Response to Referee #3

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

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

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

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

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

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

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

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

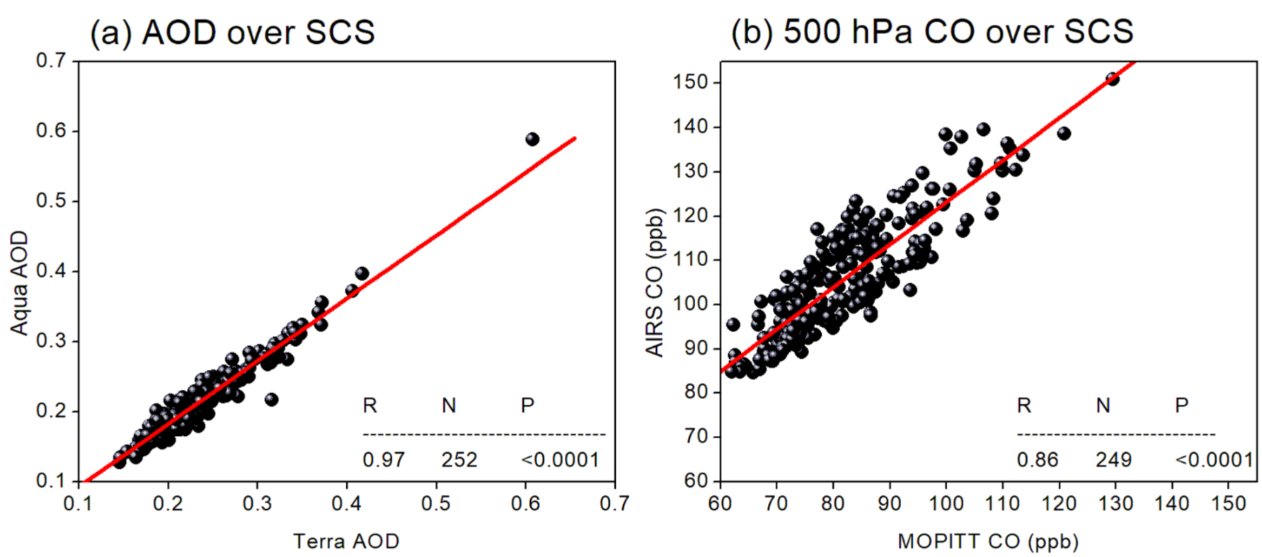

Figure R1. (a) Comparison between MODIS Terra AOD and MODIS Aqua AOD, (b) comparison between MOPITT and AIRS measured 500 hPa CO over the South China Sea during January 2003 to December 2023. (R is the correlation coefficient; N is the sample size; P is the significance value).

Transport Attribution and Circulation Analysis

The explanation of northerly transport due to the Bay of Bengal anticyclone and western North Pacific cyclone anomaly is plausible, but remains descriptive. I strongly recommend including trajectory or dispersion modeling (e.g., HYSPLIT, FLEXPART) to explicitly demonstrate that biomass burning plumes from Laos could reach the SCS. Alternatively, a composite analysis of circulation anomalies in other strong-fire years could be used to strengthen causality.

