indo-Gangetic Plain (Patna) of India: Seasonal Variation and Source Apportionment.
169 *Atmosphere*, 15(8), <https://doi.org/10.1016/j.uclim.2020.100663>, 2024.

170 Mogno, C., Palmer, P.I., Knote, C., Yao, F. and Wallington, T.J.: Seasonal distribution and
171 drivers of surface fine particulate matter and organic aerosol over the Indo-Gangetic Plain.
172 *Atmospheric Chemistry and Physics*, 21(14), pp.10881-10909, <https://doi.org/10.5194/acp-21-10881-2021>, 2021.

174 2. Lines 283-284: What is the scientific evidence for the stratospheric-to-troposphere
175 transport? Was this process included in the GEOS-Chem model?

176 Dione. This statement is supported by previous studies. Yes, the STT is included in the GEOS
177 Chem model via the unified tropospheric–stratospheric chemical mechanism (UCX). This is

178 mentioned in **Lines 313—314**.

179 *Reference:*

180 *Eastham, S.D., Weisenstein, D.K. and Barrett, S.R.: Development and evaluation of the unified*
181 *tropospheric–stratospheric chemistry extension (UCX) for the global chemistry-transport*
182 *model GEOS-Chem. Atmospheric Environment, 89, 52-63.*
183 <https://doi.org/10.1016/j.atmosenv.2014.02.001>, 2014.

184 3. Lines 285-287: How were the stagnant conditions defined here?

185 Done. Stagnant conditions refer to periods characterised by weak surface winds (<3.2 m/s),
186 shallow planetary boundary layer heights, and limited ventilation, consistent with conditions
187 that favour pollutant accumulation over the IGP and eastern Central India. This is mentioned
188 in **Lines 318—320**.

189 4. Line 335: Any plot to support the increased solar radiation penetration?

190 Done. Yes, the impact of PM on solar radiation is supported by previous studies. For instance,
191 Aladwani et al., (2024) found that PMs contribute to about 20 % of the observed change in
192 solar radiation, indicating that they significantly impact solar radiation. The reference is
193 mentioned in **Line 386**.

194 *Aladwani, S.M., Almutairi, A., Alolayan, M.A., Abdullah, H. and Abraham, L.M.: Prediction of*
195 *solar radiation as a function of particulate matter pollution and meteorological data using*
196 *machine learning models. Journal of Engineering Research.*
197 <https://doi.org/10.1016/j.jer.2024.11.005>, 2024.

198 5. Lines 341-344: Where is the evidence for stagnant meteorological conditions?

199 Done. This statement is also supported by previous studies, for instance, Gopikrishnan and
200 Kuttippurath (2024).

201 **Figure S10** has also been included in the Supplementary section to show that the Northern
202 regions experience stagnant atmospheric conditions (<3.2 m/s windspeed).

203 6. Lines 437-438: What is the supporting evidence for fire events and dust storms? The same
204 applies to other places.

205 Done. This statement is supported by previous studies (**Line 503**). Please find the references
206 here:

207 *Pio, C.A., Legrand, M., Alves, C.A., Oliveira, T., Afonso, J., Caseiro, A., Puxbaum, H., Sánchez-*
208 *Ochoa, A. and Gelencsér, A.: Chemical composition of atmospheric aerosols during the 2003*
209 *summer intense forest fire period. Atmospheric Environment, 42(32), pp.7530-7543,*
210 <https://doi.org/10.1016/j.atmosenv.2008.05.032>, 2008.

211 Vadrevu, K.P., Ellicott, E., Giglio, L., Badarinath, K.V.S., Vermote, E., Justice, C. and Lau, W.K.:
212 Vegetation fires in the himalayan region—Aerosol load, black carbon emissions and smoke
213 plume heights. *Atmospheric Environment*, 47, pp.241-251,
214 <https://doi.org/10.1016/j.atmosenv.2011.11.009>, 2012

