

1 Responses to Reviewer Comments for “**What caused record-breaking aerosol loading over the**
2 **South China Sea in April 2023**” by Saginela Ravindra Babu and Neng-Huei Lin.

3 Dear Editor,

4 Jason Cohen,

5 Please accept my sincere apologies for the delay in submitting the revised manuscript. I regret
6 missing the original deadline and appreciate your understanding. Here, we are submitting our
7 revised manuscript titled “**What caused record-breaking aerosol loading over the South China**
8 **Sea in April 2023**”. We thank all the Reviewers for their detailed and well-structured comments,
9 which significantly improved the manuscript. We have made substantial changes to the manuscript
10 in order to thoroughly address the Reviewers’ suggestions and comments. Main changes include:

- 11 ● As per the Reviewers’ suggestions, we have included HYSPLIT back-trajectory analysis,
12 daily vertical aerosol type images from CALIPSO, and vertical changes of black carbon
13 (BC) and organic carbon (OC) from MERRA-2 reanalysis in the revised manuscript.
- 14 ● The entire Introduction has been rewritten, following Reviewer 1’s recommendations.
- 15 ● The Results and Discussion section has been reorganized as suggested by Reviewer 1.
- 16 ● Text has been modified throughout the manuscript wherever required, based on the
17 Reviewers’ comments.
- 18 ● We have also compared MODIS AOD, 500-hPa geopotential height, and wind vectors for
19 the April 2023 event with other high biomass-burning years in the revised manuscript.
- 20 ● The plausible link to the El Niño–Southern Oscillation (ENSO) is also discussed by
21 analysing composites of AOD and circulation patterns for El Niño-ensuing and La Niña-
22 ensuing Aprils.
- 23 ● After careful consideration, we decided to remove the ozone analysis from the present
24 manuscript; this work will be communicated separately with more detailed modelling
25 analysis.

26 With these changes, we are convinced that the paper is highly relevant to a broad journal such as
27 **Atmospheric Chemistry and Physics**. We have provided our responses, point by point, to all
28 reviewers’ comments and suggestions. Reviewer’s comments are in normal black font, followed
29 by our respective replies in blue font.

30 Kind regards,

31 **Saginela Ravindra Babu** (on behalf of the co-authors)

32

Response to Referee #1

33 General Comment

34 The manuscript addresses the record-breaking aerosol loading over the South China Sea (SCS) in
35 April 2023, attributed to biomass burning (BB) over the northern Indochina Peninsula. While the
36 topic is of regional and global importance, the study suffers from several critical issues. The
37 methodology is overly simplistic, the novelty is limited, the logical flow is confusing, and key
38 presentation elements (maps, data classification, figures) do not meet the standards of a top-tier
39 journal. In its current form, the manuscript reads more like a descriptive case report rather than an
40 in-depth scientific analysis. Substantial revision is needed before it can be considered for
41 publication.

42 Reply: We thank the reviewer for the critical review of our original manuscript, which has helped
43 us revise it for the better. Our point-by-point responses to the review comments are provided
44 below. The authors sincerely thank the reviewer for dedicating the time and effort to evaluating
45 our manuscript and for providing thoughtful, constructive feedback. We also appreciate the
46 reviewer's recognition of the significance of our study. Their valuable comments have greatly
47 enhanced the quality and clarity of our work.

48 All figures have been revised and improved in accordance with the reviewers' suggestions to
49 enhance clarity and precision.

50 Major Comments

51 Scientific Significance and Novelty

52 Biomass burning over Indochina and its long-range transport to the SCS is a well-documented and
53 recurring phenomenon (e.g., Lin et al., 2013; Reid et al., 2013). The manuscript merely shows that
54 April 2023 recorded the highest anomalies in AOD/CO/ozone in the past two decades. Without
55 deeper analysis of what makes 2023 fundamentally different (e.g., unique transport pathways,
56 distinct chemical mechanisms, significant health/climate impacts), the work risks being a

57 replication of prior studies with little added value. The authors need to explicitly demonstrate
58 the **novelty** and scientific importance of this case beyond being “the largest on record.”

59 Reply: The authors fully recognize the well-established link between biomass burning in Indochina
60 (PSEA) and its transport to the South China Sea (SCS), Taiwan, and the western North Pacific, as
61 shown in earlier research (Lin et al., 2013; Reid et al., 2013). The authors are well aware of the
62 PSEA BB activity, its transport mechanisms, and its effects on regional weather and climate.
63 However, the reviewer may have misunderstood the study's primary focus and its significant
64 findings. While previous research indicates that most transported smoke stays north of about
65 17.5°N over the SCS, our analysis shows that **during April 2023, the smoke was unusually**
66 **transported much farther south, reaching the southern parts of the SCS and even extending**
67 **toward the southern Bay of Bengal (BoB).** This departure from typical patterns is significant.
68 To illustrate this, we present the average April AOD distribution for 2003–2022 in Supplementary
69 Figure 2 (now it is Figure 3 in the revised manuscript), which shows higher AOD levels across
70 approximately 17.5°N–25°N, from northern Indochina to Taiwan. Conversely, the SCS region
71 outlined in a black box generally exhibits very low AOD. The April 2023 event is notable for its
72 intensity and spatial coverage. The AOD anomalies obtained are 4 times the long-term mean over
73 most of the SCS and the southern BoB region in April 2023. We believe our study highlights a
74 rare, previously unreported transport event rather than simply reproducing prior work, with
75 potential consequences for regional air quality and climate. We will emphasize this aspect further
76 in the revised manuscript to clearly showcase the novelty and importance of the April 2023 case.

77 **Mismatch Between Analysis and Conclusions**

78 The conclusions claim clear attribution to Laos fires and anomalous circulation systems. However,
79 the analysis is largely descriptive, relying on anomaly maps and percentage changes. The causal
80 chain (fire activity → transport anomalies → AOD/CO increases → ozone formation) is not
81 rigorously substantiated. For example, CO–AOD correlation (~0.65) only suggests coincidence,
82 not causality. Ozone enhancement is attributed to BB emissions without distinguishing between
83 primary transport and secondary chemistry. The authors should either strengthen the causal
84 evidence (e.g., trajectory modeling, chemical transport simulations, Rossby wave diagnostics) or
85 tone down the conclusions.

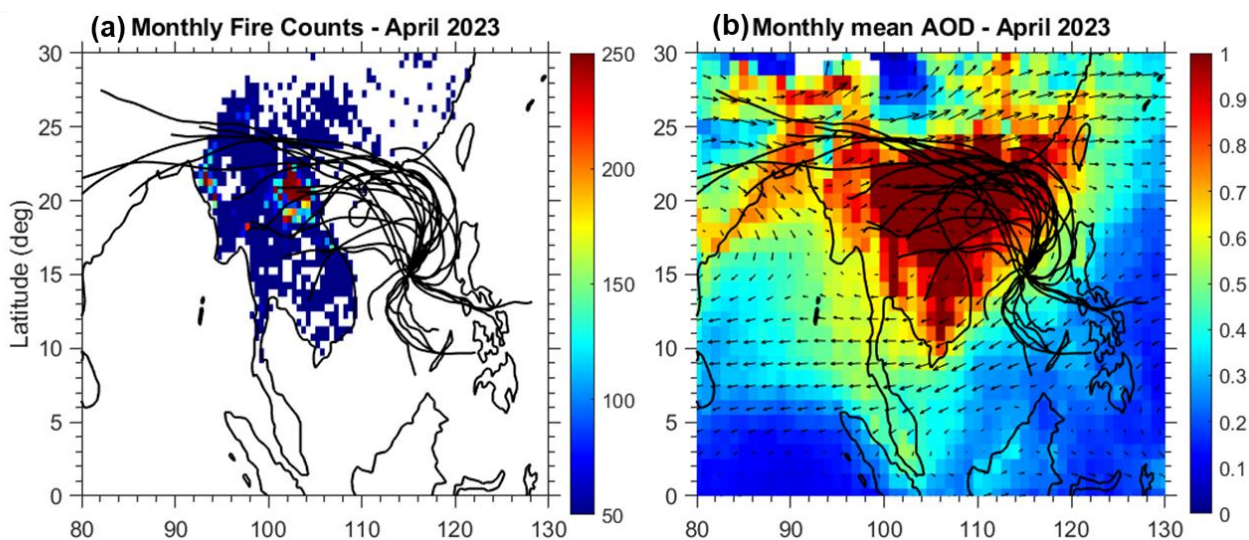
86 For example, CO–AOD correlation (~ 0.65) only suggests coincidence, not causality.

87 **Reply:** We appreciate the reviewer’s valuable comments. In the revised manuscript, we have
88 strengthened the analysis by incorporating HYSPLIT back-trajectory analysis, vertical aerosol
89 profiles from CALIPSO images, and vertical changes of black carbon (BC) and organic carbon
90 (OC) from MERRA-2 reanalysis. In addition, we have included an analysis of formic acid
91 (HCOOH) to better illustrate the role of secondary photochemical processes in ozone formation
92 over the South China Sea (SCS). These additions have been reflected in revised conclusions, with
93 careful consideration of the evidentiary limits of the present study.