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

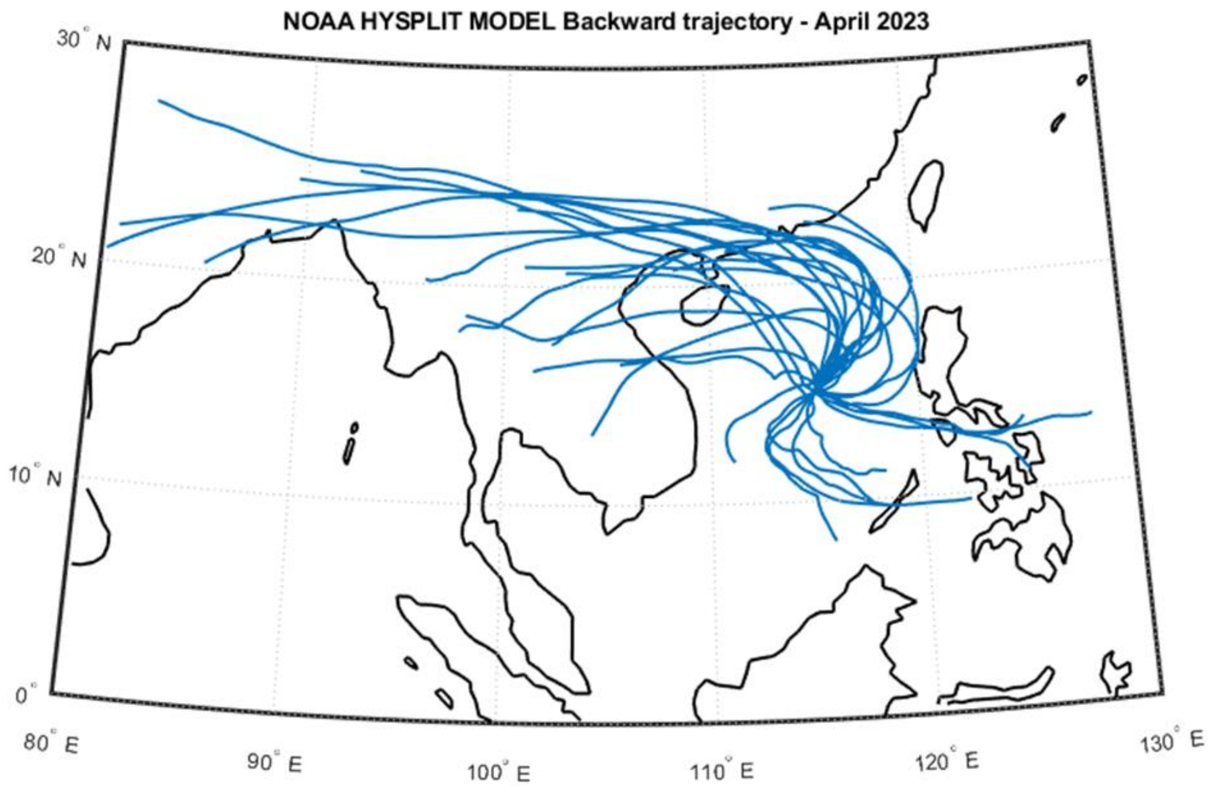

Figure R2. Daily 72-h NOAA HYSPLIT backward trajectories ending at 12:00 UTC at a representative location (15°N, 115°E) over the South China Sea at 3 km altitude in April 2023.

Following the reviewer's suggestion, we analyze the large-scale circulation and aerosol loading in other high-biomass-burning (BB) years over Peninsular Southeast Asia (PSEA). High-BB years are objectively identified by calculating standardized fire anomalies from total MODIS fire counts over PSEA, with years exceeding a 0.5 threshold classified as high-BB (Figure R7). Using this criterion, composite fields of MODIS aerosol optical depth (AOD), 500-hPa geopotential height, and wind vectors are constructed to represent typical circulation and aerosol patterns associated with enhanced biomass-burning activity. The accompanying figure 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 R3). 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.

