Responses to Reviewers' comments

To the esteemed Editor and Reviewers,

We sincerely appreciate the reviewers' time and effort in evaluating our manuscript. Their thoughtful comments and constructive suggestions have been extremely helpful in improving our work. Through careful consideration of all concerns and implementation of the reviewers' recommendations, we believe the revised manuscript has been significantly strengthened.

Please find below our detailed point-by-point responses to the reviewer's comments:

Reviewers' comments are in black.

Author's responses are in blue.

Changes in the manuscript are in red.

Yours Sincerely,

Weihua Chen

On behalf of the authors

Response to Reviewer 1

General comments:

1. Chen et al. review the methods for estimating background ozone concentrations, which determine the maximum achievable reduction in ozone pollution through mitigation of local anthropogenic emissions, with a specific focus on background ozone in China. The paper is informative and organized, but it is overly long in some sections.

Response: We thank the reviewer for the positive comments. We have revised the manuscript according to your comments.

2. It is also important for the authors to say why this review is needed when there are so many other similar recent papers reviewing ozone in China (Liu et al., 2020; Lu et al., 2019; Sahu et al., 2021; Wang et al., 2022; Xu, 2021). I think the key is that this paper analyzes background ozone specifically, but that concept is also addressed quite thoroughly in most papers reviewing drivers of ozone concentrations and trends.

Response: We thank the reviewer for this important comment regarding the novelty of our review. We acknowledge that several recent review papers (e.g., Liu et al., 2020; Lu et al., 2019; Sahu et al., 2021; Wang et al., 2022b; Xu, 2021) have substantially advanced our understanding of O_3 pollution in China, including its spatiotemporal characteristics, chemical formation regimes, meteorological drivers, and anthropogenic influences. While some of these reviews have also mentioned the concept of background O_3, typically in the context of external contributions or policy challenges, none has provided a systematic and dedicated synthesis on this topic.

At the same time, a growing body of original research has specifically addressed background O_3 in China, including its quantification, natural and non-local sources, and policy challenges (Sahu et al., 2021; Wang et al., 2022b; Chen et al., 2022; Wang et al., 2011). However, these findings remain fragmented and have not been comprehensively reviewed.

Our manuscript aims to fill this gap by: (1) systematically reviewing the evolution of the background O_3 concept; (2) providing a comparative assessment of the methods employed to estimate background O_3; and (3) synthesizing the spatiotemporal patterns of background O_3 in China within a broader global context.

Because background O_3 represents the effective lower bound of O_3 pollution control, a focused and structured review is both timely and necessary to inform scientific understanding and air quality management.

We have clarified this motivation in Lines 79–94 in the revised manuscript:

Despite its importance, understanding of background O_3 remains constrained by inconsistent definitions, diverse estimation methods, and limited regional assessments. While several recent reviews have touched on background O_3 in the broader context of O_3 pollution (Lu et al., 2019b; Liu et al., 2020; Sahu et al., 2021; Wang et al., 2022b; Xu, 2021), and a few studies have provided quantitative estimates and source apportionment of background O_3 in China (Sahu et al., 2021; Wang et al., 2022b; Chen et al., 2022; Wang et al., 2011), no dedicated, methodologically focused synthesis is available.

This study addresses that gap by: (i) systematically reviewing the evolution of the

3

background O_3 concept; (ii) providing a comparative assessment of the methods (i.e.,

in situ measurement, statistical analysis, numerical modeling, and integrated methods)

employed to estimate background O_3; and (iii) synthesizing the spatiotemporal patterns

of background O_3 in China within a broader global context, examining the spatial and

temporal variations of background O_3 across China using publicly available data.

Finally, we identify key knowledge gaps and propose future research priorities to

advance understanding and inform effective policy responses. As background O_3

increasingly shapes the O_3 landscape, this review provides timely insight into the

scientific and regulatory frontiers of O_3 pollution control both in China and globally.

3. I would also suggest that the authors significantly reduce the length of Section 4,

which is quite long-winded and repetitive.

Response: We have substantially revised this section to improve clarity and

conciseness. In particular, we streamlined Section 4.2 (Statistical analysis estimation)

by: (1) removing overly detailed descriptions of individual sub-method (e.g., PCA, K-

means, percentile, etc.) of statistical analysis estimation; (2) consolidated repetitive

statement on assumptions and limitations; (3) merging overlapping case studies to

emphasize representative findings rather than providing an exhaustive list; (4)

relocating the discussion of methodological advantages into Figure 3, thereby avoiding

redundancy across subsections.

As a result, the length of Section 4.2 has been reduced by approximately 30–40%,

and the revised text is now more concise, readable, and focused while preserving the

81   essential technical content.

82

83   4.   Section 5.2 and Figure 5 are the most interesting pieces of the review, and the

84   discussion seemed too short. Why is the integrated method a much smaller range? Is

85   there regional variability in the background ozone estimated from the integrated method?

86   Should we "trust" the results of the integrated method above the other methods and, if

87   so, why? I think this information is discussed more in Section 4.4, but I would move

88   this information to the section where Figure 5 is discussed.

89   Response: We sincerely thank the reviewer for highlighting the importance of

90   Section 5.2 and Figure 5, and for providing valuable suggestions that helped us refine

91   our discussion of the integrated method.

92   In the revised manuscript, we made the following substantive changes:

93   (1) Explaining the narrower range. We expanded Section 5.2 to clarify that the

94   narrower range of background O_3 concentrations estimates obtained from the integrated

95   methods does not indicate oversimplification but rather reflects its strength in

96   reconciling model structural consistency with observational variability. At the same

97   time, the limited number of integrated studies currently available in China may

98   contribute to the relatively low variability observed, highlighting the need for further

99   validation. International applications (Dolwick et al., 2015; Skipper et al., 2021;

100   Hosseinpour et al., 2024) provide supporting evidence for its robustness.

101   (2) Addressing reliability. We clarified that no single method can be considered

102   definitive. Each carries inherent limitations. Instead of replacing other methods, the

integrated methods serve as complementary synthesis framework that balances empirical realism with generalizability. Its ability to reduce uncertainty enhances its value for both scientific interpretation and policy-relevant applications.