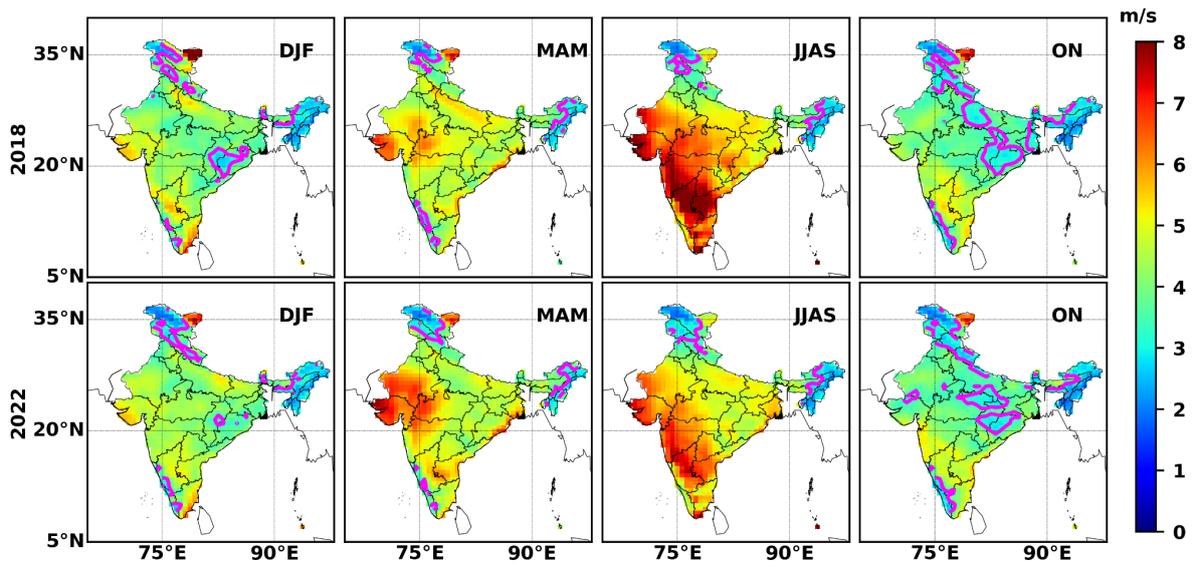
215 Badarinath, K.V.S., Kharol, S.K., Kaskaoutis, D.G., Sharma, A.R., Ramaswamy, V. and
216 Kambezidis, H.D.: Long-range transport of dust aerosols over the Arabian Sea and Indian
217 region—A case study using satellite data and ground-based measurements. *Global and
218 Planetary Change*, 72(3), pp.164-181, <https://doi.org/10.1016/j.gloplacha.2010.02.003>, 2010

219 Aher, G.R., Pawar, G.V., Gupta, P. and Devara, P.C.S.: Effect of major dust storm on optical,
220 physical, and radiative properties of aerosols over coastal and urban environments in
221 Western India. *International Journal of Remote Sensing*, 35(3), pp.871-903,
222 <https://doi.org/10.1080/01431161.2013.873153>, 2014.

223 7. Lines 488-489: Which plot or table shows the combined influence of regional circulation
224 and boundary layer height?

225 Done. We have now included **Figure S10** and **Figure S13** to show the combined influence of
226 regional circulation and PBL. A discussion is provided in **Lines 556–564**.

227 “This can be attributed to the combined influence of regional circulation (more ventilated
228 towards the southern regions versus stagnant atmospheric conditions towards the northern
229 regions) and boundary layer dynamics (Gopikrishnan and Kuttippurath, 2024). Figure SXX and
230 Figure SYY shows that, during the monsoon season, elevated Planetary Boundary Layer
231 Heights (PBLH), frequently exceeding 1.0–1.25 km, together with relatively strong wind
232 speeds (often greater than 4 m/s over central and southern India), enhance both vertical
233 mixing and horizontal ventilation. In contrast, during winter and post-monsoon, a marked
234 reduction in PBLH (generally below 0.75 km), coupled with weaker winds (commonly within
235 the stagnant <3.2 m/s conditions), limits atmospheric dispersion, promoting the accumulation
236 of pollutants near the surface and thereby contributing to the pronounced regional
237 differences in air quality.”