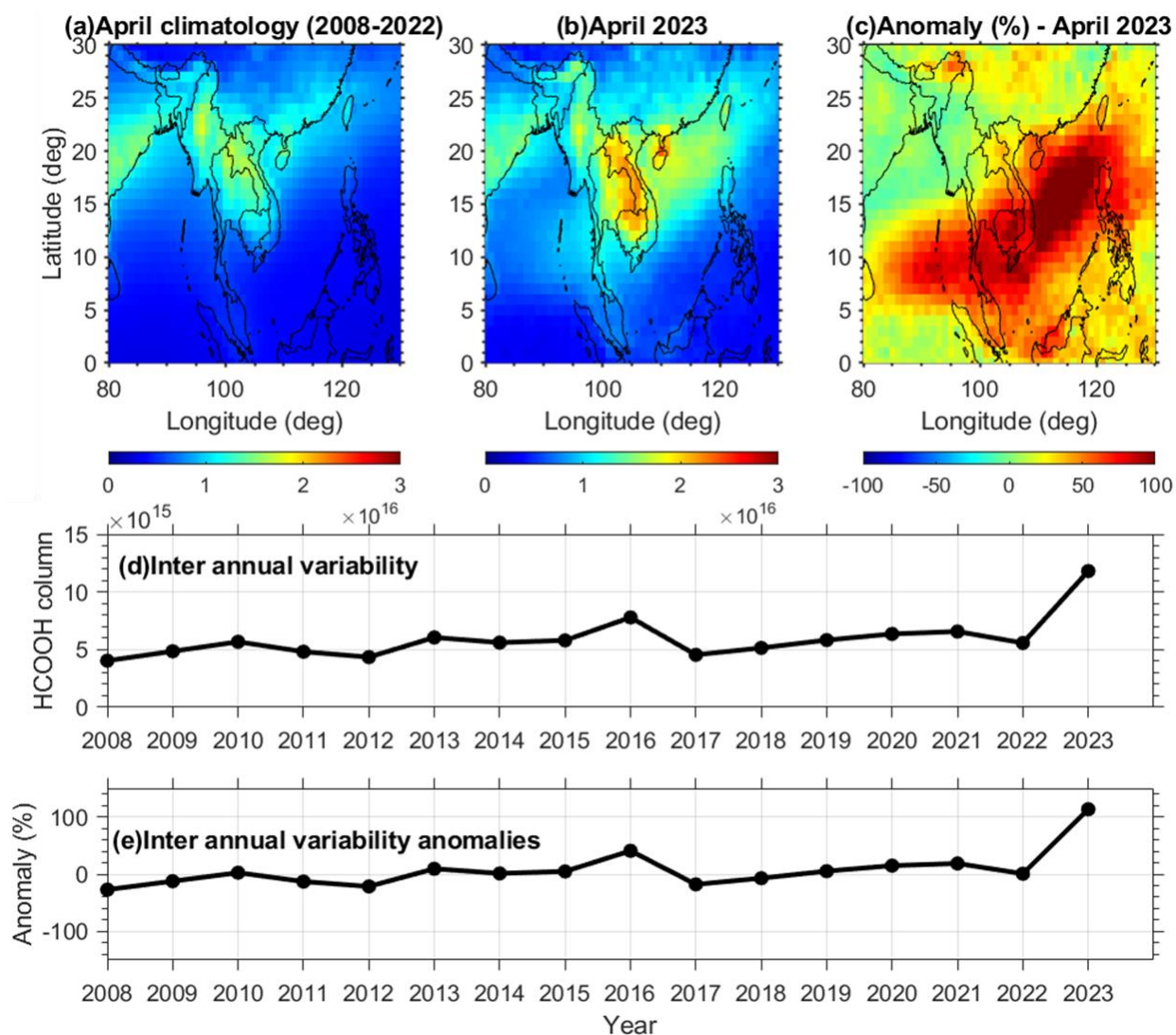
94 Regarding the CO–AOD relationship, we note that the manuscript mistakenly reported a
95 correlation coefficient of 0.65; this is in fact the coefficient of determination (R^2). The
96 corresponding correlation coefficient is $R = 0.81$, indicating a statistically robust association
97 between CO and AOD over the SCS. While we agree that correlation alone does not prove
98 causality, the strong CO–AOD relationship in this remote, marine region, largely free of local
99 anthropogenic sources, supports the interpretation of long-range transport of combustion-related
100 aerosols. Elevated CO, a tracer of incomplete combustion, observed far from urban and industrial
101 sources, is consistent with biomass burning (BB) influence. Seasonal consistency further supports
102 this interpretation: annual AOD maxima over Peninsular Southeast Asia (PSEA) in March–April
103 and over the Maritime Continent in September coincide with their respective peak fire seasons. To
104 strengthen source attribution, we analyzed daily HYSPLIT back trajectories, which show that air
105 masses arriving over the SCS during April 2023 predominantly originated from northern PSEA,
106 consistent with active BB regions during this period (Figure R1). While this trajectory analysis
107 does not constitute a complete transport attribution framework, it provides dynamical support for
108 BB influence.

109 We agree with the reviewer that ozone enhancement should not be attributed solely to BB
110 emissions, and that this attribution should distinguish between primary transport and secondary
111 photochemical production. In the revised manuscript, we explicitly clarify this distinction. Ozone
112 anomalies over the SCS coincide with elevated CO and AOD; however, quantifying ozone
113 production would require chemical transport modeling, which is beyond the scope of this study.
114 Nevertheless, additional observational evidence supports secondary chemical processing within

115 transported BB plumes. Infrared Atmospheric Sounding Interferometer (IASI) MetOp satellite
116 observations show a ~100% enhancement in formic acid (HCOOH) over the SCS in April 2023
117 (Figure R2). HCOOH is a well-established secondary oxidation product of VOCs emitted by
118 biomass burning. The simultaneous enhancements of CO (>50 ppb), AOD (~150%), and HCOOH
119 indicate that BB plumes underwent substantial photochemical aging during transport. Therefore,
120 the observed ozone enhancement is interpreted as primarily due to secondary ozone formation
121 within transported BB plumes, rather than to direct ozone transport alone. However, after careful
122 consideration, we decided to remove the ozone analysis from the present manuscript; this work
123 will be communicated separately with more detailed modelling analysis.



124
125 Figure R1. (a) Daily 72-h NOAA HYSPLIT backward trajectories ending at 12:00 UTC at a
126 representative location (15°N, 115°E) over the South China Sea at 3 km altitude, overlaid on
127 MODIS fire counts for April 2023. (b) Same as (a), but overlaid on the monthly mean MODIS
128 aerosol optical depth (AOD) for April 2023.



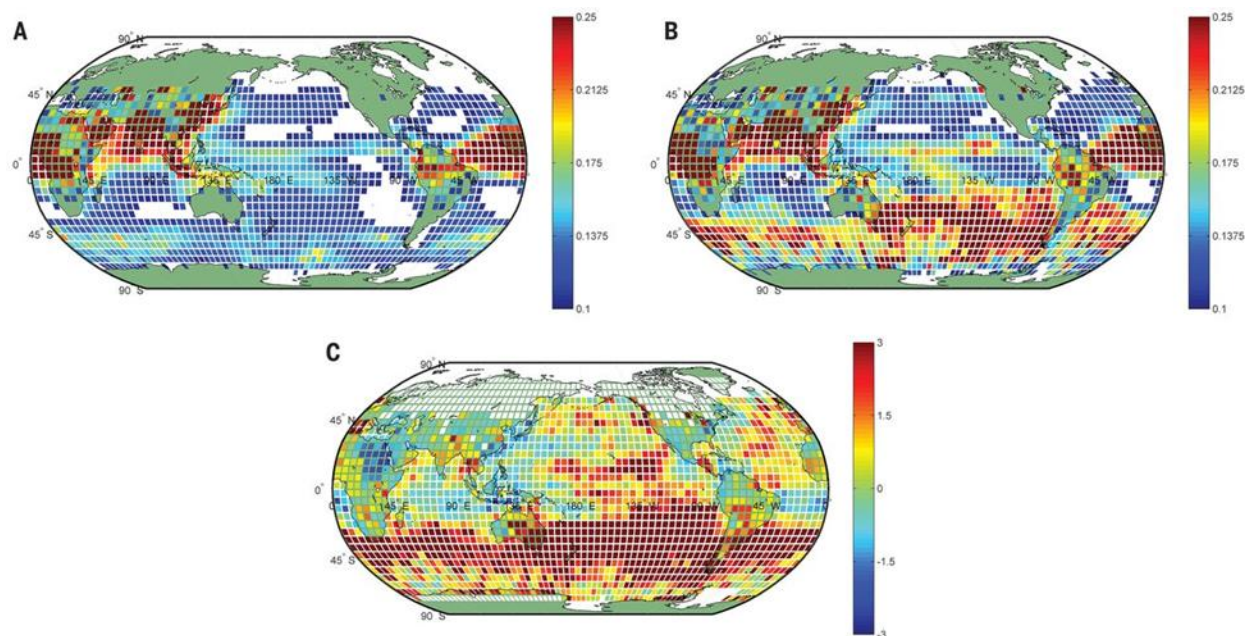
129
 130 Figure R2. The Infrared Atmospheric Sounding Interferometer (IASI) METOP satellite observed
 131 total column HCOOH (a) April long-term mean (2008-2022), (b) April 2023, (c) the percentage
 132 change in HCOOH in April 2023 compared to the long-term mean (2008-2022). (d) inter-annual
 133 variability of HCOOH in April, and (e) the observed percentage change anomaly in HCOOH over
 134 the South China Sea. IASI is a joint mission of EUMETSAT and the Centre National d'Etudes
 135 Spatiales (CNES, France). The authors acknowledge the AERIS data infrastructure for providing
 136 access to the IASI data in this study. (<https://iasi.aeris-data.fr/hcooh/>).

137 **Methodology Too Simplistic**

138 The methodology is limited to anomaly calculations relative to the 2003–2022 climatology and σ -
 139 thresholds. No advanced statistical diagnostics (EOF, regression, composite analysis) or modeling
 140 tools (WRF-Chem, GEOS-Chem, HYSPLIT) are applied. For a high-impact journal, such purely

141 descriptive methods are insufficient. More mechanistic or quantitative approaches are expected to
142 justify publication.

143 **Reply:** We appreciate the reviewer's comment. Calculating anomalies relative to a long-term
144 climatological period (2003–2022 in our case) is a well-established and widely accepted method in
145 atmospheric and climate sciences (Avery et al., 2017; Hirsch and Koren, 2021; Hedelius et al., 2021;
146 Rieger et al., 2021; Stone et al., 2025; Prasanth et al., 2025). Comparing these anomalies with the
147 corresponding monthly standard deviations provides a quantitative measure of their extremity. In
148 our study, we clearly state that the observed AOD anomaly in April 2023 exceeded the long-term
149 mean by more than four standard deviations, indicating an exceptionally event. It is also noted that
150 similarly focused studies have successfully employed such methods. For example, Hirsch and
151 Koren (2021), in their *Science* article ("Record-breaking aerosol levels explained by smoke
152 injection into the stratosphere"), used fundamental anomaly analysis to identify record-high AOD
153 levels resulting from the Australian wildfires (See the attached figure below). This highlights that
154 the suitability of methodology depends on the study objective, and complex statistical techniques
155 are not always required for publication in high-impact journals.



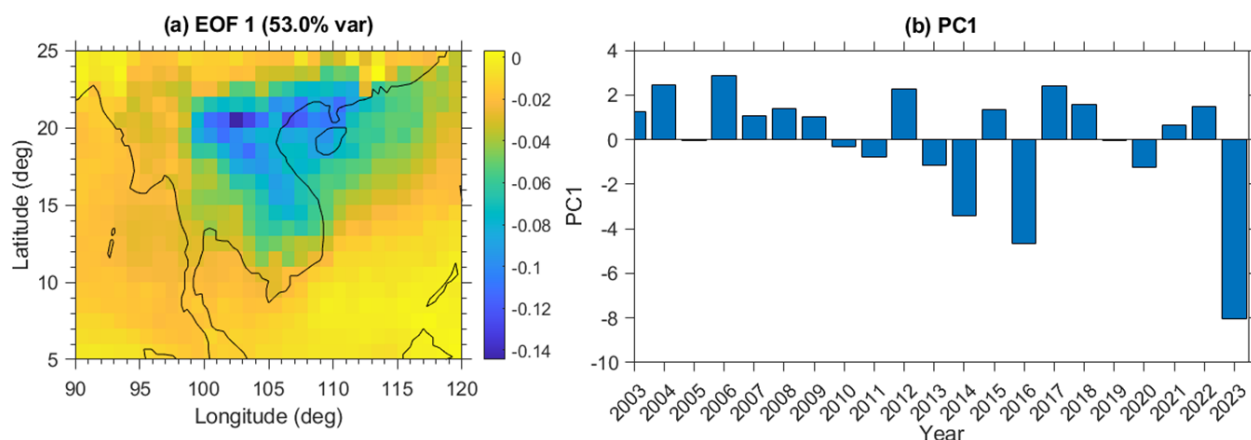
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157 **Fig. 2 The SH anomaly for January 2020 (spatial resolution of 5° by 5°).**

158 (A) Interannual (2003 to 2019) monthly average AOD values for January. (B) Monthly AOD
159 values for January 2020. A notable increase in the AOD values over the SH is observed. (C) The

160 change in January 2020 AOD values compared with the interannual January average (expressed
161 in standard deviation units). (source: Hirsch and Koren, 2021, *Science*.)