These revisions (Lines 589–606) strengthen the connection between Section 5.2 and Figure 5, and improve the coherence of the narrative by situating key discussions within the section most relevant to the integrated method:

In contrast, the integrated methods – combining in situ observation, statistical analysis, and numerical results – yield the narrowest range (32–37 ppb), with the value of 34.5 ± 1.6 ppb. This narrow range reflects their strength in reconciling the structural consistency of models with real-world variability, rather than oversimplification. By harmonizing data sources, integrated methods reduce methodological noise and yield more robust, policy-relevant estimates. The limited number of applications, however, may also contribute to the observed low variability. Although studies in China remain scarce, international applications underscore their potential. For instance, Skipper et al. (2021) showed that incorporating spatial and temporal bias corrections improved the consistency of model-derived background O_3 estimates by 28% relative to unadjusted models. Similarly, Hosseinpour et al. (2024) demonstrated that a random forest machine learning (RF-ML) algorithm integrating multiple data sources with nonlinear feature analysis produced background O_3 estimates most consistent with in situ observations for correcting air quality model simulations and outperformed the original CAMx model, multivariate regression, and other ML algorithms. Collectively, these studies highlight the value of integrated methods in producing consistent estimates, particularly

for regulatory applications and long-term trend assessments. Nevertheless, further

validation is needed to determine whether the observed low variability reflects true

methodological robustness or limited sampling. Importantly, no single method is

definitive. Each carries inherent assumptions. Integrated methods therefore provide a

complementary framework that balances empirical realism with generalizability.

5. In addition, I would expect the paper to have more discussion of the seasonality of

background ozone, which is significant in a region like China (Chen et al., 2023).

Response: We thank the reviewer for highlighting the importance of seasonal

variability in background O_3, especially given China's large climatic and geographic

heterogeneity. We have added a subsection to discuss the seasonal variation of

background O_3 in Lines 687–719 of the revised manuscript.

5.4 Seasonal variation of background ozone in China

Figure 7 illustrates the seasonal variations in mean background O_3 concentrations

across China and its seven subregions during 1994–2020. Nationally, background O_3

exhibits pronounced seasonality, with comparable peaks in spring (47.2 ± 10.6 ppb) and

summer (47.3 ± 15.4 ppb), and a pronounced minimum in winter (33.2 ± 9.8 ppb).

Regional patterns reveal clear differences in seasonal maxima. In Southwest China

(SWC) and Northeast China (NEC), peaks occurred in spring (52.1 ± 9.9 ppb and 38.8

± 4.4 ppb, respectively), largely driven by stratosphere–troposphere exchange (STE)

and enhanced downward transport over elevated terrain, and also influenced by

prevailing winds that transport NO_x and VOCs from Southeast Asia and other regions

into these areas (Liu et al., 2019; Lu et al., 2019a; Xu et al., 2018; Wang et al. 2011; Ye et al., 2024). In contrast, North China (NC), Northwest China (NWC), and East China (EC) recorded summer maxima (56.8 ± 10.8, 55.0 ± 8.5, and 48.3 ± 16.9 ppb, respectively), consistent with the influence of the East Asian Summer Monsoon (EASM), which enhances precursor inflow and stimulates photochemical O_3 formation under high temperatures and intense solar radiation (Gao et al., 2005; Liu et al., 2019, 2021; He et al., 2021). South China (SC) and Central China (CC) reached their highest levels in autumn (46.9 ± 10.4 and 43.0 ± 14.2 ppb, respectively), likely reflecting inland pollutant transport by northeasterly winds combined with favorable sunlight conditions (Xie et al., 2022; Shen et al., 2019; Luo et al., 2019).

Seasonal minima also varied by region. Winter lows were observed in Northeast China (NEC, 24.5 ± 3.6 ppb), North China (NC, 24.9 ± 5.2 ppb), and East China (EC, 25.2 ± 8.1 ppb), reflecting weak photochemistry under low temperatures and reduced solar radiation. In contrast, South China (SC, 24.8 ± 5.0 ppb) and Central China (CC, 28.7 ± 10.0 ppb) exhibited summer minima, attributable to frequent precipitation and high humidity suppressing O_3 production. Southwest China (SWC) maintained persistently low levels in both summer (31.0 ± 8.2 ppb) and autumn (31.0 ± 4.6 ppb), whereas Northwest China (NWC) showed relatively lower concentrations in autumn (41.8 ± 8.9 ppb) and winter (41.9 ± 5.1 ppb).

In summary, the seasonal cycle of background O_3 in China is shaped by the interplay of regional meteorology and precursor emissions, while vertical exchange and interregional transport further modulate seasonal peaks and troughs across regions.
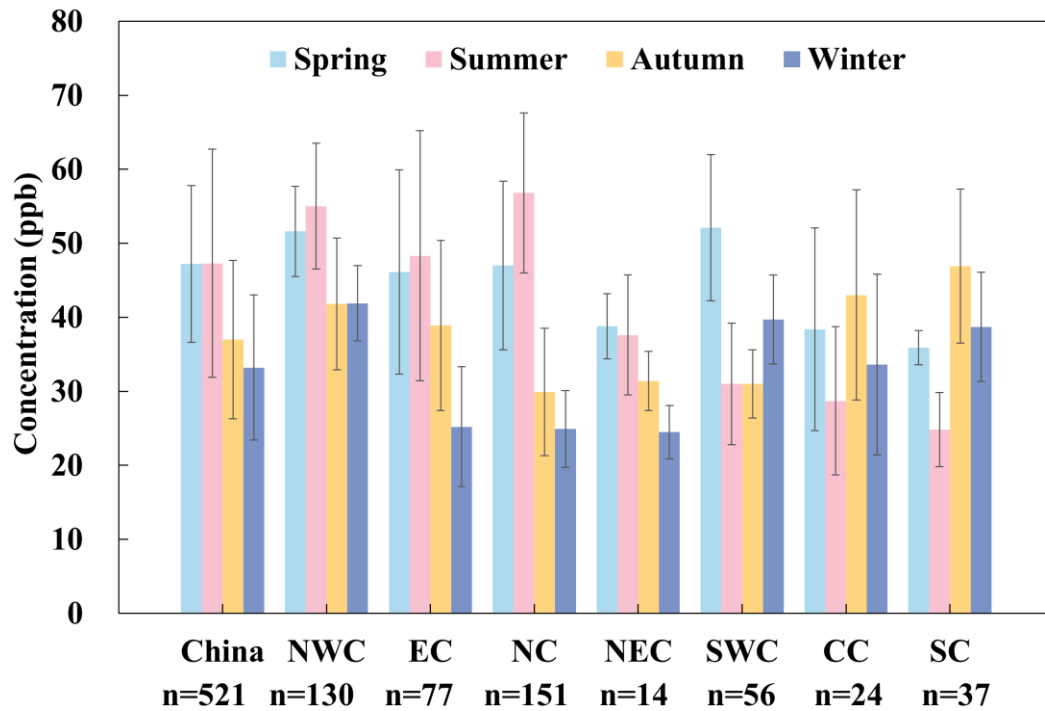
Figure 7: Seasonal variations in mean background O₃ concentrations across seven regions of China during 1994–2020. All data sources are compiled and summarized in Table S1. The values of "n =" indicates the number of individual data records or assembly estimates used in the analysis for each region and season.