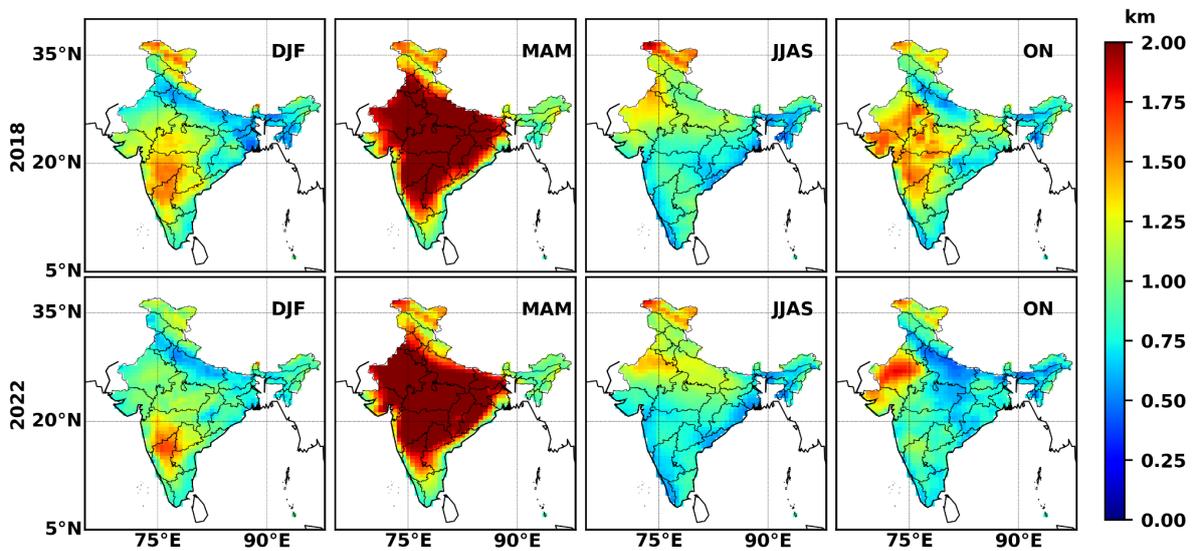


238

239 **Figure S10:** Seasonally averaged surface windspeed (m/s) over India for the years 2018 and
 240 2022. The magenta contour indicates a wind speed of 3.2 m/s.

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244 **Figure S13:** The Planetary Boundary Layer Height (PBLH) in km in India for the years 2018 and
 245 2022.

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250 8. Lines 495-496: How did you conclude that “the HO₂ uptake effect is an order of magnitude
251 smaller than the direct meteorological impact (20–40 µg/m³)”?

252 Done. **Figure 4** shows the impact of HO₂ uptake effect, whereas **Figure 3** shows the overall
253 change in ozone during the period. Comparing these two figures, we can conclude that the
254 HO₂ uptake effect is an order of magnitude smaller than the direct meteorological impact
255 (20–40 µg/m³).

256 9. Line 499: Did you define “persistently polluted environments” at somewhere?

257 Done. Persistently polluted environments refer to locations where high pollutant
258 concentrations are maintained over extended periods (for instance, concentrations exceeding
259 the annual average limit of 60 µg/m³ for PM₁₀ and the 8-hour maximum of 100 µg/m³ for O₃),
260 rather than occurring only during short episodic events. This is mentioned in **Lines 575—578**.

261 **Technical Comments:**

262 1. Line 49: Please include the full name for the PM when it is used for the first time.

263 Done. Please see **Line 48**.

264 2. Lines 50 – 53: The sentence is long to read. Please cut it into two sentences.

265 Done. Please see **Line 53**.

266 3. Lines 65: Why not use the abbreviation for ozone and particulate matter? O₃ and PM have
267 been introduced before.

268 Done. Please see **Line 65**.

269 4. Line 96: Is it the right place to cite Figures S1 and S2?

270 Done. Since the meteorological differences between the two years form the basis of this
271 study, we consider it important to inform the reader of the magnitude of these differences at
272 the outset. We therefore believe that citing these figures at this point is appropriate.

273 5. Lines 108-126: Could you please divide the whole paragraph into several paragraphs based
274 on regions? It is too long to read as a whole paragraph. If you could manage to present the
275 information in a table, that would be best.

276 Done. We have now included a table, **Table S1** in the supplementary data.

277 6. BLO3: I do not think the use of BLO3 is necessary. It occurs only three times.

278 Done. Please see **Lines 171, 172, 174**.

279 7. Figure S9: Could you provide the full names for different aerosol species in the caption?

280 Done, please see the caption of **Figure S9**.

281 8. Line 350: What is HxOy?

282 Done. HxOy is the odd-hydrogen family. This is now mentioned in **Line 409**.

283 9. Lines 578-579: It is unclear that “changing meteorological conditions can be reduced by
284 additional efforts in reducing anthropogenic NOx emissions”

285 Done, we have now revised the sentence in **Lines 603—605** as:

286 “Thus, the unintended increase in surface ozone associated with declining PM levels under
287 changing meteorological conditions can be mitigated through additional efforts in reducing
288 anthropogenic NOx emissions.”

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292 **Response to Reviewer #4**

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294 The authors have addressed the referee comments appropriately. The revised manuscript is
295 recommended to be accepted.

296 Thank you for the recommendation to accept the manuscript.

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301 REV2/V02/30122025

302