162 However, we fully agree with the reviewer that approaches such as EOF analysis,
163 regression, and chemical transport modeling (e.g., WRF-Chem, GEOS-Chem) are highly valuable
164 for exploring underlying mechanisms and causal relationships. Following the reviewer's helpful
165 suggestion, we have included HYSPLIT backward trajectory analysis in the revised manuscript to
166 provide additional evidence for long-range transport from biomass-burning regions (see Figure R1).
167 We also examined AOD variability across the study region using EOF analysis; the results are
168 shown in the attached figure (Figure R3) for your reference. An EOF analysis was applied to the
169 observed monthly mean AOD time series in the study region (90-120E, 5-25N) to determine the
170 dominant modes of variability over the period. The spatial distribution and temporal amplitude are
171 negative, resulting in a positive value. A higher negative value indicates higher AOD. Figure 2(a)
172 shows higher AOD in the northern PSEA and the coastal area of southern China. The result of EOF1
173 * PC1 (multiplication) is the same.



174
175 Figure R3. (a) The spatial distribution, and (b) its corresponding time-varying amplitude for the
176 vector EOF analysis mode 1 of the April AOD in SCS during 2003 to 2023.

177 We agree that chemical transport models such as WRF-Chem and GEOS-Chem could provide
178 further insight into the chemical and physical processes involved. However, incorporating such
179 models is beyond the scope of this observational and event-focused study. We will clearly state this
180 limitation in the revised manuscript and consider it a priority for future research.

181 **Logical Flow and Structure**

182 The introduction devotes excessive space to global wildfire events (Canada, Hawaii,
183 Mediterranean), which dilutes the focus on the SCS case.

184 Reply: Thank you for your insightful comment. The discussion of global wildfire events (e.g., in
185 Canada, Hawaii, and the Mediterranean) was included in the introduction to highlight the unusually
186 active and widespread nature of wildfires during the study period, placing the South China Sea
187 (SCS) event within a broader global context. However, we understand that this may have diluted
188 the focus on the SCS case. In response, we have revised the introduction to briefly summarize the
189 global activity while more clearly emphasizing the relevance and distinctiveness of the SCS aerosol
190 episode, ensuring that the central focus of the study remains clear.

191 The Results and Discussion section frequently shifts between AOD, CO, fire counts, meteorology,
192 circulation, and ozone, without a clear hierarchical structure. This leads to a confusing narrative.

193 The manuscript would benefit from a re-organization: Phenomenon confirmation → Source
194 attribution → Circulation mechanisms → Chemical/ozone impacts → Implications.

195 Reply: Thank you for the valuable suggestion. We have reorganized the Results and Discussion
196 section of the revised manuscript as recommended. The new structure improves the flow from
197 phenomenon confirmation to source and circulation analysis. The revised sections are as follows:
198 3.1 Record-breaking aerosol loading over the SCS in April 2023, 3.2 Transport and source
199 attribution of the April 2023 aerosol event, 3.3 Large-scale meteorological and dynamical
200 circulation anomalies in April 2023.

201 **Data Classification and Transparency**

- 202 • Satellite products (MODIS, MOPITT, AIRS, OMI/MLS), reanalysis datasets (MERRA-2,
203 GLDAS, GPCP), and in-situ measurements (AERONET, ozonesondes) are all mixed together
204 in one section.
- 205 • It is difficult for the reader to distinguish between direct observations, model-assimilated
206 reanalysis, and ground truth data.

207 • The Data and Methodology section should be reorganized into clear categories: (1) Satellite
208 remote sensing, (2) Reanalysis/model products, (3) Ground-based observations.

209 Reply: Thanks for the voluble suggestion. We have revised the Data and Methodology section as
210 suggested. We also included a table describing the data used in the present study.

211 **Table 1.** Details of various data products used in the present study.

Data	Resolution	Source
Aerosol Optical Depth (AOD)	$1^\circ \times 1^\circ$	Aqua and Terra satellite/MODIS
Carbon Monoxide (CO)	$1^\circ \times 1^\circ$	MOPITT and AIRS
Burned Area (BA)	500 m	Aqua and Terra satellite/MODIS
MODIS Collection 6.1 Fire Anomalies		combined Terra and Aqua satellite/MODIS
Wind and Geopotential Height	$0.5^\circ \times 0.625^\circ$	MERRA reanalysis

212 Use of Supplementary Figures

213 Key evidence (e.g., climatological AOD distributions, long-term time series) is presented only in
214 Supplementary Figures. Essential results should be in the main text, with Supplementary reserved
215 for additional details or robustness checks. As written, the paper is not self-contained.

216 Reply: We appreciate the reviewer's valuable comment. We agree that the climatological AOD
217 distributions and long-term time series provide essential context. As suggested by the reviewer, we
218 have moved the key figures showing the climatological AOD distributions and the long-term AOD
219 time series from the Supplementary Materials to the main text (now Figures 2 and 3, respectively).

220 **Map Presentation and Political Sensitivity**

221 Several figures show solid boundary lines in regions with disputed territories (e.g., South China
222 Sea). International journals require disputed boundaries to be indicated with dashed lines and/or
223 with a neutral disclaimer in the captions. The authors must revise all maps accordingly to comply
224 with cartographic and editorial standards.

225 **Reply:** We appreciate the reviewer's careful observation and constructive comment. Following the
226 recommendation, we have revised all maps to comply with editorial standards.

227 **Lack of Impact Assessment**

228 The study stops at describing anomalies. There is no evaluation of downstream consequences
229 (e.g., impacts on regional air quality, radiative forcing, health risks). Without such discussion, the
230 significance of the findings remains limited.

231 **Reply:** Thank you for your comment. The primary objective of this study is to identify the drivers
232 and underlying physical mechanisms responsible for the record-breaking aerosol loading over the
233 South China Sea. In the revised manuscript, we have additionally compared MODIS AOD, 500-
234 hPa geopotential height, and wind vectors for the April 2023 event with those from other high-
235 biomass-burning years. The plausible link to the El Niño–Southern Oscillation (ENSO) is also
236 discussed by analyzing composites of AOD and circulation patterns for El Niño-ensuing and La
237 Niña-ensuing Aprils. A more comprehensive evaluation of the downstream impacts on radiative
238 forcing, atmospheric processes, and air quality is beyond the scope of this study and will be
239 addressed in a follow-up investigation.

240 **Minor Comments**

241 Figures are overcrowded, with small fonts and inconsistent styles (gradient colors vs. hatching).
242 Improve readability and adopt a uniform design.

243 **Reply:** We have taken utmost care in the figures in the revised manuscript.

244 Figure 8 schematic is overly simplistic compared to the complexity of earlier figures; it should more
245 clearly contrast climatological vs. 2023 circulation states.

246 **Reply:** We have redrawn the figure in the revised manuscript.

247 Reference formatting is inconsistent; some entries are incomplete or lack DOI.

248 [Reply: Corrected in the revised manuscript](#)

249 The writing style is verbose. The introduction should be shortened and sharpened to highlight the
250 scientific problem.

251 [Reply: Corrected in the revised manuscript](#)

252 The format are not clearly uniform between $1^\circ \times 1^\circ$ in L116 and 0.25° in L124. The font format of
253 L124-125 is different from other context.

254 [Reply: Corrected in the revised manuscript](#)

255 L140, why the skin temperature is used in this work?

256 [Reply: It is a typo mistake. We used the surface temperature from the AIRS satellite. We have
257 corrected this typo in the revised manuscript.](#)

258 L187, L198, add $^\circ$ for the logitude and latitude.

259 [Reply: Corrected in the revised manuscript](#)

260 L185, Sup. Figures, L188, Sup—Figures, P201, Sup. Fig. and so on, keep the same citaiton style,
261 refer to the papers in the top journals.

262 [Reply: Corrected in the revised manuscript](#)

263 L 241, the maps are not correct, as we know, there are still undecided boarders between China and
264 India, the author should clearly state them in the maps.

265 [Reply: Corrected in the revised manuscript](#)

266 [References](#)

267 [Hirsch, E. and Koren, I.: Record-breaking aerosol levels explained by smoke injection into the
268 stratosphere, Science, 371, 1269–1274, <https://doi.org/10.1126/science.abe1415>, 2021.](#)

269 [Avery, M., Davis, S., Rosenlof, K. et al. Large anomalies in lower stratospheric water vapour and
270 ice during the 2015–2016 El Niño. Nature Geosci 10, 405–409 \(2017\).
271 <https://doi.org/10.1038/ngeo2961>](#)

272 [Hedelius, J. K., Toon, G. C., Buchholz, R. R., Iraci, L. T., Podolske, J. R., Roehl, C. M., Wennberg,
273 P. O., Worden, H. M., and Wunch, D.: Regional and urban column CO trends and anomalies as
274 observed by MOPITT over 16 years, J. Geophys. Res.-Atmos., 126, e2020JD033967,
275 <https://doi.org/10.1029/2020JD033967>, 2021.](#)

276 [Rieger, L. A., Randel, W. J., Bourassa, A. E., and Solomon, S.: Stratospheric Temperature and
277 Ozone Anomalies Associated With the 2020 Australian New Year Fires, Geophys. Res. Lett., 48,
278 e2021GL095898, <https://doi.org/10.1029/2021GL095898>, 2021.](#)

279 Stone, K., Solomon, S., Yu, P., Murphy, D. M., Kinnison, D., and Guan, J.: Two-years of
280 stratospheric chemistry perturbations from the 2019–2020 Australian wildfire smoke, *Atmos.*
281 *Chem. Phys.*, 25, 7683–7697, <https://doi.org/10.5194/acp-25-7683-2025>, 2025.

282 Prasanth, S., Anand, N. S., Sunilkumar, K., Jose, S., Arun, K., Satheesh, S. K., and Moorthy, K. K.:
283 Australian bushfire emissions result in enhanced polar stratospheric clouds, *Atmos. Chem. Phys.*,
284 25, 7161–7186, <https://doi.org/10.5194/acp-25-7161-2025>, 2025.

285 We once again thank the reviewer for carefully reviewing the manuscript and for offering potential
286 solutions that significantly improved its content.

287

288

Response to Referee #2

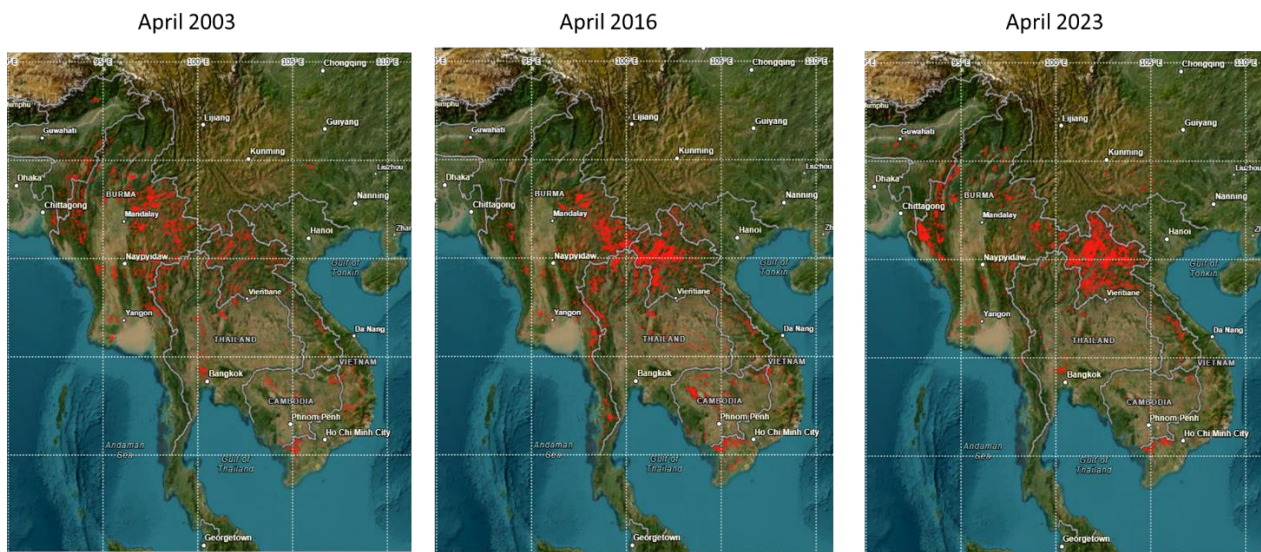
289 This paper investigates the drivers of the record-breaking aerosol loading event over the South
290 China Sea in April 2023, combining satellite observations, reanalysis data, and ground-based
291 measurements. The study convincingly shows that large-scale biomass burning in northern Laos
292 and Myanmar, combined with anomalous circulation patterns, caused unprecedented aerosol
293 transport into the SCS. The integration of multiple datasets (MODIS, MOPITT, AIRS, OMI/MLS,
294 and MERRA-2) strengthens the analysis, and the paper provides timely insights into extreme
295 aerosol events under changing climate conditions. Overall, this work makes a valuable
296 contribution to understanding regional transboundary pollution processes. I recommend minor
297 revisions before acceptance.