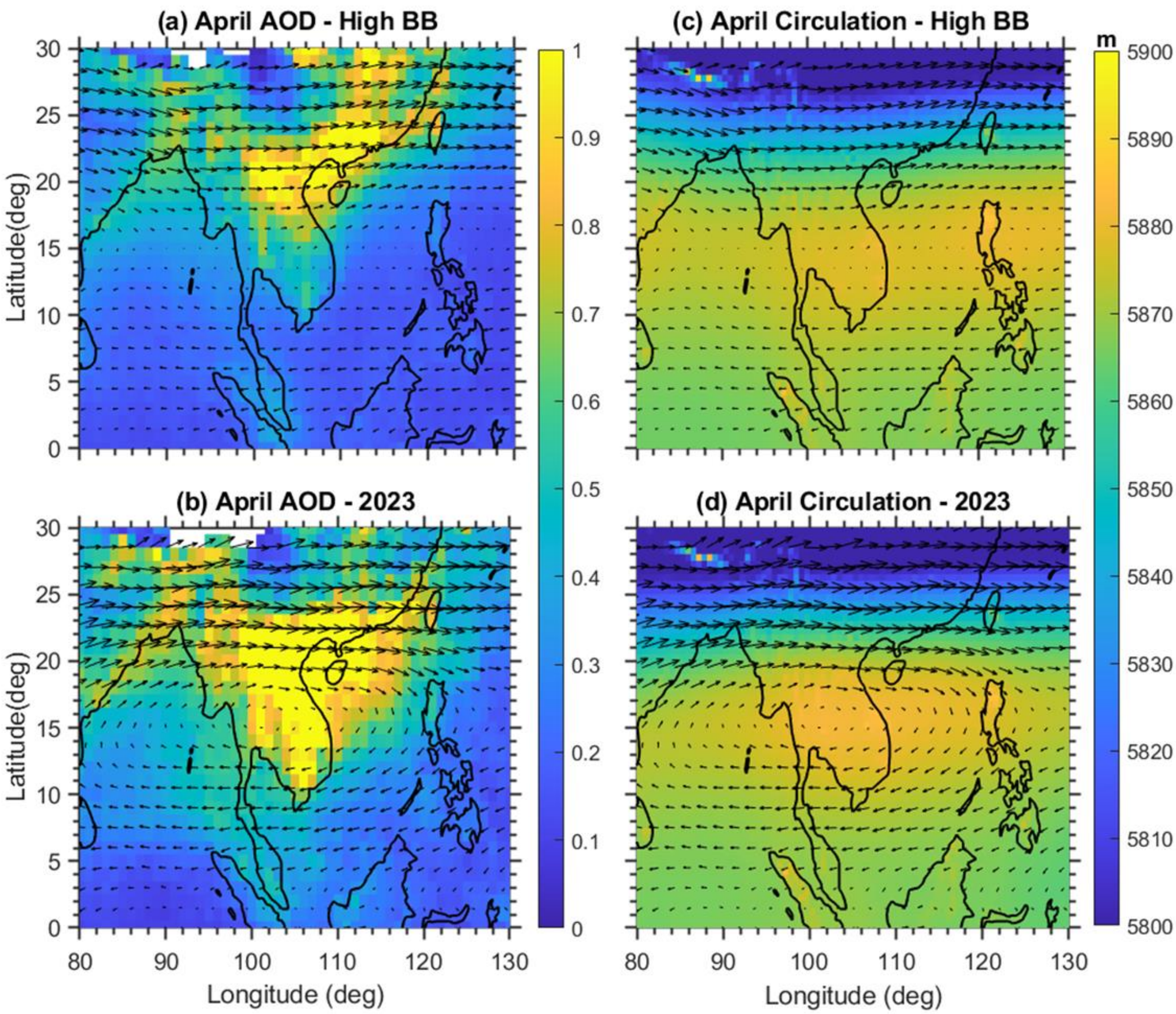

Figure R3. Spatial distribution of MODIS aerosol optical depth (AOD) and MERRA-2 500-hPa geopotential height with wind vectors for April: (a) AOD composite for high biomass-burning years, (b) AOD for 2023, (c) 500-hPa geopotential height and wind vectors for high biomass-burning years, and (d) 500-hPa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

Link to Large-Scale Climate Drivers

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

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

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

Additionally, we constructed composites of MODIS AOD and 500-hPa wind vectors for El Niño and La Niña years during 2003–2022 (Figure R4). The results reveal an apparent increase in AOD over northern PSEA and the coastal regions of South China during El Niño years compared to La Niña years. The associated circulation patterns also differ, with El Niño years characterized by a stronger anticyclonic system over PSEA extending from the Bay of Bengal, consistent with enhanced aerosol accumulation in the region. These results support the interpretation that ENSO-related circulation anomalies strongly modulate regional aerosol loading and fire activity.

