Response to Referee #2

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

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

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

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

Following the reviewer's suggestion, we further examined the MODIS burned area data for April 2003, 2016, and 2023 and present a comparison of their spatial distributions in the figure below (Figure R1). The results indicate that the spatial distributions of burned areas in 2016 and 2023 are generally similar, with the most extensive burning occurring in northern Laos compared with 2003. However, the burned area in 2023 was more concentrated and extensive in northern Laos than in 2016. We further included the overall burned-area variability over PSEA (combining all PSEA countries) from 2003 to 2023 in April as a supplement figure in the revised manuscript. We noticed that the burned area in April 2023 is the highest with 2.27 Mha during the 2003 to

2023 period for the PSEA region. We also included each country's Burned Area (BA) and the contribution percentage for the total BA in Table 1. For your reference, we have attached the interannual variability of BA for April over PSEA in Figure R2.

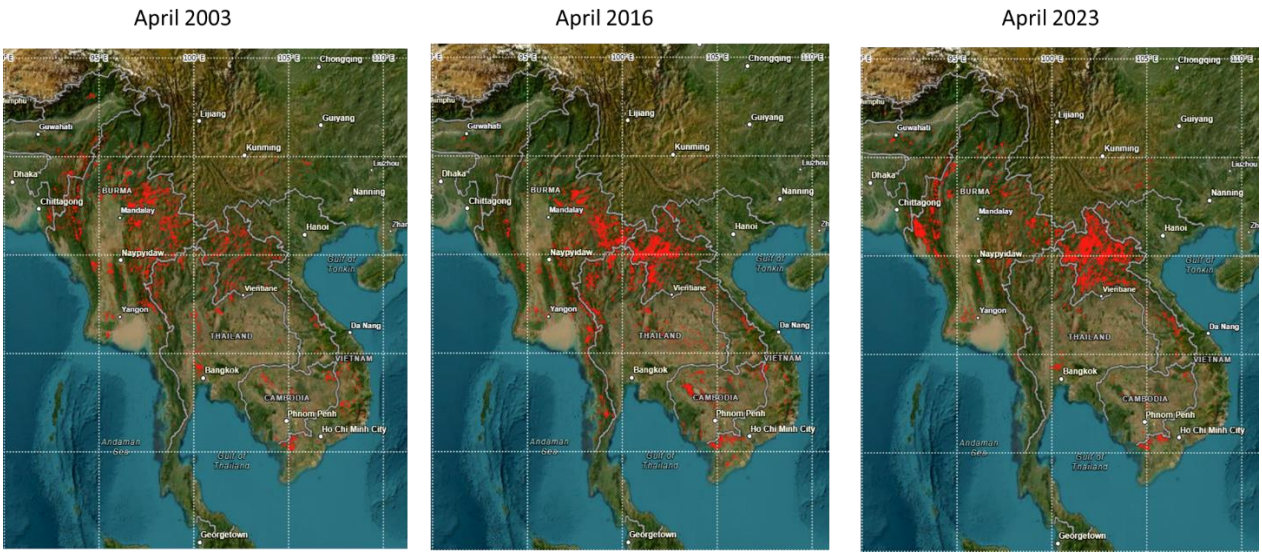

Figure R1. The spatial distribution of MODIS burned area (BA) in April 2003, 2016, and 2023. (Source: https://firms.modaps.eosdis.nasa.gov/)