6.   Finally, I suggest adding the following citations from potentially relevant studies. Han et al. (2019) quantify the influence of foreign ozone on East Asia using GEOS-Chem simulations. Colombi et al. (2023) found that subsidence of elevated free troposphere ozone drove surface background ozone in East Asia in May to exceed 50 ppb, which is much higher than the background values in North America and Europe. Wang et al. (2022) showed that the high free tropospheric ozone in East Asia has been increasing in the last two decades, which may lead to increased background ozone. Ma et al. (2025) diagnose causes of high free tropospheric ozone. Luo et al. (2024) also discuss STE as a source of background ozone in the North China Plain. There may be many other papers I am missing, but I leave the decision of whether to add these

184 citations up to the authors' discretion.

185 Response: We sincerely thank the reviewer for suggesting these highly relevant

186 and up-to-date references, which substantially strengthen our discussion of the sources

187 and long-term trends of background O_3 in East Asia and China. We have carefully

188 reviewed each of the recommended studies and have incorporated them into Sections

189 5.5 of the revised manuscript.

190 Lines 738–743:

191 Several studies have shown that the influx of O_3 and its precursors from other

192 regions, including Southeast Asia, Europe, North America, India, and the Middle East,

193 can elevate background O_3 concentration in China by 2–15 ppb (Han et al., 2019; Wang

194 et al., 2011; Wang et al., 2022b; Li et al., 2014; Ni et al., 2018). This influence is

195 particularly pronounced during specific seasons when atmospheric circulation

196 facilitates the transboundary transport of atmospheric pollutants (Colombi et al., 2023;

197 Ma et al., 2025; Ni et al., 2018; Sahu et al., 2021; Ye et al., 2024).

198 Lines 747–749:

199 Wang et al. (2022b) also found that emissions outside the Yangtze River Delta

200 regions contributed as much as 63% to O_3 pollution within the region.

201 Lines 753–758:

202 This process is most active during spring, when stratospheric O_3 is transported

203 downward into the troposphere (Ding and Wang, 2006; Lu et al., 2019a; Ma et al., 2025;

204 Xu et al., 2018). Wang et al. (2011) estimated that STE contributes approximately 7 ppb

205 to background O_3 concentrations in northern China during the spring season. Luo et al.

206 (2024) further revealed that STE contributed an average of 9.6 ppb to surface O_3 over

207 the North China Plain during 19–20 May 2019.

208

209 7.   Overall, I think this review is potentially useful, but would benefit from shortening

210 Section 4 and more clearly stating why this review is different and necessary given the

211 many other reviews of ozone in China from the last 5 years.

212   Response: We thank the reviewer for the positive overall assessment and

213 constructive suggestions. In line with the recommendation, we have shortened Section

214 4 while improving clarity and readability. In addition, we have strengthened the

215 Introduction to more explicitly highlight the novelty of this review relative to recent

216 studies on O_3 in China. These revisions are detailed in our response to comments #2

217 and #3.

218

219 **Specific comments:**

220 8.   I suggest adding a sentence that clearly describes the concept of background

221 ozone to the Introduction of the paper? For example, around line 68 in the introduction,

222 I think a sentence is needed that says something like: "Background surface ozone is

223 defined as the ozone that would be present in a given region in the absence of local

224 anthropogenic emissions, and can be influenced by local natural factors or distant

225 anthropogenic and natural factors." It is stated in the abstract, but should be defined

226 again in the introduction.

227   Response: We thank the reviewer for this thoughtful suggestion and fully agree

that an explicit early definition of background O_3 is essential to guide readers'

understanding of the scope and focus of the review.

Accordingly, we have added the following sentence in the Introduction (Lines 41–

44) of the revised manuscript:

Background O_3 refers to the O_3 concentration present in the absence of local

anthropogenic precursor emissions. It originates from a variety of natural and non-local

processes, including methane (CH_4) oxidation, stratosphere–troposphere exchange

(STE), vegetation, soil, lightning, wildfires and long-range pollutants transport, as

shown in Fig. 1 (Dolwick et al., 2015; Thompson, 2019).

9.   Figure 1 is a nice visualization. I like how the beaker implies chemical reactions

occurring in the atmosphere, and shows how anthropogenic emissions add ozone on top

of the background.

Response: We sincerely thank the reviewer for the positive feedback on Figure 1.

We are pleased that the design successfully conveys both the chemical processes in the

atmosphere (as symbolized by the beaker) and the additive effect of anthropogenic

emissions on top of the background O_3.

10.   Line 163: The conversion from $\mu g\ L^{-3}$ to ppb is strange to me. Why would you

assume a temperature of 0˚C? How big of a difference does it make if you assume a

more reasonable temperature and pressure rather than STP? Could you use

meteorological data to assume a more accurate and precise temperature and pressure?

250   Response: We thank the reviewer for this important and constructive comment. In

251   the original manuscript, the conversion from mass concentration ($\mu g \cdot m^{-3}$) to volume

252   mixing ratios (ppb) was based on standard temperature and pressure (STP, 0 °C and

253   101.325 kPa) following the original "Ambient Air Quality Standards" (GB 3095–2012)

254   issued by the Ministry of Ecology and Environment of China. However, as the reviewer

255   rightly notes, this assumption does not represent the typical meteorological conditions

256   in China and differs from internationally recognized reference states, such as 25 °C in

257   the United States (U.S. EPA, 2011), 20 °C in the European Union (European Parliament

258   and Council, 2008).