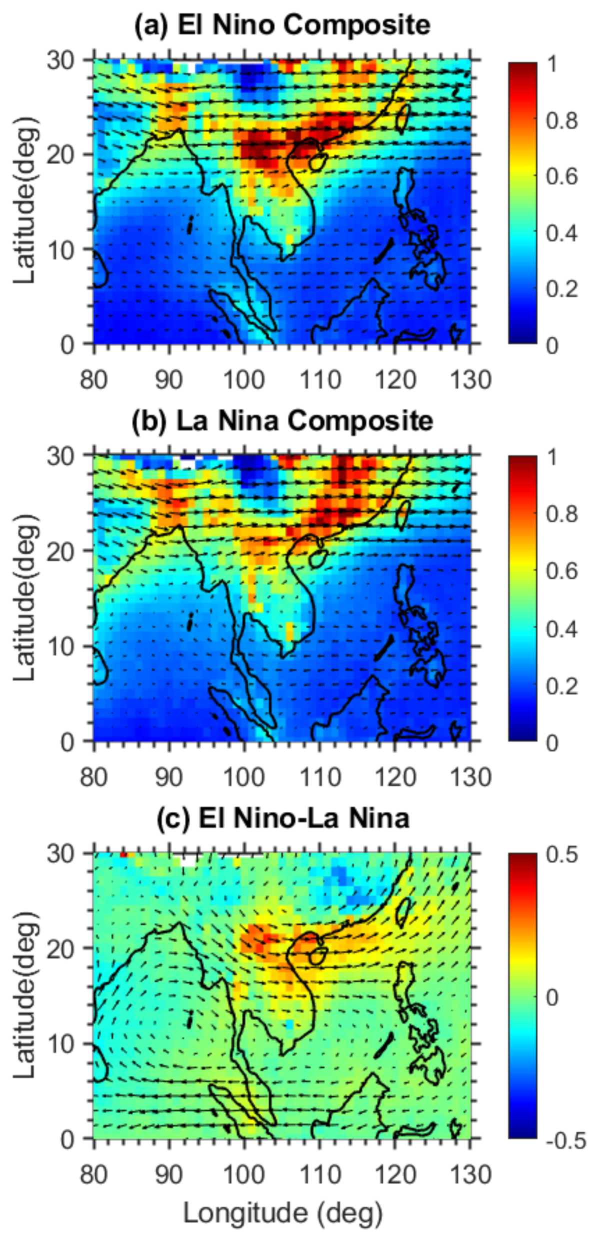

Figure R4. Composite fields of MODIS aerosol optical depth (AOD) and 500-hPa wind vectors for April: (a) El Niño years, (b) La Niña years, and (c) the difference between El Niño and La Niña composites.

Minor Comments

Figures and Visualization

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

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

Terminology Consistency

The text alternates between "TCO" and "TOC" for tropospheric ozone. Please standardize terminology throughout.

Reply: Corrected in the revised manuscript.

