What caused record-breaking aerosol loading over the South China Sea in April 2023

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Abstract:

In April 2023, record-breaking aerosol optical depth (AOD) levels were observed over the South China Sea (SCS). This study investigates the sources, transport pathways, and large-scale dynamical conditions associated with this extreme aerosol event. Observations from the Moderate Resolution Imaging Spectroradiometer (MODIS) revealed the highest April AOD in the 2003-2023 satellite record, with values increasing by approximately 150% relative to the 2003-2022 climatological mean and exceeding 4σ above normal conditions. Enhanced carbon monoxide (CO) concentrations were simultaneously detected in the free to mid-troposphere (700-500 hPa) by Measurements of Pollution in the Troposphere (MOPITT) and Atmospheric Infrared Sounder (AIRS), indicating substantial long-range transport of combustion-related pollution. MODIS fire count and burned-area datasets further indicated intensified biomass-burning (BB) activity over northern Peninsular Southeast Asia (PSEA) during the same period. Backward trajectory simulations using the NOAA Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model suggested that a large fraction of air masses arriving over the SCS originated from northern PSEA, supporting the interpretation that BB emissions from this region contributed substantially to the elevated aerosol loading over the SCS. Dynamical analyses revealed a persistent anti-cyclonic anomaly over northern PSEA at 500 hPa, accompanied by an eastward-shifted Bay of Bengal anticyclone at 700 hPa and a western North Pacific cyclonic anomaly at both levels. These circulation anomalies likely altered the prevailing regional flow by shifting climatological southerlies toward northerly anomalies, thereby favoring aerosol transport and accumulation over the SCS. Overall, the results suggest that the extreme aerosol event was associated with the combined influence of intensified BB emissions and anomalous atmospheric circulation, highlighting the important role of coupled emissions and atmospheric dynamics in shaping regional aerosol extremes.

~~In April 2023, the South China Sea (SCS) experienced an unprecedented surge in aerosol loading, with aerosol optical depth (AOD) reaching the highest levels recorded during the 2-decade period of Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data (2003–2023). AOD increased by ~150% relative to the long-term mean (2002-2022), indicating an anomaly exceeding 4σ, and was accompanied by pronounced enhancement in carbon monoxide (CO) at 700 and 500 hPa. Using multi-sensor satellite measurements and MERRA-2 reanalysis, we investigated the sources, driving mechanisms, and atmospheric dynamics behind this extreme aerosol event. MODIS fire counts, burned-area data, and NOAA HYSPLIT back-trajectory analyses identify intense biomass-burning (BB) across northern Peninsular Southeast Asia (PSEA) as the dominant source, particularly from Laos and Myanmar. The BB was facilitated by anomalous meteorological conditions associated with a persistent tropospheric anti-cyclonic anomaly over PSEA, which suppressed convection and promoted subsidence, elevated surface temperatures, and led to widespread drought. The dynamical large-scale circulation anomalies further revealed substantially altered transport pathways. A coupled dynamical pattern involving a western North Pacific (WNP) cyclone, a BoB anticyclone at 700 hPa, and a PSEA anticyclone at 500 hPa generated persistent northerly flow over the SCS, redirecting smoke plumes southward toward the SCS and southern BoB rather than along the climatological pathway toward Taiwan and the northwestern Pacific. These findings reveal how the combined influence of extreme BB emissions and anomalous circulation produced the record aerosol loading over the SCS, highlighting critical links among BB emissions and atmospheric dynamics in shaping regional air quality extremes.~~

Key words: Aerosol loading; South China Sea; MODIS; ~~Biomass burning~~Biomass-burning