298 **Reply:** We thank Reviewer #2 for the positive review and fair remarks, which have all been
299 carefully implemented in the manuscript.

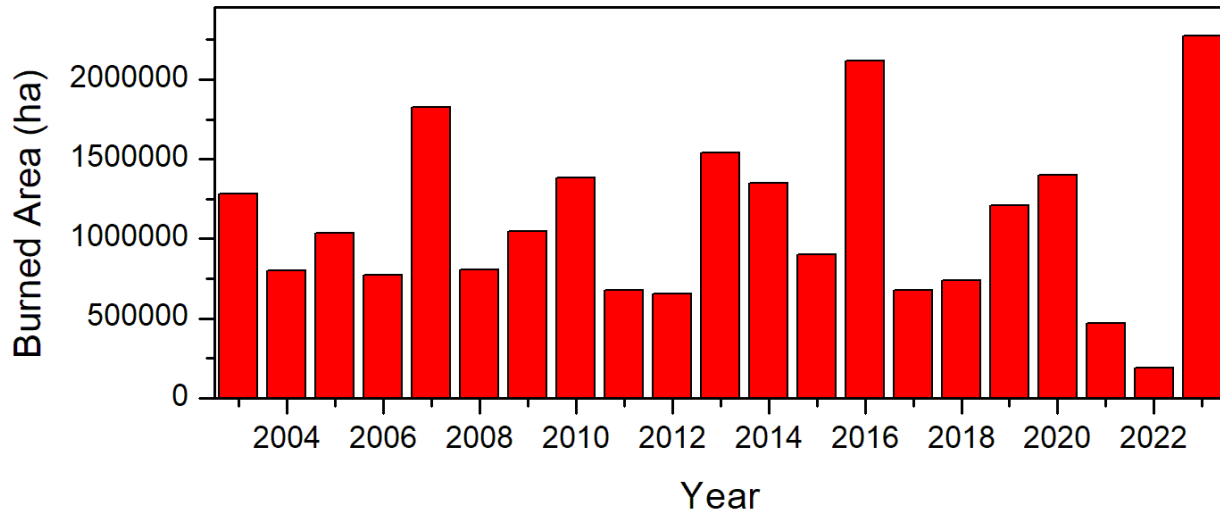
300 (1) The fire activity analysis over Laos is a highlight of the study. Since you mention that 2023
301 had the largest monthly burned area on record, adding a supplementary figure comparing 2023
302 with other extreme fire years (e.g., 2016, 2003) would strengthen the historical context.

303 Thank you for your valuable suggestion. We have already included the monthly burned area for
304 Laos from January 2003 to December 2023 in Supplementary Figure 7. Additionally,
305 Supplementary Figure 8 illustrates the interannual variability in April's burned area over the same
306 period. These two figures clearly show that the largest monthly burned area during 2003–2023 was
307 in April 2023, totaling 1.08 Mha.

308 Following the reviewer's suggestion, we further examined the MODIS burned area data
309 for April 2003, 2016, and 2023 and present a comparison of their spatial distributions in the figure
310 below (Figure R1). The results indicate that the spatial distributions of burned areas in 2016 and
311 2023 are generally similar, with the most extensive burning occurring in northern Laos compared
312 with 2003. However, the burned area in 2023 was more concentrated and extensive in northern
313 Laos than in 2016. We further included the overall burned-area variability over PSEA (combining
314 all PSEA countries) from 2003 to 2023 in April as a supplement figure in the revised manuscript.
315 We noticed that the burned area in April 2023 is the highest with 2.27 Mha during the 2003 to
316 2023 period for the PSEA region. We also included each country's Burned Area (BA) and the
317 contribution percentage for the total BA in Table 1. For your reference, we have attached the
318 interannual variability of BA for April over PSEA in Figure R2.



319
320 Figure R1. The spatial distribution of MODIS burned area (BA) in April 2003, 2016, and 2023.
321 (Source: <https://firms.modaps.eosdis.nasa.gov/>)



322

323 [Figure R2. Interannual variability in Burned Area over Peninsula Southeast Asia in April from](#)
 324 [2003 to 2023.](#)

325 (2) The study identifies biomass burning in Laos as the major contributor to the April 2023 event.
 326 Could the authors clarify whether other regional fire sources (e.g., Maritime Continent or southern
 327 China) were quantitatively excluded, or whether their contributions are negligible compared to
 328 Laos?

329 [Reply: Thank you for the insightful comment. After a thorough investigation of the spatial](#)
 330 [distribution of burned areas and fire counts, we confirmed that the contributions from the Maritime](#)
 331 [Continent and southern China were negligible for the extreme AOD observed in April 2023. As](#)
 332 [shown in Figure R3, the burned area was predominantly concentrated over the PSEA region, with](#)
 333 [little to no burning detected over the Maritime Continent or southern China. Therefore, these](#)
 334 [regions were excluded from our calculations.](#)



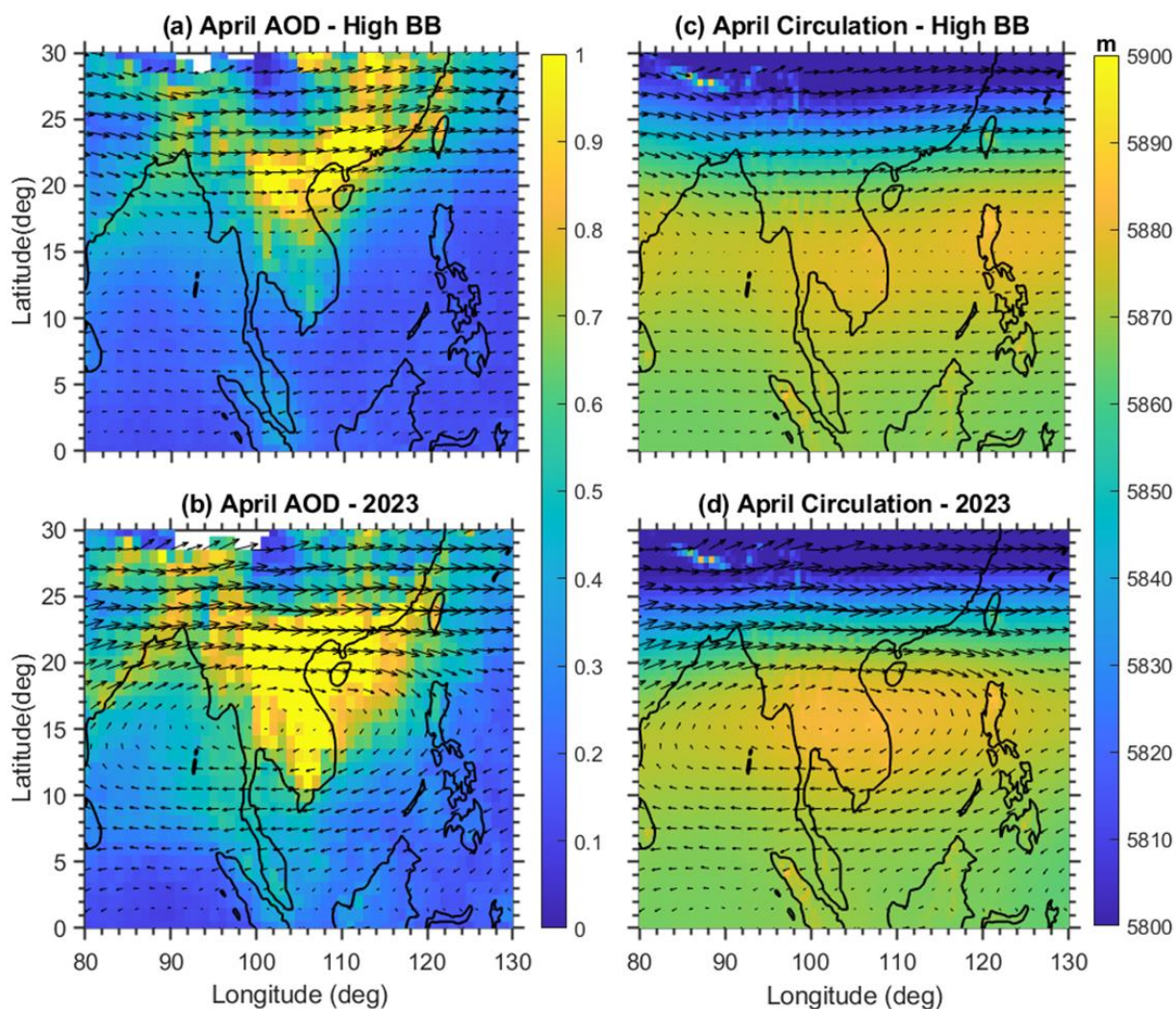
335

336 Figure R3. Spatial distribution of the MODIS Global Burned Area Product in April 2023. (Source:
 337 <https://firms.modaps.eosdis.nasa.gov/>)

338 (3) The circulation analysis (anticyclone over Bay of Bengal and cyclone over WNP) is central to
 339 the conclusions. It would help if the authors could briefly discuss whether such anomalous
 340 circulation patterns are unique to 2023, or if similar circulation shifts have occurred in past years
 341 without producing record-breaking aerosol loading.