Ground-Based Validation

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

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

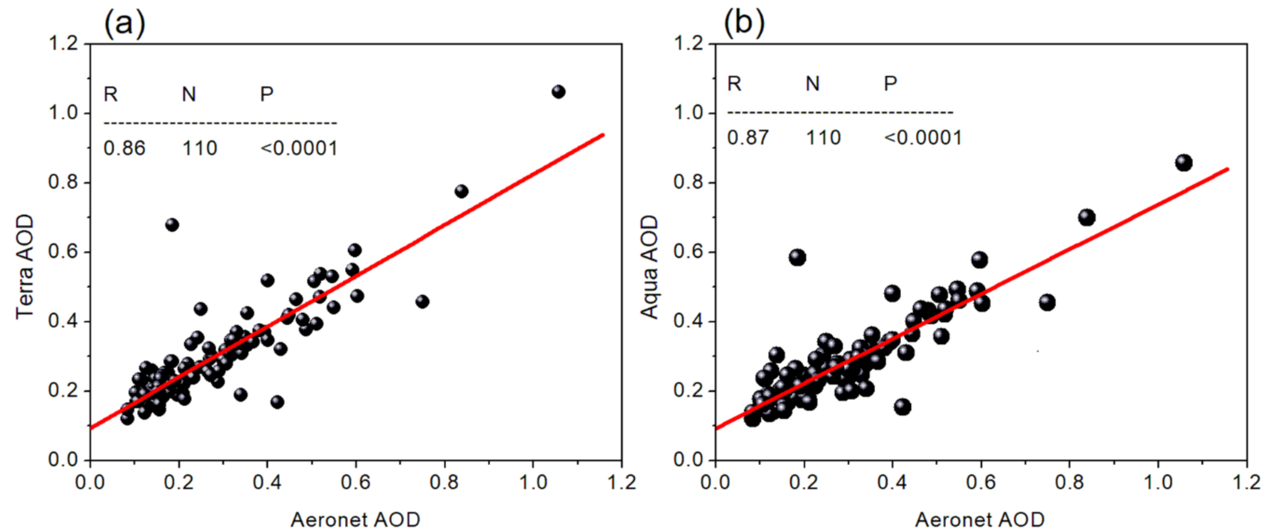

Figure R5. (a) Comparison between AERONET AOD and MODIS Terra AOD, (b) AERONET AOD and MODIS Aqua AOD over Dongsha Island during January 2009 to December 2023. (R is the correlation coefficient; N is the sample size; P is the significance value)

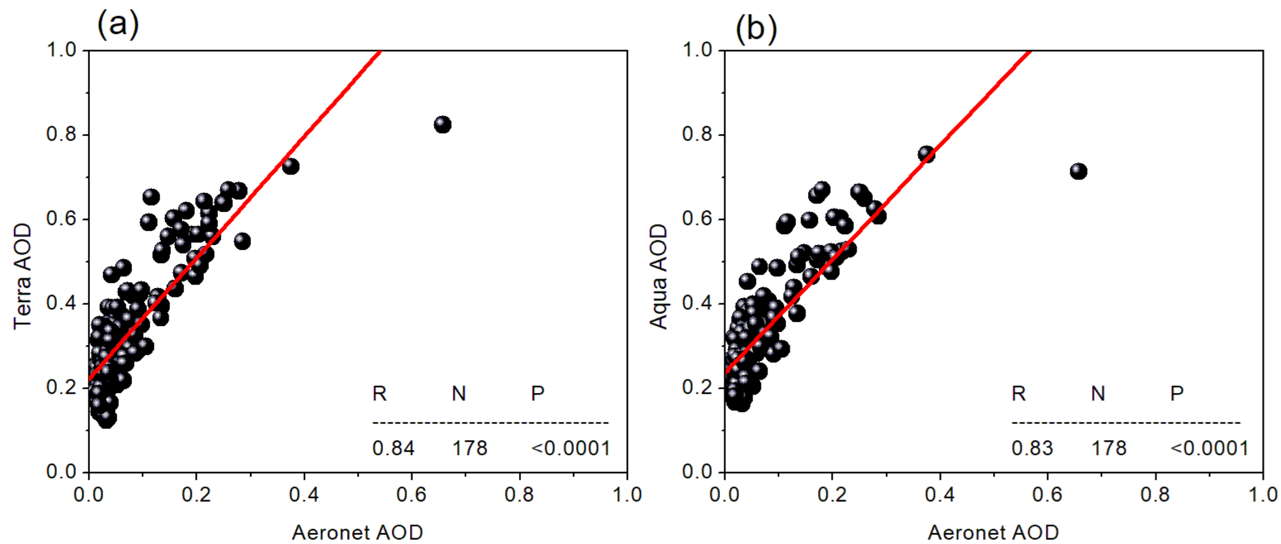

Figure R6. (a) Comparison between AERONET AOD and MODIS Terra AOD, (b) AERONET AOD and MODIS Aqua AOD over LABS during January 2006 to December 2023. (R is the correlation coefficient; N is the sample size; P is the significance value)