259   To address this, we have revised our calculations using a reference state of 25 °C

260   (298.15 K) and 101.325 kPa, consistent with the 2018 amendment to GB 3095–2012

261   and international practice. This corresponds to a molar volume of 24.5 $L \cdot mol^{-1}$. We

262   further validate this adjustment, we performed an analysis using meteorological data

263   from over 400 national monitoring sites across China, spanning four representative

264   months (January, April, July, and October 2022). Applying the ideal gas law (V_m =

265   RT/P), we found that 95% of the calculated molar volumes under actual ambient

266   conditions fall within the range of 20.16–30.4 $L \cdot mol^{-1}$, with the revised value of 24.5

267   $L \cdot mol^{-1}$ well within this representative range. Therefore, this updated assumption better

268   reflects the climatological conditions in most Chinese regions and improves

269   comparability with international datasets and modeling studies.

270   All relevant conversion results in the manuscript have been updated accordingly.

271   Since these adjustments affect only numerical values and do not alter the conceptual

To ensure consistency with international standard and comparability with global

datasets, unit conversions were performed using Eq. (1):

$$ppb = \left(\frac{24.5 \text{ L mol}^{-1}}{48 \text{ g mol}^{-1}}\right) \times (\mu\text{g m}^{-3}), \tag{1}$$

Where 48 g mol^{-1} is the molar mass of O_3 and 24.5 L mol^{-1} is the molar

volume of an ideal gas under the reference conditions of 25 °C and 1013.25 hPa, as

specified in the 2018 amendment to China's Ambient Air Quality Standards (GB 3095–

2012) issued by the Ministry of Ecology and Environment

(https://www.mee.gov.cn/gkml/sthjbgw/sthjbgg/201808/t20180815_451398.htm).

These reference conditions are consistent with international practices, such as 25 °C in

the U.S. (U.S. EPA, 2011), 20 °C in the European Union (European Parliament and

Council, 2008) and better reflect typical meteorological conditions across most regions

of China.

11.   Figure 3 is pretty wordy and not easy to absorb the information presented. I

suggest significantly revising this figure to make it easier to digest and more visually

appealing. At the very least, the authors should remove unnecessary words (e.g.,

"suitable" is over-used).

Response: We sincerely thank the reviewer for this valuable suggestion. We agree

that the original Figure 3 was overly text-heavy and could hinder comprehension. To

address this, we have substantially revised the figure by: (1) removing redundant and

299
300 **Figure 3: Summary of the advantages, limitations, and applicability of different estimation methods for**
301 **background O$_3$.**

302

303   12.   Figure 4: Could you please make the shading of each region be a color that

304   represents the magnitude of the background ozone concentration? For example, a

305   color bar that ranges from 25 to 50 ppb where lower background ozone is a lighter

306   color and higher background is a darker color. It is hard to view the spatial variability

307   of background ozone from the bar charts.

308   Response: We thank the reviewer for this insightful suggestion. We agree that

309   the original bar chart format limited the visualization of spatial variability. Accordingly,

15

310   we have redesigned Figure 4 as a regionally shaded map, where background O$_3$

311   concentrations are represented by a discrete color scale ranging from 24 to 49 ppb

312   (lighter colors indicate lower values and darker colors higher values). This revision

313   greatly improves the clarity and intuitiveness of spatial patterns. The updated figure,

314   caption, and corresponding text have been incorporated into the revised manuscript

315   (Lines 559–563):

316
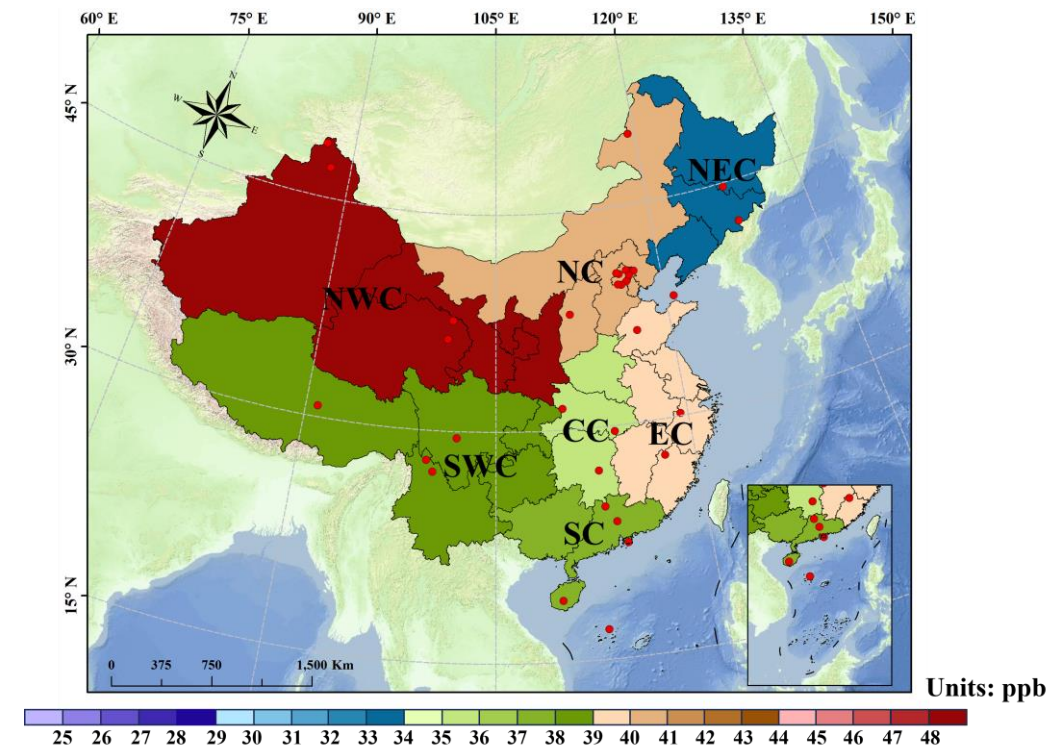
317 **Figure 4: Spatial distribution of background O$_3$ concentrations (1994–2020) across various regions of China.**
318 **The locations of 33 background monitoring stations are indicated with red dots. The seven regions include**
319 **Northeast China (NEC), North China (NC), East China (EC), Central China (CC), Northwest China (NWC),**
320 **Southwest China (SWC), and South China (SC).**

321

322   13.   Figure 5: where are the estimates of background ozone from numerical

323   modeling, statistical methods, and integrated methods coming from? I assume it is from

324   Table S1, but there is no citation or reference to table S1 in figure caption. Is n= at the

325   bottom of each box referring to the number of studies compiled or the number of

326   measurements? Overall, this caption should be more descriptive.