342 Reply: We thank the reviewer for this insightful comment. In the revised manuscript, we examined
 343 historical circulation patterns during other high-biomass-burning years over the study region. The
 344 accompanying Figure R4 compares April 2023 with the high-BB composite, allowing an
 345 assessment of whether the circulation and aerosol conditions in 2023 resemble those commonly
 346 observed during severe biomass-burning periods. The comparison reveals notable differences
 347 between 2023 and other high-BB years (Figure R4). In particular, April 2023 is characterized by
 348 a pronounced anticyclonic high-pressure system over PSEA that is stronger and more spatially

349 coherent than in the high-BB composite. Correspondingly, AOD levels in 2023 are substantially
350 higher than those in the high-BB composite, indicating unusually intense aerosol loading. These
351 distinctions suggest that the circulation configuration in 2023 may have played a greater role in
352 aerosol accumulation and transport than in typical high-biomass-burning years.
353



354 Figure R4. Spatial distribution of MODIS aerosol optical depth (AOD) and MERRA-2 500-hPa
355 geopotential height with wind vectors for April: (a) AOD composite for high biomass-burning
356 years, (b) AOD for 2023, (c) 500-hPa geopotential height and wind vectors for high biomass-
357 burning years, and (d) 500-hPa geopotential height and wind vectors for 2023.
358

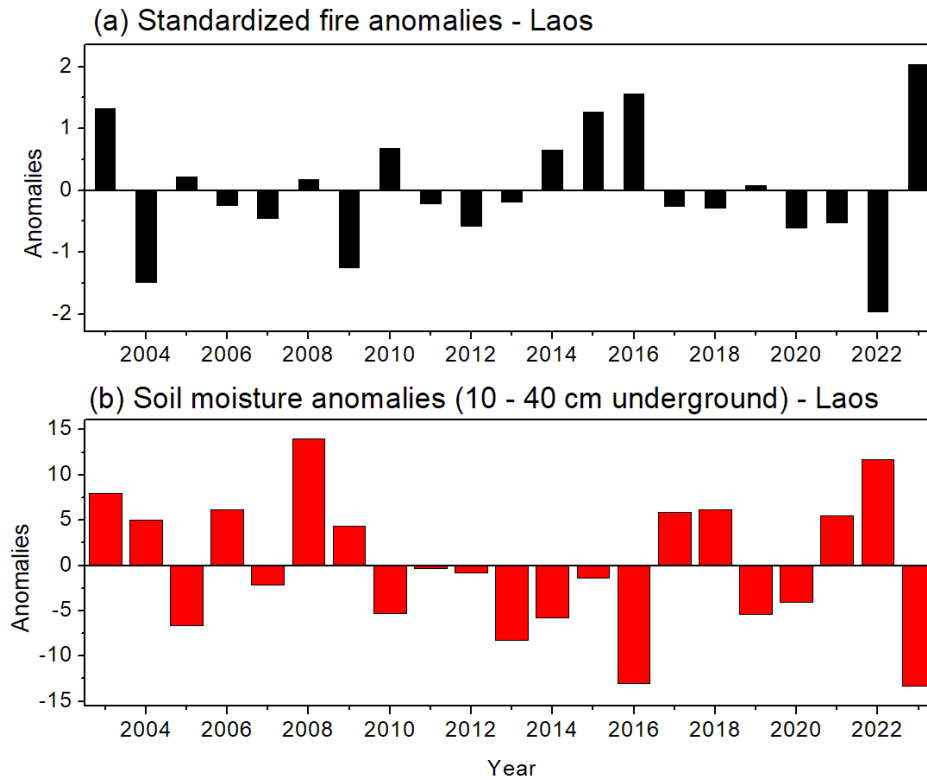
359

360 (4) The study shows a strong correlation ($r \sim 0.65$) between AOD and CO anomalies. Could the
361 authors expand on the physical interpretation? For example, does this imply biomass burning was
362 the sole driver, or might secondary aerosol formation also have amplified AOD?

363 Reply: We thank the reviewer for the insightful comment. The authors want to clarify that the
364 manuscript mistakenly reported a correlation coefficient of 0.65; in fact, this is the coefficient of
365 determination (R^2). The corresponding correlation coefficient is $R = 0.81$, indicating a statistically
366 robust association between CO and AOD over the South China Sea (SCS). The AOD enhancement
367 over the South China Sea was predominantly transport-driven. That said, we do not exclude the
368 role of secondary aerosol formation. However, the further investigation of vertical aerosol
369 distribution from CALIPSO images and the MERRA-2 black carbon (BC) and organic carbon
370 (OC), followed by the NOAA HYSPLIT back trajectories, clearly demonstrates that the PSEA BB
371 is the primary factor for the record-breaking aerosol loading over SCS in April 2023.

372 (5) The discussion links record-low soil moisture in Laos with enhanced fire intensity. Would it
373 be possible to show a supplementary time series of soil moisture anomalies alongside fire counts
374 to more directly demonstrate this relationship?

375 Reply: We thank the reviewer for this helpful suggestion. In response, we have added a
376 supplementary time series showing standardized fire anomalies alongside soil moisture anomalies
377 over Laos (Figure R5). The analysis indicates that low soil moisture is significantly correlated with
378 enhanced fire activity during April 2023, with 2023 exhibiting an extreme negative soil moisture
379 anomaly concurrent with strong positive fire anomalies. A similar co-occurrence of anomalously
380 low soil moisture and elevated fire activity is also evident in 2016, a year previously identified as
381 having intensified burning. These results provide more direct observational support for the link
382 between soil moisture deficits and enhanced fire intensity, and the new figure is included in the
383 Supplementary Material.



384

385 Figure R5. Inter annual variability in (a) standardized fire anomalies, (b) soil moisture anomalies
 386 over Laos in April during 2003 to 2023.

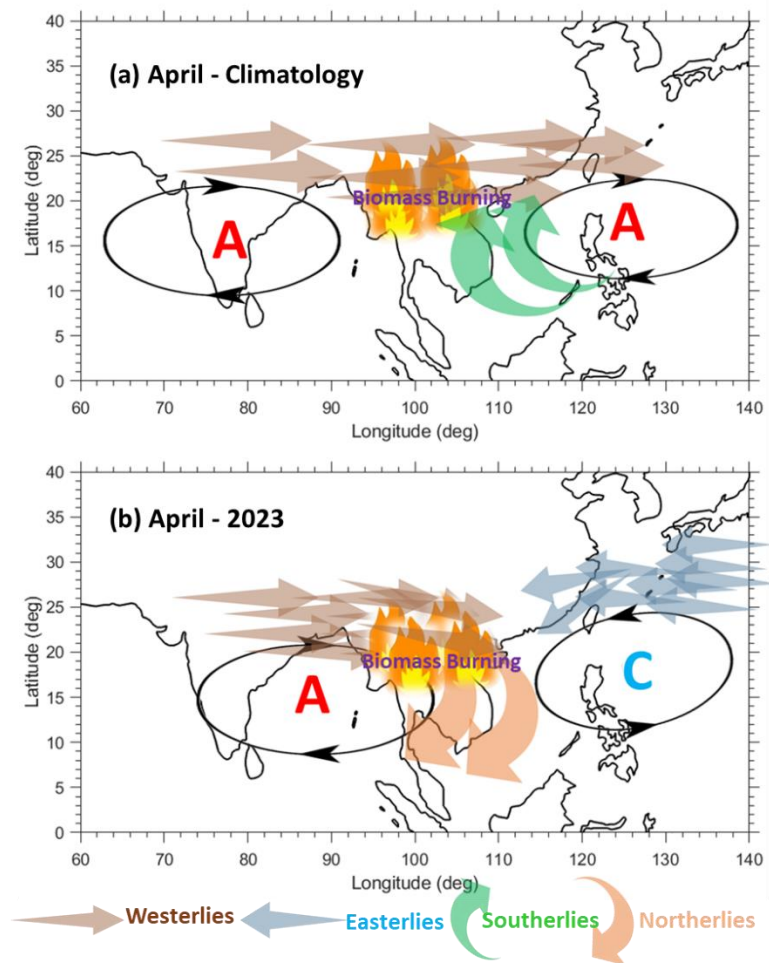
387 (6) Figure 2-4 provides rich information, but it is quite dense. For readers who are not familiar
 388 with the dataset, more explanatory notes or simplified illustrations (such as highlighting Laos as a
 389 fire hotspot) can improve accessibility. Figure 2c can be changed in color to highlight the contrast
 390 between Aqua and Terra.

391 Reply: We thank the reviewer for this helpful suggestion. In the revised manuscript, we have
 392 replotted most of the figures to improve clarity and accessibility. Additional explanatory notes
 393 have been added where appropriate, and key features such as Laos as a major biomass-burning
 394 hotspot are now more clearly highlighted. In addition, Figure 2c has been revised with an updated
 395 color scheme to better distinguish and emphasize the contrast between Aqua and Terra MODIS
 396 observations.

397 (7) The schematic diagram in Figure 8 is excellent. Consider changing the color scheme of A/C
 398 cyclone and east-west wind to improve readability.

399 Reply: We thank the reviewer for the positive and encouraging comment. In the revised
 400 manuscript, we have further improved the schematic diagram in Figure 8 by adjusting the color

401 scheme of the anticyclonic/cyclonic circulation and the east–west wind components to enhance
402 visual contrast and readability. The revised figure is provided below for reference (Figure R6).



403
404 **Figure R6.** Schematic diagram illustrating the physical mechanisms driving the record-breaking
405 aerosol loading over the South China Sea in April 2023. A indicates an anticyclonic anomaly, and
406 C indicates a cyclonic anomaly.

407
408 (8) The description of datasets is clear, but it would be useful to briefly summarize in one table the
409 different satellite/reanalysis products used, their spatial/temporal resolutions, and the key
410 variables. This would make the methodology section more reader-friendly.

411 **Reply:** In response to the reviewer's comment, we have now included a table summarizing the
412 datasets.

413

414

415

Table 1. Details of various data products used in the present study.

Data	Resolution	Source
Aerosol Optical Depth (AOD)	1° × 1°	Aqua and Terra satellite/MODIS
Carbon Monoxide (CO)	1° × 1°	MOPITT and AIRS
Burned Area (BA)	500 m	Aqua and Terra satellite/MODIS
MODIS Collection 6.1 Fire Anomalies		combined Terra and Aqua satellite/MODIS
Wind and Geopotential Height	0.5° × 0.625°	MERRA reanalysis

416

417 (9) Since the paper emphasizes Southeast Asian fire climatology, it may be helpful to cite prior
418 works that have quantified the magnitude and variability of fire activity in this region, such as
419 Cohen (2014) and Cohen et al. (2017). Adding these references would provide a stronger
420 background for the discussion of extreme fire activity in 2023. ([https://doi.org/10.1088/1748-](https://doi.org/10.1088/1748-9326/9/11/114018)
421 [9326/9/11/114018](https://doi.org/10.1088/1748-9326/9/11/114018); <https://doi.org/10.5194/acp-17-721-2017>)

422 Reply: We thank the reviewer for this helpful suggestion. We have added the recommended
423 references (Cohen, 2014; Cohen et al., 2017) to the revised manuscript and incorporated them into
424 the background and discussion sections. These studies provide essential context on the magnitude,
425 spatial distribution, and interannual variability of fire activity in Southeast Asia, and they
426 strengthen the framing of the extreme biomass-burning conditions observed in 2023 relative to
427 historical variability.

428 (10) When mentioning black carbon transport and associated trace gases, the authors may consider
429 citing recent top-down studies on BC and CO emissions in Asia (e.g., Wang et al., 2021; Wang et
430 al., 2025). These works would complement the current study by highlighting related emission and
431 transport perspectives. (<https://doi.org/10.1029/2021EF002167>; [https://doi.org/10.1038/s41612-](https://doi.org/10.1038/s41612-025-00977-2)
432 [025-00977-2](https://doi.org/10.1038/s41612-025-00977-2))

433 Reply: We thank the reviewer for this helpful suggestion. In the revised manuscript, we have
434 incorporated a discussion of changes in black carbon (BC) and organic carbon (OC) in April 2023
435 based on the MERRA-2 reanalysis. In addition, we have added the recommended top-down studies
436 on BC and CO emissions and transport over Asia (Wang et al., 2021; Wang et al., 2025), which
437 provide valuable complementary perspectives on emission strength and long-range transport.
438 These references strengthen the broader context of our findings and help link the observed aerosol
439 and trace-gas enhancements to regional emission and transport processes.