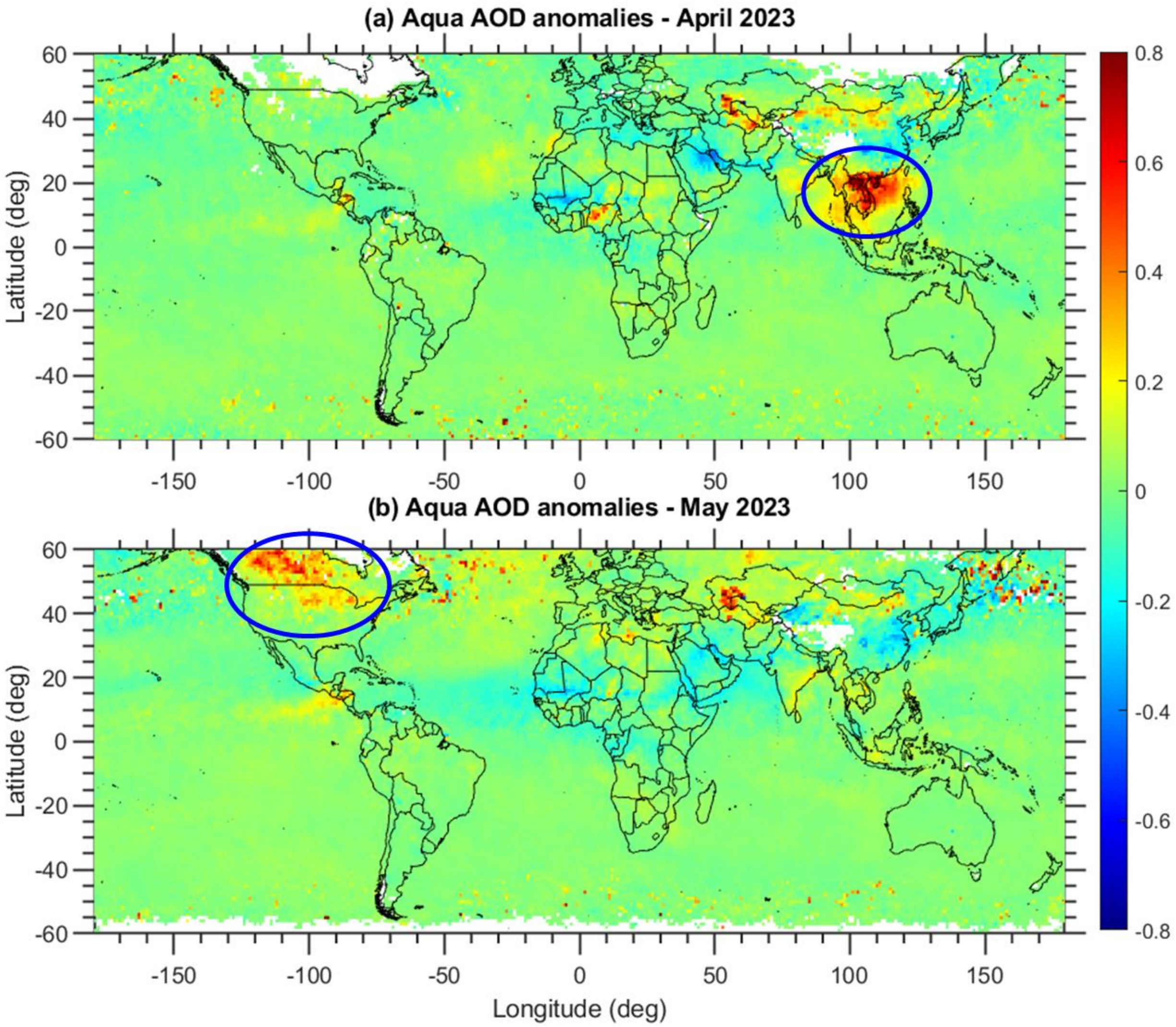
1. Introduction

Atmospheric aerosols play a vital role in Earth’s climate by impacting radiation balance, cloud microphysics, and air quality (Ramanathan et al., 2001; Anderson et al., 2003; Forster et al., 2021; IPCC, 2023). These particles scatter and absorb solar radiation directly, influencing radiative effects, and also modify cloud properties, lifespan, and precipitation by serving as nuclei for condensation and ice formation. As a result, aerosols affect atmospheric thermodynamics, cloud–radiation interactions, and the water cycle (Twomey et al., 1977; IPCC, 2023). Monitoring aerosol levels over remote ocean regions is especially important because these areas provide a baseline for natural background aerosol levels and help evaluate the effects of long-range transport on regional climate through radiative and cloud processes (Pani et al., 2023). In addition to anthropogenic emissions, natural events such as wildfires and agricultural biomass-burning (BB) are significant episodic sources, emitting large quantities of aerosol particles and trace gases that substantially affect both regional and global climate systems (Crutzen and Andreae, 1990; Ramanathan et al., 2001; Lin et al., 2013; Reid et al., 2013; Kolden et al., 2024).