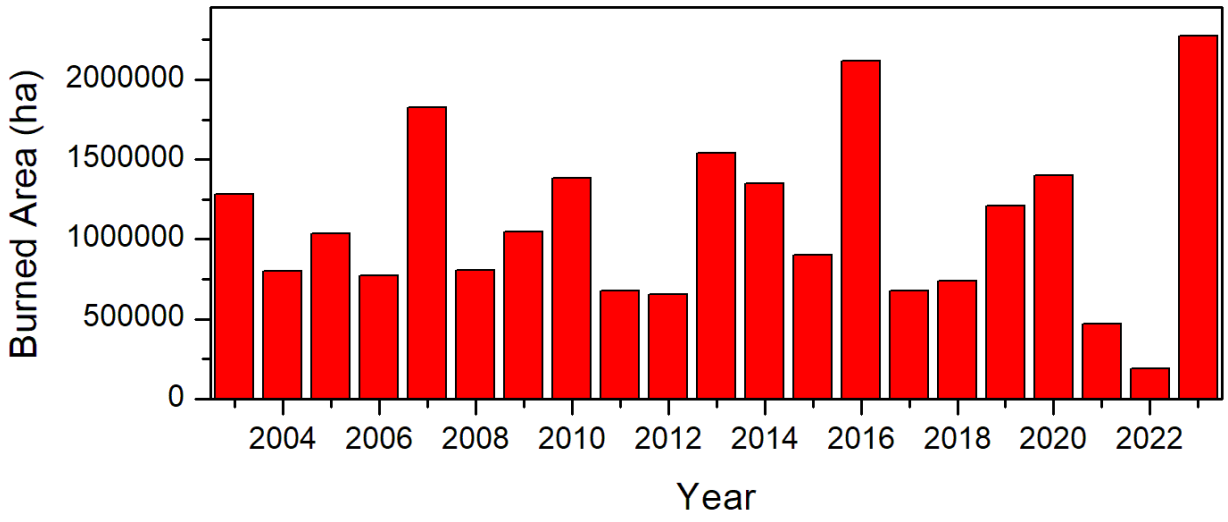

Figure R2. Interannual variability in Burned Area over Peninsula Southeast Asia in April from 2003 to 2023.

(2) The study identifies biomass burning in Laos as the major contributor to the April 2023 event. Could the authors clarify whether other regional fire sources (e.g., Maritime Continent or southern

China) were quantitatively excluded, or whether their contributions are negligible compared to Laos?

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

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

(3) The circulation analysis (anticyclone over Bay of Bengal and cyclone over WNP) is central to the conclusions. It would help if the authors could briefly discuss whether such anomalous

circulation patterns are unique to 2023, or if similar circulation shifts have occurred in past years without producing record-breaking aerosol loading.

Reply: We thank the reviewer for this insightful comment. In the revised manuscript, we examined historical circulation patterns during other high-biomass-burning years over the study region. The accompanying Figure R4 compares April 2023 with the high-BB composite, allowing an assessment of whether the circulation and aerosol conditions in 2023 resemble those commonly observed during severe biomass-burning periods. The comparison reveals notable differences between 2023 and other high-BB years (Figure R4). In particular, April 2023 is characterized by a pronounced anticyclonic high-pressure system over PSEA that is stronger and more spatially coherent than in the high-BB composite. Correspondingly, AOD levels in 2023 are substantially higher than those in the high-BB composite, indicating unusually intense aerosol loading. These distinctions suggest that the circulation configuration in 2023 may have played a greater role in aerosol accumulation and transport than in typical high-biomass-burning years.