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443 **We once again thank the reviewer for carefully reviewing the manuscript and for offering**
444 **potential solutions that significantly improved its content.**

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Response to Referee #3

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461 The manuscript presents a thorough analysis of an unprecedented aerosol loading event over the
462 South China Sea (SCS) in April 2023, using multiple satellite datasets and reanalysis products.
463 The authors convincingly identify biomass burning in Laos and Myanmar as the primary source,
464 and they discuss the unusual circulation anomalies that directed smoke transport into the SCS. The
465 study is timely, relevant, and potentially impactful, especially given the increasing frequency of
466 climate–fire extremes. However, I believe the manuscript requires further development before it
467 can be accepted. My major concerns relate to the quantification of uncertainties, the robustness of
468 transport attribution, and the integration of climate drivers. I detail my comments below.

469 We highly appreciate the thoughtful and valuable suggestions from the reviewer, which will help
470 us improve the quality of our manuscript. We have revised the manuscript with consideration of
471 the reviewer’s comments/suggestions.

472
473 The manuscript reports extreme anomalies in MODIS AOD ($>4\sigma$) and MOPITT/AIRS CO ($>3\sigma$),
474 but little discussion is provided regarding retrieval errors, biases, or limitations. Please provide a
475 clearer treatment of uncertainties, for example: known MODIS biases over ocean and land, vertical
476 sensitivity limits in MOPITT CO, and representativeness of reanalysis aerosol products. A
477 sensitivity analysis (e.g., comparison across Aqua vs. Terra MODIS, MOPITT vs. AIRS CO)
478 would help quantify robustness.

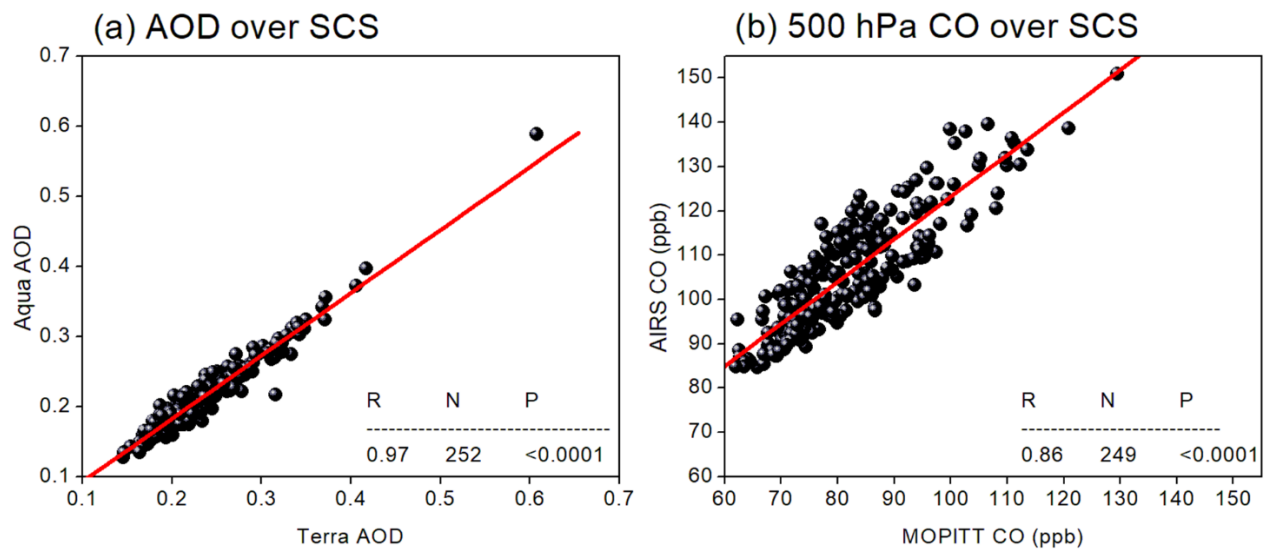
479 Reply: We thank the reviewer for this critical comment. In the revised manuscript, we have
480 expanded the discussion of uncertainties and limitations for the satellite and reanalysis products
481 used in this study. We have also carried out comparisons between Aqua and Terra MODIS AOD,
482 as well as MOPITT and AIRS CO at 500 hPa over the South China Sea (see attached Figure R1),
483 to assess robustness.

484 For MODIS AOD, the estimated uncertainty is approximately ± 0.05 over ocean and ± 0.15
485 over land. The Collection 6.1 (C6.1) products used in this study have been shown to capture
486 temporal variations effectively and agree closely with ground-based observations (Wei et al.,
487 2019b). Validation against Aerosol Robotic Network (AERONET) measurements demonstrates
488 that the merged Dark Target and Deep Blue (DTB) products accurately capture aerosol variability
489 at both regional and global scales (Sayer et al., 2014; Wei et al., 2019). Comparison of Terra and

490 Aqua MODIS AOD confirms consistent temporal patterns, with extreme anomalies exceeding 4σ
491 observed in both datasets.

492 For MOPITT CO, primary sources of uncertainty include vertical sensitivity limits and
493 retrieval biases. The observed enhancements ($>3\sigma$) are consistent with independent AIRS CO
494 measurements, supporting the robustness of the reported anomalies. Although MOPITT's
495 sensitivity decreases near the surface, combining both instruments' observations and applying
496 quality filters mitigates this limitation.

497 We have added these discussions in the revised manuscript and highlighted that, despite
498 known uncertainties, the extreme anomalies reported are robust across multiple datasets and
499 instruments, including MODIS Aqua/Terra, MOPITT, AIRS, and reanalysis fields. Relevant
500 validation studies are now explicitly cited (Sayer et al., 2014; Wei et al., 2019; Ziemke et al.,
501 2006).



502

503 Figure R1. (a) Comparison between MODIS Terra AOD and MODIS Aqua AOD, (b) comparison
504 between MOPITT and AIRS measured 500 hPa CO over the South China Sea during January 2003
505 to December 2023. (R is the correlation coefficient; N is the sample size; P is the significance
506 value).

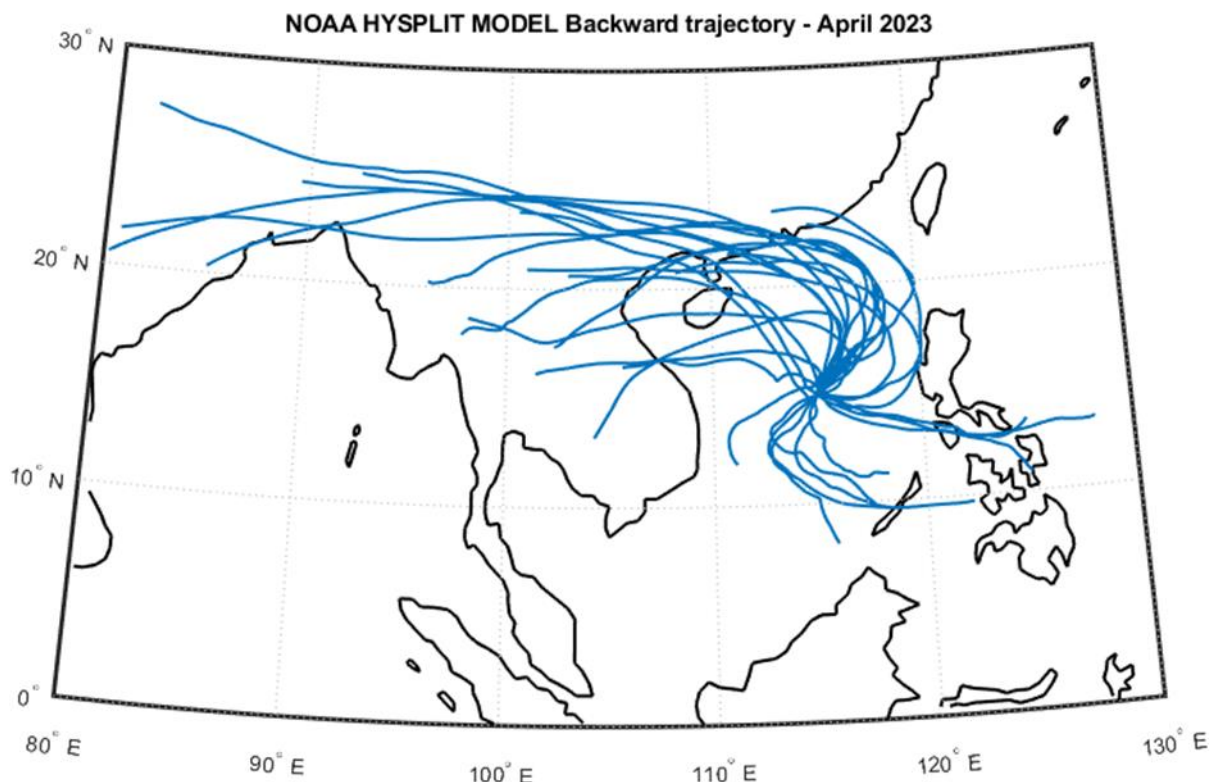
507

508 Transport Attribution and Circulation Analysis

509 The explanation of northerly transport due to the Bay of Bengal anticyclone and western North
510 Pacific cyclone anomaly is plausible, but remains descriptive. I strongly recommend including

511 trajectory or dispersion modeling (e.g., HYSPLIT, FLEXPART) to explicitly demonstrate that
512 biomass burning plumes from Laos could reach the SCS. Alternatively, a composite analysis of
513 circulation anomalies in other strong-fire years could be used to strengthen causality.

514 Reply: Thanks for the helpful suggestion. In the revised manuscript, we have included an analysis
515 of the CALIPSO and MERRA-2 vertical aerosol distributions in April 2023. As aerosol optical
516 depth (AOD) is a column-integrated measure, it does not provide information on the vertical
517 distribution of aerosols. To overcome this limitation, we analyzed observations from the Cloud-
518 Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO), which reveal pronounced
519 enhancements of smoke aerosols over the South China Sea (SCS). Elevated smoke layers were
520 also observed over the southern Bay of Bengal (BoB) in April 2023, predominantly within the
521 mid-troposphere at altitudes of approximately 3–5 km. Consistent with these lidar observations,
522 MERRA-2 reanalysis data indicate substantial increases in aerosol mass concentrations in 2023,
523 with black carbon (BC) increasing by ~250% and organic carbon (OC) by ~350%. The most
524 pronounced enhancements occur between 700 and 600 hPa, closely matching the altitude range
525 identified by CALIPSO. The concurrence of satellite and reanalysis evidence points to a severe
526 pollution episode in April 2023 over and near the SCS, characterized by elevated aerosol layers
527 indicative of long-range transported biomass-burning smoke. To examine the transport
528 mechanism, we have further analyzed HYSPLIT back trajectories for April 2023. We have run
529 daily HYSPLIT back trajectories at random (15N-115E, 3000 m), and the resulting trajectories are
530 shown in the following Figure R2. It is clear that air masses arriving over the SCS during April
531 2023 predominantly originated from the northern PSEA, consistent with the active BB regions
532 observed during this period.