327   Response: We thank the reviewer for this constructive comment. We confirm that

328   the estimates in Figure 5 were compiled from Table S1 in the Supplementary

329   Information. In the revised manuscript, the figure caption has been updated to explicitly

330   reference Table S1 as the data source and to clarify that "n =" denotes the number of

331   individual data records or compiled estimates (i.e., regional mean values reported in

332   peer-reviewed studies), rather than raw measurements or publications. These revisions

333   (Lines 637–639) make the caption more descriptive and improve clarity for readers:

334   Figure 5: Estimated regional average background O_3 concentrations in China from

335   1994 to 2020 based on multiple methods. All data sources are compiled and

336   summarized in Table S1. The values of "n =" below each box indicate the number of

337   individual data records used in the analysis for each method category.

338

339   14.   Section 5.3 and Figure 6: Why is NC the only region that has two separate lines

340   showing the trends in background ozone?

341   Response: We sincerely thank the reviewer for this thoughtful observation. The

342   North China (NC) region is shown with two separate trend lines in Figure 6 because of

343   methodological differences among studies. Specifically, Ma et al. (2016) reported a

344   long-term series based on MDA8 O_3 concentrations using in situ filtering, while most

345   other studies in NC used hourly averages over shorter periods with different estimation

346   methods. As a result, the MDA8 O_3 – based estimates are systematically higher than

17

347   the hourly average – estimates, and combining them would introduce bias. To preserve

348   methodological consistency and ensure clarity in trend interpretation, we therefore

349   display the two datasets separately. This distinction highlights the contrast between

350   long-term MDA8 O_3 trends and shorter-term hourly average studies. We have clarified

351   it in Lines 659–666 of the revised manuscript:

352   Notably, for North China (NC), two separate trend lines are presented in Figure

353   6(c), reflecting methodological differences among studies: Ma et al. (2016) provided a

354   long-term record using MDA8 O_3 concentrations filtered from in situ observations,

355   while most other studies used hourly averages over shorter or discontinuous periods.

356   Since MDA8 O_3-based estimates are inherently higher than hourly means, aggregating

357   them would bias trend interpretation. Therefore, separate presentation ensures

358   consistency. Furthermore, MDA8 O_3 records are scarce elsewhere (typically fewer than

359   four data points), precluding dual-trend comparison.

360

361   15.   Same comment for Figure 7 as made for Figure 4. Please consider shading the

362   regions according to the background ozone concentration

363   Response: We have replotted Figure 7 (now is Figure 8) as a regionally shaded

364   map in Line 816 of the revised manuscript:
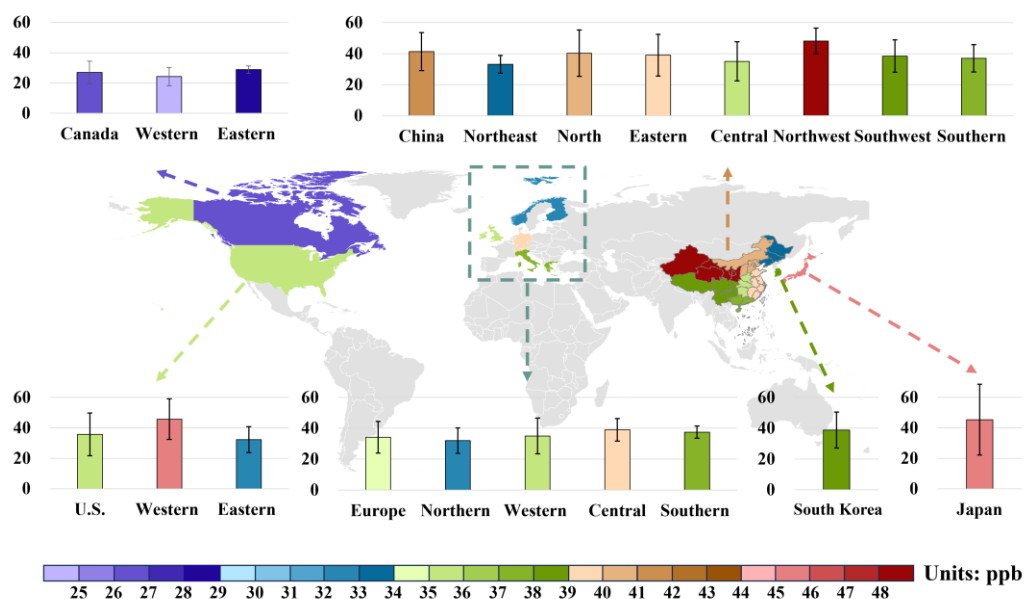
Figure 8: Average background O₃ concentrations in the U.S., Canada, Europe, South Korea, Japan, and China.

16.   The conclusions section is informative and written well.

Response: We sincerely thank the reviewer for their positive and encouraging comments regarding the conclusions section.

Technical corrections:

17.   Lines 8–10: The first sentence of the abstract is worded in a confusing way. I suggest: Background ozone (O_3) refers to baseline O_3 concentrations in the absence of local anthropogenic emissions, critical for understanding and mitigating tropospheric O_3 pollution.

Response: We thank the reviewer for the helpful suggestion. We have revised the first sentence of the abstract (Lines 8–9) to make the definition clearer and more concise:

Background ozone (O_3) represents the baseline concentrations in the absence of

380   local anthropogenic emissions and is critical for understanding and mitigating

381   tropospheric O_3 pollution.

382

Response to Reviewer 2

Major comments：

1.   Chen et al. present a comprehensive review of definitions and methods for estimating tropospheric background ozone concentration, with a specific focus on China. The manuscript is well-structured and demonstrates considerable effort in literature compilation. However, I have several major concerns that should be addressed before the manuscript can be considered for publication.

Response: We sincerely thank the reviewer for the constructive feedback and recognizing the value of our literature review. Detailed responses to each comment are provided below.

2.   For Section 3, the authors discuss multiple definitions, including USBO, PRBO, RBO, and NBO. While the historical evolution is clearly present, the distinctions between these items may be difficult for readers to follow. I suggest adding a summary table outlining the key characteristics of each definition, such as name, included and excluded sources, and typical applications. Alternatively, the authors could consider incorporating these details into Figure 2.