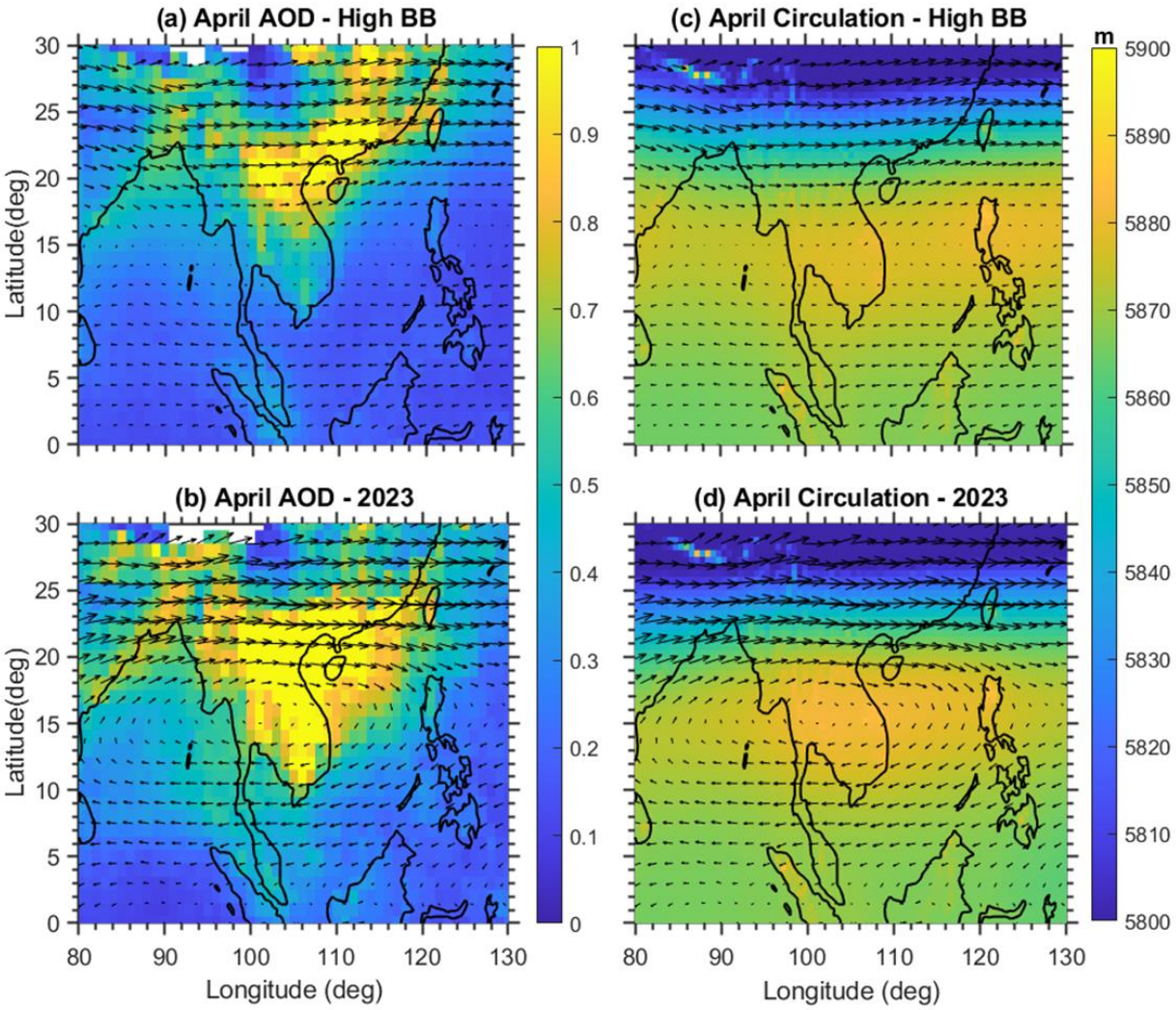

Figure R4. Spatial distribution of MODIS aerosol optical depth (AOD) and MERRA-2 500-hPa geopotential height with wind vectors for April: (a) AOD composite for high biomass-burning years, (b) AOD for 2023, (c) 500-hPa geopotential height and wind vectors for high biomass-burning years, and (d) 500-hPa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

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

Reply: We thank the reviewer for the insightful comment. The authors want to clarify that the manuscript mistakenly reported a correlation coefficient of 0.65; in fact, this is the coefficient of determination (R^2). The corresponding correlation coefficient is R = 0.81, indicating a statistically robust association between CO and AOD over the South China Sea (SCS). The AOD enhancement

over the South China Sea was predominantly transport-driven. That said, we do not exclude the role of secondary aerosol formation. However, the further investigation of vertical aerosol distribution from CALIPSO images and the MERRA-2 black carbon (BC) and organic carbon (OC), followed by the NOAA HYSPLIT back trajectories, clearly demonstrates that the PSEA BB is the primary factor for the record-breaking aerosol loading over SCS in April 2023.