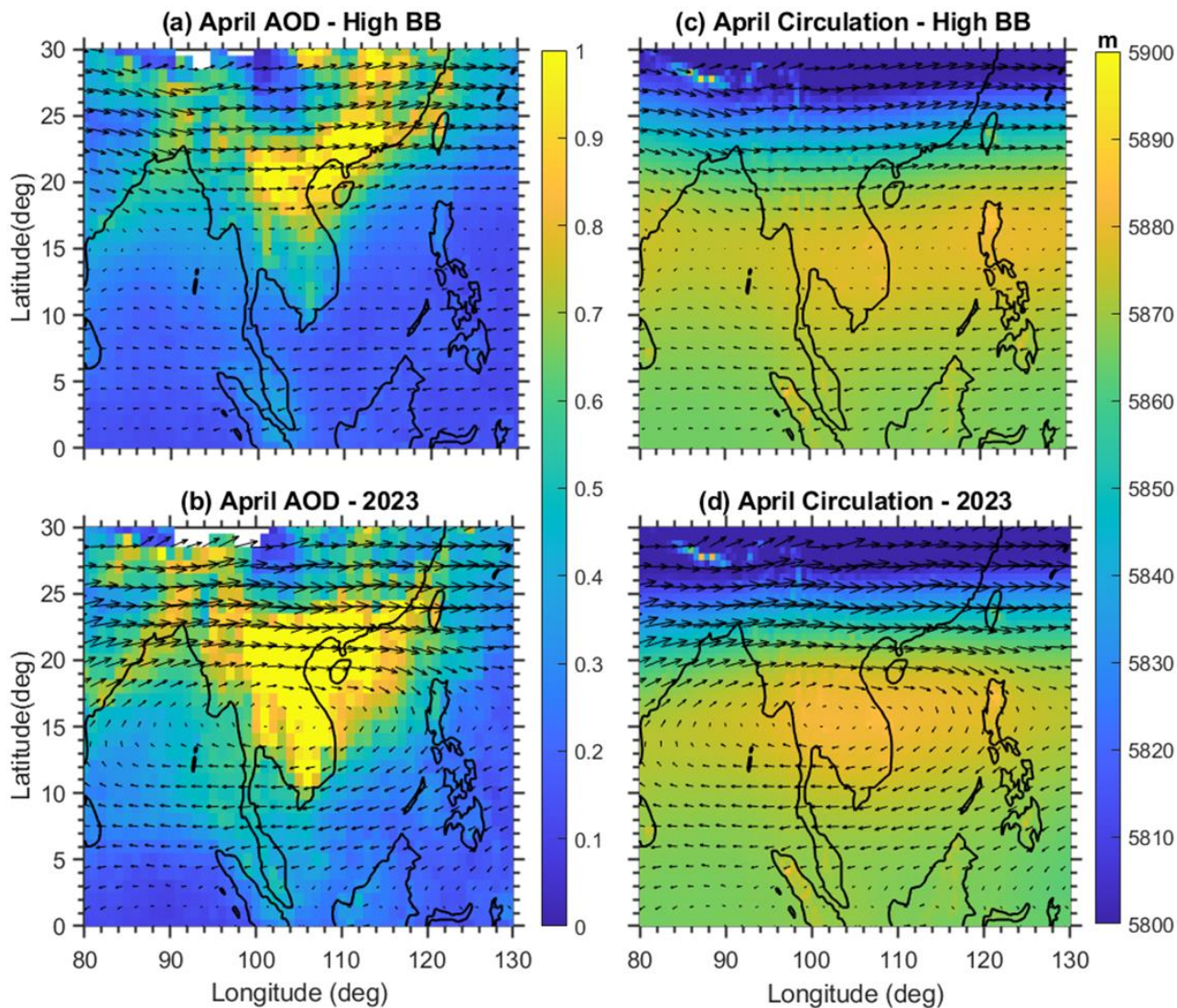


533

534 Figure R2. Daily 72-h NOAA HYSPLIT backward trajectories ending at 12:00 UTC at a
 535 representative location (15°N, 115°E) over the South China Sea at 3 km altitude in April 2023.

536 Following the reviewer’s suggestion, we analyze the large-scale circulation and aerosol
 537 loading in other high-biomass-burning (BB) years over Peninsular Southeast Asia (PSEA). High-
 538 BB years are objectively identified by calculating standardized fire anomalies from total MODIS
 539 fire counts over PSEA, with years exceeding a 0.5 threshold classified as high-BB (Figure R7).
 540 Using this criterion, composite fields of MODIS aerosol optical depth (AOD), 500-hPa
 541 geopotential height, and wind vectors are constructed to represent typical circulation and aerosol
 542 patterns associated with enhanced biomass-burning activity. The accompanying figure compares
 543 April 2023 with the high-BB composite, allowing an assessment of whether the circulation and
 544 aerosol conditions in 2023 resemble those commonly observed during severe biomass-burning
 545 periods. The comparison reveals notable differences between 2023 and other high-BB years
 546 (Figure R3). In particular, April 2023 is characterized by a pronounced anticyclonic high-pressure
 547 system over PSEA that is stronger and more spatially coherent than in the high-BB composite.
 548 Correspondingly, AOD levels in 2023 are substantially higher than those in the high-BB

549 composite, indicating unusually intense aerosol loading. These distinctions suggest that the
550 circulation configuration in 2023 may have played a greater role in aerosol accumulation and
551 transport than in typical high-biomass-burning years.



552
553 Figure R3. Spatial distribution of MODIS aerosol optical depth (AOD) and MERRA-2 500-hPa
554 geopotential height with wind vectors for April: (a) AOD composite for high biomass-burning
555 years, (b) AOD for 2023, (c) 500-hPa geopotential height and wind vectors for high biomass-
556 burning years, and (d) 500-hPa geopotential height and wind vectors for 2023.

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561 **Link to Large-Scale Climate Drivers**

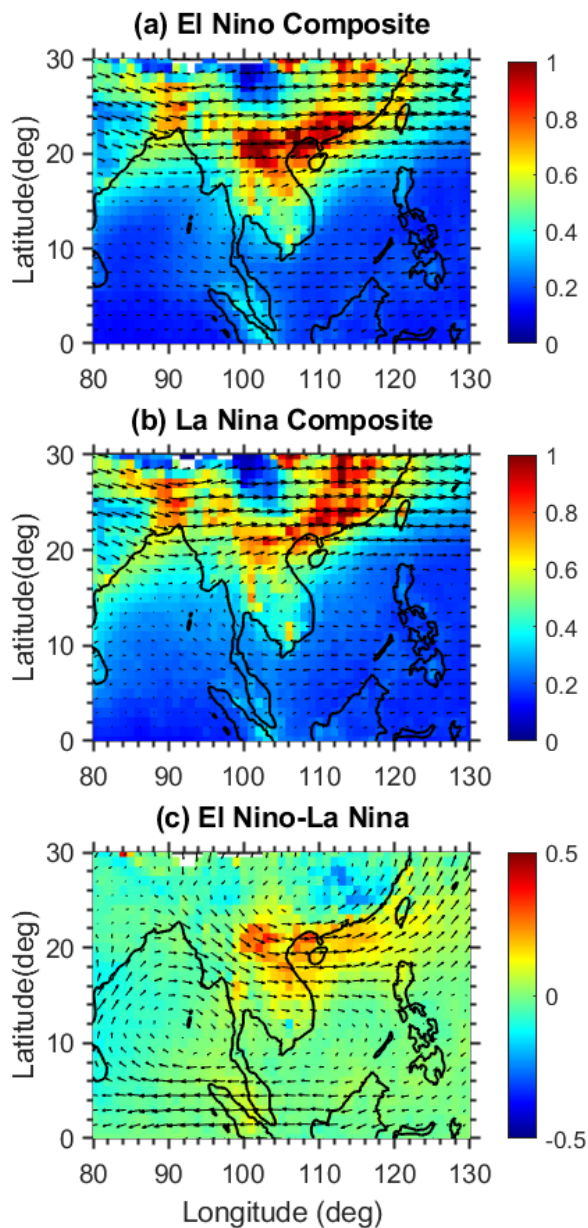
562 The manuscript notes the La Niña–El Niño transition and a tri-polar SST anomaly structure but
563 does not fully connect these anomalies to the extreme biomass burning and circulation changes.
564 Please expand the discussion to show whether such SST/ENSO anomalies have historically
565 coincided with enhanced PSEA burning or altered circulation patterns. This would greatly
566 strengthen the broader climate relevance of the study.

567 **Reply:** Thank you for this valuable suggestion. We agree that establishing a more explicit linkage
568 between sea surface temperature (SST)/ENSO anomalies and regional fire and circulation
569 responses will enhance the broader climate relevance of the study. The interannual variability of
570 biomass-burning (BB) activity over Indochina has been closely tied to the El Niño–Southern
571 Oscillation (ENSO), as reported in previous studies (Yin, 2020; Zhu et al., 2021; Zheng et al.,
572 2023). ENSO is a dominant driver of interannual BB variability across South and Southeast Asia.
573 During El Niño events, prolonged drought and suppressed precipitation intensify fire activity over
574 northern Indochina, particularly in spring (Zhu et al., 2021). Zheng et al. (2023) further showed
575 that fire occurrences increase substantially during El Niño years, coinciding with more fire-prone
576 meteorological conditions compared to La Niña years. This asymmetry reflects stronger
577 correlations between fire weather and the ENSO index during El Niño phases, associated with
578 positive low-level geopotential height anomalies and reduced water vapor transport over Southeast
579 Asia (March–May), both of which favor enhanced burning.

580 However, the record-breaking aerosol event in April 2023 occurred during the La Niña–El
581 Niño transition, following an unusual triple-dip La Niña. This transitional state appears distinct
582 from previously documented ENSO–fire relationships and may have contributed to atypical
583 circulation and moisture anomalies. In the revised manuscript, we have expanded the discussion
584 to highlight these connections and compare the 2023 transition pattern with historical ENSO
585 phases, thereby emphasizing the broader climatic context of the observed extreme biomass
586 burning.

587 Additionally, we constructed composites of MODIS AOD and 500-hPa wind vectors for
588 El Niño and La Niña years during 2003–2022 (Figure R4). The results reveal an apparent increase
589 in AOD over northern PSEA and the coastal regions of South China during El Niño years
590 compared to La Niña years. The associated circulation patterns also differ, with El Niño years

591 characterized by a stronger anticyclonic system over PSEA extending from the Bay of Bengal,
592 consistent with enhanced aerosol accumulation in the region. These results support the
593 interpretation that ENSO-related circulation anomalies strongly modulate regional aerosol loading
594 and fire activity.



595
596 Figure R4. Composite fields of MODIS aerosol optical depth (AOD) and 500-hPa wind vectors
597 for April: (a) El Niño years, (b) La Niña years, and (c) the difference between El Niño and La Niña
598 composites.

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601 **Minor Comments**

602 **Figures and Visualization**

603 Several figures (e.g., Figs. 2, 3, 5, 6) are visually dense with overlapping hatching and color
604 contours. Please simplify or separate key results, and ensure legends are large and consistent.

605 **Reply:** We thank the reviewer for this suggestion. In the revised manuscript, we have improved
606 the clarity and visual presentation of all figures.