Response: We thank the reviewer for this constructive suggestion. To improve clarity in distinguishing among NBO, USBO, PRBO, and RBO, we have substantially revised Figure 2. The updated version explicitly highlights the key elements of each concept, presented in a side-by-side format that links definitions (left box) with their corresponding features and applications (right box). This integrated design captures the

405   intent of a summary table while maintaining the visual continuity of the historical

406   evolution, making the distinctions among different concepts clearer and more

407   accessible to readers. The revised Figure 2 is provided in Section 3 of the revised

408   manuscript:

409
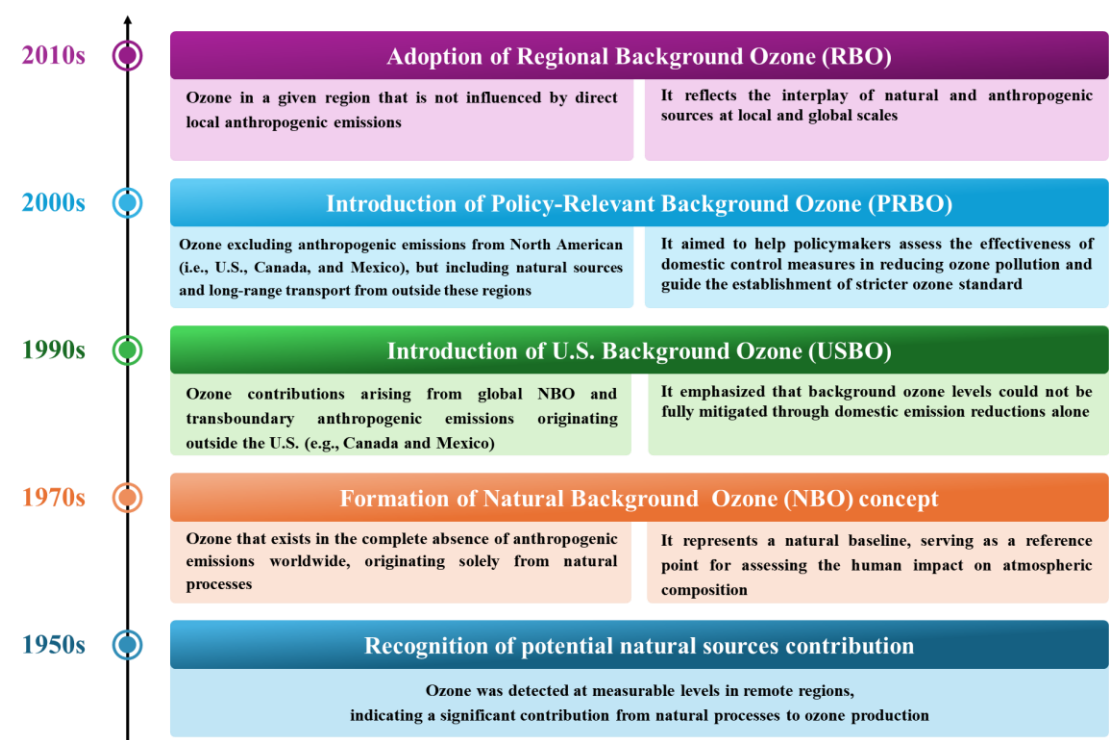
410   **Figure 2: Historical evolution of background O₃ concepts: definitions (left box) and characteristics (right box).**

411

412   3. In Section 4.2, the authors introduce several statistical methods estimating

413   background O_3. It would be helpful if the authors could compare the results from these

414   different methods at the same location, using an example to illustrate their differences

415   to highlight the respective advantages and disadvantages of each approach.

416   Response: We thank the reviewer for this insightful comment. We fully agree that

417   a direct comparison of background O_3 estimates derived from different methods at the

418   same location would provide a clearer illustration of their respective strengths and

419   limitations. However, such a systematic comparison is not feasible in the present study

420   because (1) not all methods introduced in Section 4.2 have been applied in China, and

421   those that have (e.g., PCA, TCEQ, temperature-ozone relationship, and nocturnal O_3

422   methods) require different observational datasets with region-specific applicability; and

423   (2) existing studies across China vary in spatial coverage and study periods, making it

424   difficult to apply multiple approaches consistently to the same region.

425   To address the reviewer's concern, we expanded our discussion by incorporating

426   evidence from studies that have compared multiple methods within the same region.

427   For example, in Shandong, Wang et al. (2022a) reported that PCA (using ambient O_3

428   alone) yielded background O_3 about 20 ppb higher than the TCEQ approach, with

429   seasonal patterns more consistent with background-site observations, whereas the

430   TCEQ method tended to underestimate background O_3 due to residual urban influences.

431   In the inland southeastern United States, Yan et al. (2021) found systematic differences

432   across three methods (O_3-CO-HCHO, 1-σ O_3-NO_z, and percentile-based), reflecting

433   varying sensitivities to anthropogenic signals. Similarly, Chen et al. (2022) revealed

434   that the nocturnal O_3 method underestimated background O_3 by up to 30% compared

435   with the temperature-ozone relationship method in China during polluted seasons.

436   We have expanded the discussion in Lines 607–635 of the revised manuscript:

437   Method-dependent discrepancies underscore the complexity of estimating

438   background O_3. Variability arises from differences in input data, model assumptions,

439   and the parameterization of physical and chemical processes (Jaffe et al., 2018; Skipper

440   et al., 2021; Wang et al., 2022a; Yan et al., 2021). For instance, in situ measurement

estimation method is directly influenced by local meteorological and emission

conditions, whereas the numerical modeling estimation method is subject to

uncertainties in simulating processes such as natural emissions, transboundary transport,

and photochemical reactions. Ideally, direct comparison of background O_3 estimates

derived from multiple methods at the same location would clarify their relative

strengths and limitations. However, such comparison was not feasible here due to

methodological and data constraints. First, the dataset used in this study is limited to

China, where only a subset of the methods described in Sect. 4.2 has been applied, each

requiring specific datasets and exhibiting region-dependent applicability. Second,

background O_3 exhibits pronounced spatial and temporal variability, while existing

studies often target different subregions and time periods, making consistent co-located

comparisons impractical. Despite these challenges, several studies have conducted

preliminary intercomparisons within the same region. In Shandong, Wang et al. (2022a)

reported that PCA (using ambient O_3 alone) yielded background O_3 about 20 ppb higher

than the TCEQ approach, with seasonal patterns more consistent with background-site

observations. The TCEQ method tended to underestimate background O_3 because

minimum MDA8 O_3 values were often influenced by residual urban emissions. In the

inland southeastern U.S., Yan et al. (2021) found the O_3-CO-HCHO method yielded the

lowest estimates (10–15 ppb), the 1-σ O_3-NO_z method intermediated values (15–25

ppb), and the 5th percentile method the highest (20–30 ppb), likely due to anthropogenic

influences in urban downwind regions. Likewise, Chen et al. (2022) revealed that the

nocturnal O_3 method underestimated background O_3 by up to 30% compared with the

temperature-ozone relationship method during polluted seasons in China.