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

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

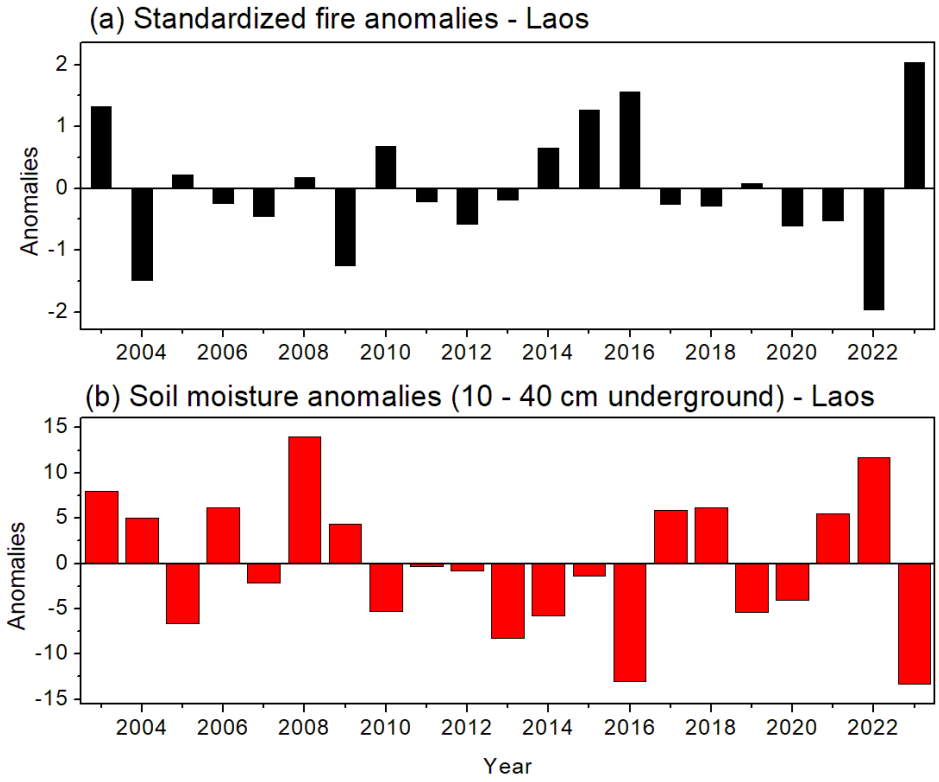

Figure R5. Inter annual variability in (a) standardized fire anomalies, (b) soil moisture anomalies over Laos in April during 2003 to 2023.

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

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

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

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

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

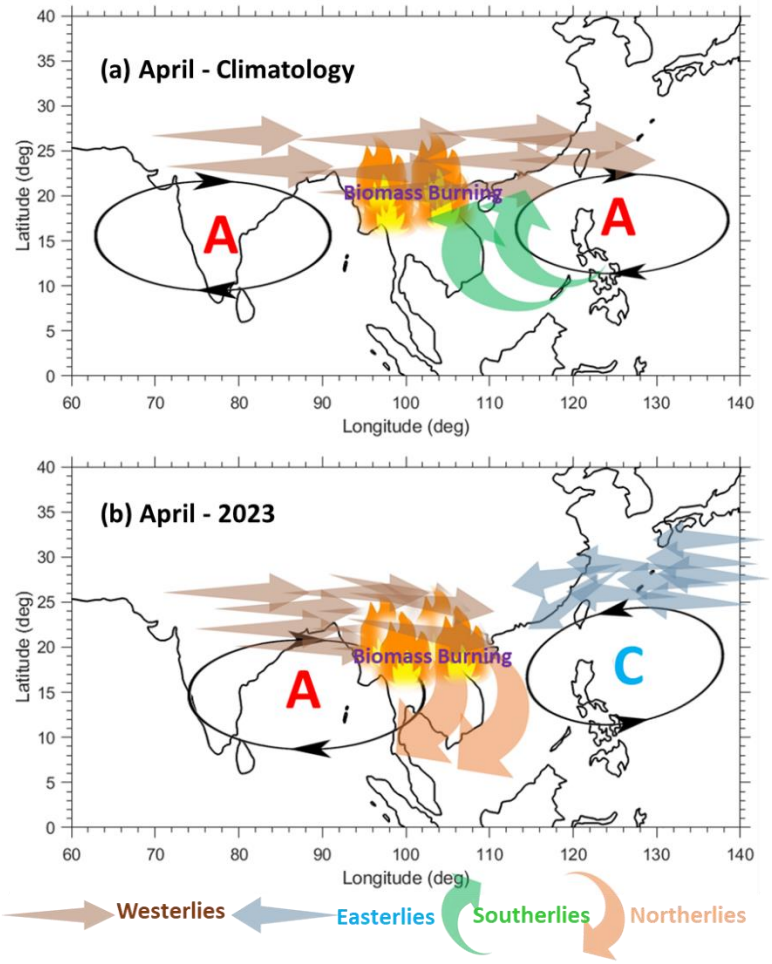

Figure R6. Schematic diagram illustrating the physical mechanisms driving the record-breaking aerosol loading over the South China Sea in April 2023. A indicates an anticyclonic anomaly, and C indicates a cyclonic anomaly.

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

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

Table R1. 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
Tropospheric Column Ozone (TCO)	1° × 1°	OMI/MLS
Burned Area (BA)	500 m	Aqua and Terra satellite/MODIS
Fire Anomalies	0.25° × 0.25°	Aqua and Terra satellite/MODIS
Wind and Geopotential Height	0.5° × 0.625°	MERRA reanalysis

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

Reply: We thank the reviewer for this helpful suggestion. We have added the recommended references (Cohen, 2014; Cohen et al., 2017) to the revised manuscript and incorporated them into the background and discussion sections. These studies provide essential context on the magnitude, spatial distribution, and interannual variability of fire activity in Southeast Asia, and they

strengthen the framing of the extreme biomass-burning conditions observed in 2023 relative to historical variability.

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

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

We once again thank the reviewer for carefully reviewing the manuscript and for offering potential solutions that helped us significantly improve its content.