607

608 **Terminology Consistency**

609 The text alternates between “TCO” and “TOC” for tropospheric ozone. Please standardize
610 terminology throughout.

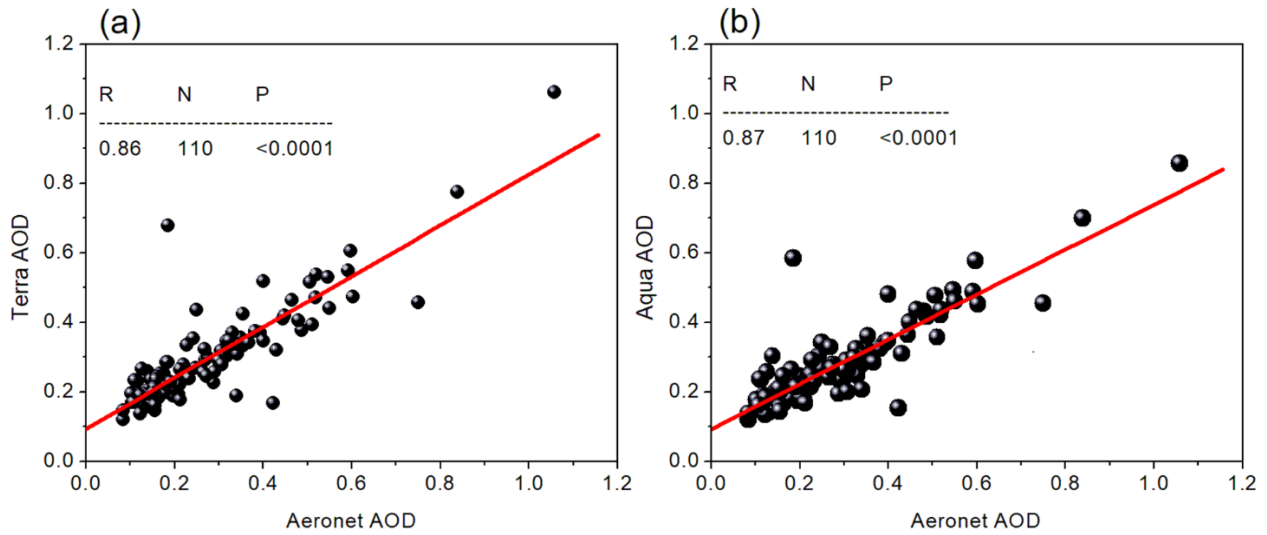
611 **Reply:** Corrected in the revised manuscript.

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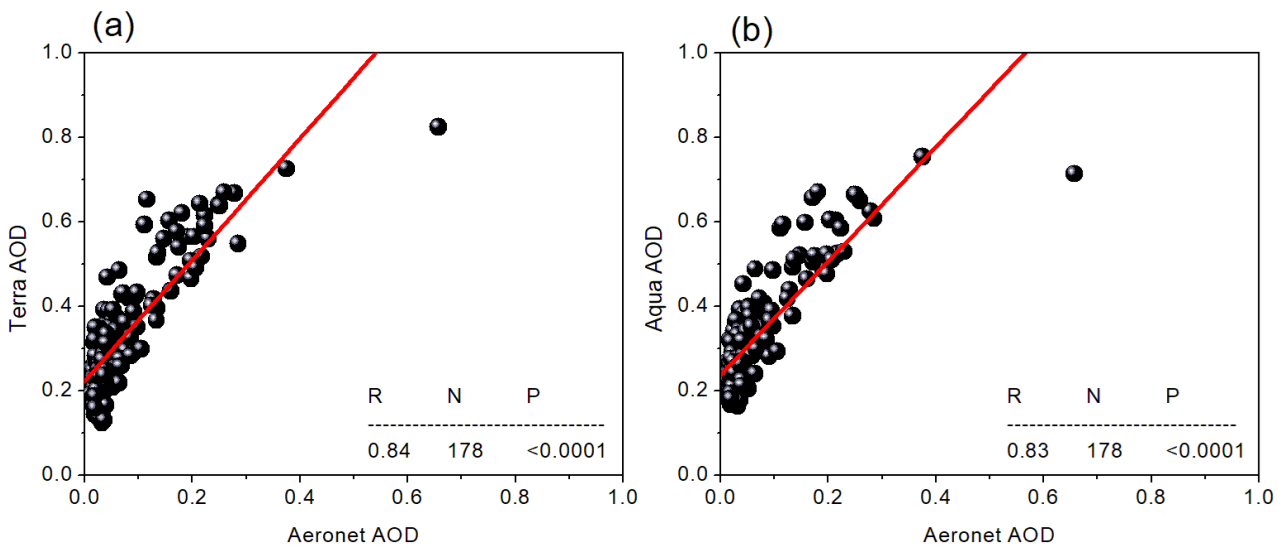
613 **Ground-Based Validation**

614 AERONET data from Dongsha Island and Lulin are mentioned but not analyzed in detail. I suggest
615 including explicit time series plots and quantitative comparisons with satellite AOD to reinforce
616 credibility.

617 **Reply:** We thank the reviewer for this suggestion. In the revised manuscript, we have added
618 explicit details, including time-series plots and quantitative evaluations, to strengthen the
619 credibility of the satellite observations. Specifically, we now provide direct comparisons between
620 AERONET AOD and MODIS AOD at these sites, highlighting both seasonal variability and
621 absolute agreement. Monthly AERONET AOD time series at Dongsha Island and Lulin are also
622 included to provide context (Figure R5 and R6). These additions allow a more comprehensive
623 assessment of the satellite-derived AOD and reinforce the reliability of our aerosol analysis.



624
 625 Figure R5. (a) Comparison between AERONET AOD and MODIS Terra AOD, (b) AERONET
 626 AOD and MODIS Aqua AOD over Dongsha Island during January 2009 to December 2023. (R is
 627 the correlation coefficient; N is the sample size; P is the significance value)



628
 629 Figure R6. (a) Comparison between AERONET AOD and MODIS Terra AOD, (b) AERONET
 630 AOD and MODIS Aqua AOD over LABS during January 2006 to December 2023. (R is the
 631 correlation coefficient; N is the sample size; P is the significance value)
 632

633 Literature Context

634 The manuscript could benefit from more thorough discussion of prior SCS and Southeast Asian
 635 biomass burning studies (e.g., 7-SEAS campaigns, Lin et al. 2013; Reid et al. 2013). This would
 636 help contextualize the novelty of the April 2023 event.

637 Reply: We appreciate the reviewer’s suggestion. Following the advice, we have discussed further
638 more about the previous 7-SEAS studies in the revised manuscript.

639

640 **Language and Style**

641 Some sentences are repetitive (e.g., emphasis on Laos’ share of BB activity) and could be
642 streamlined. Please also ensure consistent reference to “Supplementary Figures” rather than “Sup.
643 Figures.”

644 Reply: We thank the reviewer for this comment. We have carefully revised the manuscript to
645 streamline repetitive sentences, particularly those emphasizing Laos’ contribution to biomass-
646 burning activity, and to improve clarity and readability. Additionally, we have standardized all
647 references to supplementary material, using “Supplementary Figures” consistently throughout the
648 text.

649

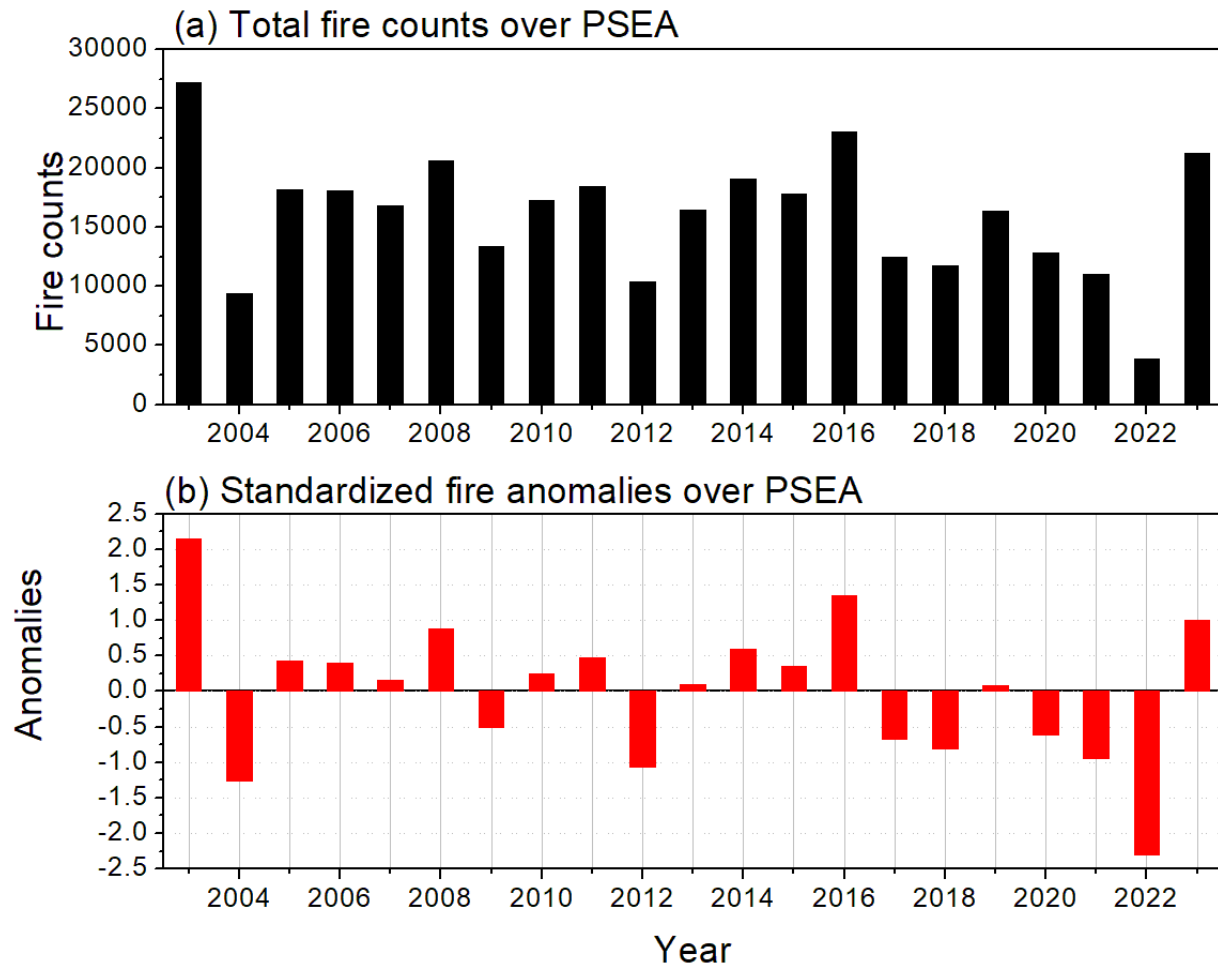
650 **Outlook / Future Work**

651 The conclusions briefly mention aerosol–radiation interactions and links to heatwaves. I encourage
652 a more explicit outlook section, highlighting next steps such as quantifying radiative forcing or
653 simulating impacts with chemistry–climate models.

654 Reply: We thank the reviewer for this valuable suggestion. In the revised manuscript, we have
655 expanded the outlook/future work section to provide a more explicit discussion of potential next
656 steps. Specifically, we highlight opportunities to quantify aerosol–radiation interactions and
657 estimate the associated radiative forcing, as well as to investigate the regional climate impacts,
658 including heatwaves, using chemistry–climate or Earth system model simulations. These
659 directions will help build on the present study by linking observed extreme biomass burning and
660 aerosol enhancements to broader climate and atmospheric consequences.

661

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663

664 Figure R7. Inter-annual variability in (a) total fire counts, (b) the standardized fire anomalies over
 665 Peninsula Southeast Asia (PSEA) from 2003 to 2023.

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671 We once again thank the reviewer for carefully reviewing the manuscript and for offering potential
 672 solutions that significantly improved its content.

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