Collectively, these studies demonstrate that methodological choices alone can lead to discrepancies of 10–20 ppb in background O_3 estimates within the same region. Careful interpretation therefore requires explicit attention to methodological assumptions, data representativeness, and sensitivity to emission influences. Moving forward, the development of harmonized datasets would enable the consistent application of multiple methods at the same regions and time periods, providing more robust intercomparisons and clearer insights into the strengths and limitations of each approach.

4. Also, the manuscript suggests that integrated methods improve the estimation of background O_3 by combining various data sources and techniques in section 4.4. How it is unclear how these results compare quantitatively with those from individual methods discussed in the above sections. And how strong are we confident with these integrated results? Providing a concrete example or case study to illustrate the improvement would strengthen this section.

Response: We thank the reviewer for this constructive comment and agree that a quantitative comparison between integrated methods and the individual approaches would strengthen the discussion. At present, however, studies that directly apply both integrated and single-method estimations to the same region and time period are not available, limiting the possibility of a fully consistent side-by-side comparison.

To address this point, we have revised Section 4.4 to highlight quantitative

evidence where integrated methods have been evaluated against individual approaches.

For example, Skipper et al. (2021) reported that incorporating spatial and temporal bias corrections improved the consistency of model-derived background O_3 estimates by 28% compared with the unadjusted model. Likewise, Hosseinpour et al. (2024) demonstrated that a random forest machine learning (RF-ML) algorithm integrating multiple data sources with nonlinear feature analysis produced background O_3 estimates most consistent with in situ observations for correcting air quality model simulations and outperformed the original CAMx model, multivariate regression, and other ML algorithms. These case studies provide concrete examples of the advantages of integrated methods.

Regarding confidence, we note that the reliability of integrated methods depends on the representativeness of the underlying observational and modeling datasets and the assumptions embedded in the integration process. Nonetheless, current evaluations consistently indicate that such frameworks reduce systematic biases, improve spatial-temporal coherence, and align more closely with independent in situ estimates. While further validation is needed using side-by-side comparisons with single-method estimates, existing evidence supports their strong potential to deliver more reliable and policy-relevant background O_3 estimates.

We have incorporated these clarifications and supporting examples in Lines 589–606 of the revised manuscript:

In contrast, the integrated methods – combining in situ observation, statistical analysis, and numerical results – yield the narrowest range (32–37 ppb), with the value

of 34.5 ± 1.6 ppb. This narrow range reflects their strength in reconciling the structural

consistency of models with real-world variability, rather than oversimplification. By

harmonizing data sources, integrated methods reduce methodological noise and yield

more robust, policy-relevant estimates. The limited number of applications, however,

may also contribute to the observed low variability. Although studies in China remain

scarce, international applications underscore their potential. For instance, Skipper et al.

(2021) showed that incorporating spatial and temporal bias corrections improved the

consistency of model-derived background O_3 estimates by 28% relative to unadjusted

models. Similarly, Hosseinpour et al. (2024) demonstrated that a random forest machine

learning (RF-ML) algorithm integrating multiple data sources with nonlinear feature

analysis produced background O_3 estimates most consistent with in situ observations

for correcting air quality model simulations and outperformed the original CAMx

model, multivariate regression, and other ML algorithms. Collectively, these studies

highlight the value of integrated methods in producing consistent estimates, particularly

for regulatory applications and long-term trend assessments. Nevertheless, further

validation is needed to determine whether the observed low variability reflects true

methodological robustness or limited sampling. Importantly, no single method is

definitive. Each carries inherent assumptions. Integrated methods therefore provide a

complementary framework that balances empirical realism with generalizability.

5. The meta-analysis is a key strength of this manuscript, but details on how the data

were compiled and interpreted are limited. Clarifying the data processing criteria and

handling of uncertainties would enhance this part of the work.

Response: We thank the reviewer for highlighting the importance of clarifying data processing criteria and the treatment of uncertainties in our meta-analysis. We have substantially revised Section 2 to provide a more transparent description of how the data were compiled, screened, and harmonized.

Lines 114–121:

To ensure the reliability and comparability of compiled background O_3 estimates, we adopted strict inclusion criteria: (i) reported values must specify temporal coverage and measurement or estimation methods; (ii) study location must be clearly identifiable within China; and (iii) data must originate from peer-reviewed publications, official reports, or other authoritative sources. All values considered in this study had already undergone rigorous quality control and screening by the original authors; therefore, no further outlier removal was performed. Where necessary, datasets were harmonized through standardized unit conversions and consistent temporal categorization to enhance comparability.

Lines 164–168:

To ensure robustness, individual data points that deviated markedly from the overall regional trend were excluded, whereas consecutive deviations were retained to preserve temporal continuity. Here, "deviation" refers to values that differ substantially from most annual data within the aggregated regional dataset – likely reflecting spatial heterogeneity – rather than statistical outliers at the level of individual studies.

551 **Minor comments:**

552 6. Line 132: there is an unnecessary comma

553 Response: Modified as suggested.

554

555 7. Line 355: "causa technique" likely intended as "causal technique"

556 Response: Modified as suggested.

557

558 **Reference**

559 Chen, W., Guenther, A. B., Shao, M., Yuan, B., Jia, S., Mao, J., Yan, F., Krishnan, P.,

560   and Wang, X.: Assessment of background ozone concentrations in China and

561   implications for using region-specific volatile organic compounds emission

562   abatement to mitigate air pollution, Environ. Pollut., 305, 119254,

563   https://doi.org/10.1016/j.envpol.2022.119254, 2022.