Literature Context

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

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

Language and Style

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

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

Outlook / Future Work

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

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

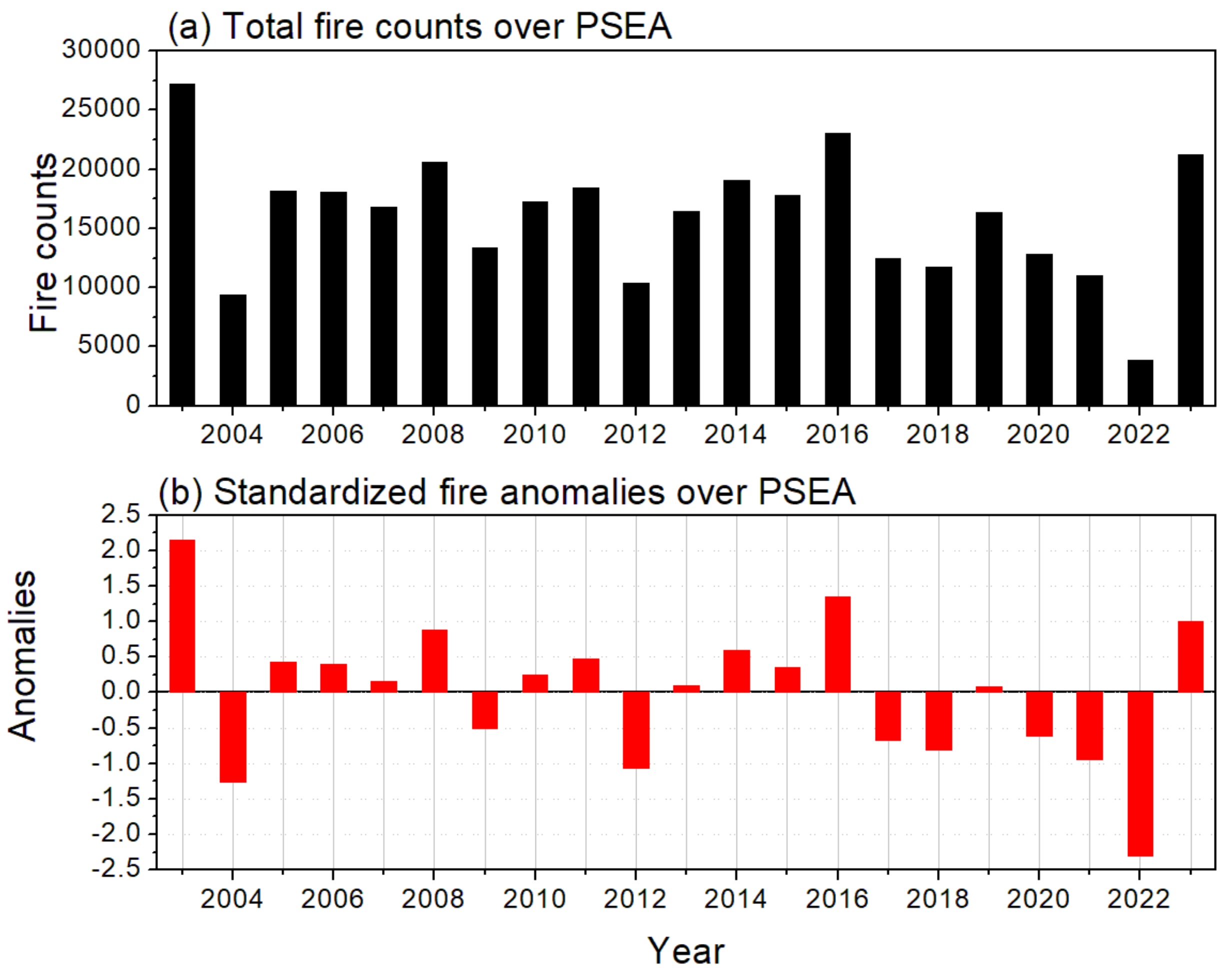

Figure R7. Inter-annual variability in (a) total fire counts, (b) the standardized fire anomalies over Peninsula Southeast Asia (PSEA) from 2003 to 2023.

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