564 Chen, Z., Xie, Y., Liu, J., Shen, L., Cheng, X., Han, H., Yang, M., Shen, Y., Zhao, T.,

565   and Hu, J.: Distinct seasonality in vertical variations of tropospheric ozone over

566   coastal regions of southern China, Sci. Total Environ., 874, 162423,

567   https://doi.org/10.1016/j.scitotenv.2023.162423, 2023.

568 Colombi, N. K., Jacob, D. J., Yang, L. H., Zhai, S., Shah, V., Grange, S. K., Yantosca,

569   R. M., Kim, S., and Liao, H.: Why is ozone in South Korea and the Seoul

570   metropolitan area so high and increasing?, Atmos. Chem. Phys., 23, 4031–4044.

571   https://doi.org/10.5194/acp-23-4031-2023, 2023.

572 Dolwick, P., Akhtar, F., Baker, K. R., Possiel, N., Simon, H., and Tonnesen, G.:

573   Comparison of background ozone estimates over the western United States based on

574   two separate model methodologies, Atmos. Environ., 109, 282–296,

575   https://doi.org/10.1016/j.atmosenv.2015.01.005, 2015.

576 European Parliament and Council: Directive on ambient air quality and cleaner air for

577   Europe, 2008/50/EC, https://eur-lex.europa.eu/eli/dir/2008/50/oj (last access: 1

578   August 2025), 2008.

579 Han, H., Liu, J., Yuan, H., Wang, T., Zhuang, B., and Zhang, X.: Foreign influences on

580   tropospheric ozone over East Asia through global atmospheric transport, Atmos.

581   Chem. Phys., 19, 12495–12514. https://doi.org/10.5194/acp-19-12495-2019, 2019.

582 Hosseinpour, F., Kumar, N., Tran, T., and Knipping, E.: Using machine learning to

583   improve the estimate of U.S. background ozone, Atmos. Environ., 316, 120145,

584   https://doi.org/10.1016/j.atmosenv.2023.120145, 2024.

585 Liu, H., Zhang, M., and Han, X.: A review of surface ozone source apportionment in

586   China, Atmos. Oceanic Sci. Lett., 13, 470–484,

587   https://doi.org/10.1080/16742834.2020.1768025, 2020.

588   Lu, X., Zhang, L., and Shen, L.: Meteorology and climate influences on tropospheric

589   ozone: a review of natural sources, chemistry, and transport patterns, Curr. Pollut.

590   Rep., 5, 238–260. https://doi.org/10.1007/s40726-019-00118-3, 2019.

591   Luo, Y., Zhao, T., Meng, K., Hu, J., Yang, Q., Bai, Y., Yang, K., Fu, W., Tan, C., Zhang,

592   Y., Zhang, Y., and Li, Z.: A mechanism of stratospheric O_3 intrusion into the

593   atmospheric environment: a case study of the North China Plain, Atmos. Chem. Phys.,

594   24, 7013–7026, https://doi.org/10.5194/acp-24-7013-2024, 2024.

595   Ma, X., Huang, J., Hegglin, M. I., Jöckel, P., and Zhao, T.: Causes of growing middle-

596   to-upper tropospheric ozone over the northwest Pacific region, Atmos. Chem. Phys.,

597   25, 943–958, https://doi.org/10.5194/acp-25-943-2025, 2025.

598   Ma, Z., Xu, J., Quan, W., Zhang, Z., Lin, W., and Xu, X.: Significant increase of surface

599   ozone at a rural site, north of eastern China, Atmos. Chem. Phys., 16, 3969–3977,

600   https://doi.org/10.5194/acp-16-3969-2016, 2016.

601   Sahu, S. K., Liu, S., Liu, S., Ding, D., and Xing, J.: Ozone pollution in China:

602   Background and transboundary contributions to ozone concentration & related health

603   effects across the country, Sci. Total Environ., 761, 144131,

604   https://doi.org/10.1016/j.scitotenv.2020.144131, 2021.

605   Skipper, T. N., Hu, Y., Odman, M. T., Henderson, B. H., Hogrefe, C., Mathur, R., and

606   Russell, A. G.: Estimating US background ozone using data fusion, Environ. Sci.

607   Technol., 55, 4504–4512, https://doi.org/10.1021/acs.est.0c08625, 2021.

608   U.S. Environmental Protection Agency: Electronic Code of Federal Regulations, Title

609   40: Protection of Environment – Chapter I (Environmental Protection Agency), Part

610   53: Ambient air monitoring reference and equivalent methods,

611   https://www.ecfr.gov/current/title-40/chapter-I/part-53, (last access: 1 August 2025).

612   Wang, F. T., Zhang, K., Xue, J., Huang, L., Wang, Y. J., Chen, H., Wang, S. Y., Fu, J.

613   S., and Li, L.: Understanding regional background ozone by multiple methods: A

614   case study in the Shandong region, China, 2018–2020, J. Geophys. Res.-Atmos., 127,

615   e2022JD036809, https://doi.org/10.1029/2022JD036809, 2022a.

616   Wang, T., Xue, L., Feng, Z., Dai, J., Zhang, Y., and Tan, Y.: Ground-level ozone

617   pollution in China: a synthesis of recent findings on influencing factors and impacts,

618   Environ. Res. Lett., 17, 063003, https://doi.org/10.1088/1748-9326/ac69fe, 2022b.

619   Wang, Y., Zhang, Y., Hao, J., and Luo, M.: Seasonal and spatial variability of surface

620   ozone over China: contributions from background and domestic pollution, Atmos.

621   Chem. Phys., 11, 3511–3525, https://doi.org/10.5194/acp-11-3511-2011, 2011.

622   Xu, X.: Recent advances in studies of ozone pollution and impacts in China: a short

623   review,   Curr.   Opin.   Env.   Sci.   Hl.,   19,   100225,

624   https://doi.org/10.1016/j.coesh.2020.100225, 2021.

625   Yan, Q., Wang, Y., Cheng, Y., and Li, J.: Summertime clean-background ozone

626   concentrations derived from ozone precursor relationships are lower than previous

627   estimates in the southeast United States, Environ. Sci. Technol., 55, 12852–12861,

628   https://doi.org/10.1021/acs.est.1c03035, 2021.