The South China Sea (SCS), situated in Asia, is the largest marginal sea in the tropical–subtropical western North Pacific (WNP), serving as a vital natural laboratory for examining aerosol variability in a relatively pristine marine environment (Reid et al., 2013; Lin et al., 2013; Pani et al., 2023). Although it is an oceanic region, the atmosphere over the SCS is significantly influenced by emissions from nearby continents and regional circulation patterns (Pani et al., 2023). Typically, the SCS is dominated by a monsoon system, with the northeast monsoon occurring during boreal winter and spring, and the southwest monsoon during boreal summer and autumn (Cui et al., 2016). These seasonal wind patterns play a key role in aerosol transport, often carrying natural and human-made pollutants from East Asia into the SCS basin over long distances. In addition to continental outflow from East Asia, ~~biomass burning~~BB emissions from surrounding areas notably influence aerosol concentrations over the SCS. During the summer monsoon months, particularly August to October, persistent peatland and forest fires across the Maritime Continent (MC) generate large smoke plumes that drift toward the southern SCS (Ravindra Babu et al., 2023). Moreover, extensive open BB~~biomass burning~~ in spring over Peninsular Southeast Asia (PSEA), including Myanmar, Thailand, Cambodia, Laos, and Vietnam, serves as a key source of aerosols affecting the SCS atmosphere (Chan et al., 2003; Ou-Yang et al., 2012; Yadav et al., 2017; Liao et al., 2021; Wang et al., 2021; Pani et al., 2023; Wang et al., 2025). This region is recognized as a global hotspot for BB~~biomass burning~~ (Lin et al., 2013; Reid et al., 2013; Cohen, 2014; Cohen et al., 2017; Pani et al., 2019), significantly contributing to carbon emissions and aerosol loading during the peak fire season in March and April (Ravindra Babu and Lin, 2023). These fires mainly stem from slash-and-burn farming practices occurring annually across PSEA (Lee et al., 2016; Tsay et al., 2016; Huang et al., 2020), releasing substantial particulate matter and trace gases into the air (Ou-Yang et al., 2022). As a result, aerosol variability in the SCS region is largely driven by the interaction between regional emission sources and the prevailing monsoon circulation, which influences aerosol transport, dispersion, and accumulation within the basin (Pani et al., 2023).

The year 2023 saw exceptional wildfires worldwide due to record-high global mean surface temperatures, which affected carbon emissions and aerosol levels (Esper et al., 2024; Forster et al., 2024; Min, 2024; Raghuraman et al., 2024; Kolden et al., 2024; Liu et al., 2024; Byrne et al., 2024; MacCarthy et al., 2024). It is reported that 70% of the total burning occurs in the Northern Hemisphere (Kolden et al., 2024). Among all, Canadian wildfires emerged as the primary hotspot, with significant fires in both the eastern and western regions causing notable increases in carbon monoxide (CO) and tropospheric aerosols over the past twenty years (Liu et al., 2024; Byrne et al., 2024; MacCarthy et al., 2024). Although the unprecedented Canadian wildfires in 2023 received considerable scientific attention and were well documented in several studies, the record-breaking aerosol loading over the SCS in April 2023 attracted relatively little international attention. The historic event over the SCS in April 2023 can be seen through the Moderate Resolution Imaging Spectroradiometer (MODIS) Aqua AOD anomalies compared to the long-term mean (2003-2022), which shows extreme positive anomalies over the SCS and surrounding regions during that month, contrasting with the rest of the globe (**Fig. 1**). However, AOD anomalies in May illustrate the absence of positive anomalies over the SCS and instead show higher positive anomalies over North America, which are related to the Canadian wildfires. The time series of monthly mean AOD over the SCS further confirms a record-high AOD in April 2023 relative to the MODIS data from 2003 to 2023 (**Fig. 2d**). The exceptional aerosol loading in April 2023 is unusual for remote marine locations such as the SCS and warrants further investigation. In this study, we investigated the factors and physical processes that contributed to the unprecedented aerosol levels observed in April 2023, using extensive data collected from multiple sources over an extended period. The following three major topics are examined in detail within this study:

- How extreme are these AOD anomalies, and what magnitude was increased?
- What are the sources for these record-breaking aerosol loadings over SCS?
- Were dynamic and large-scale circulations responsible for this event?


(a) Aqua AOD anomalies - April 2023

(b) Aqua AOD anomalies - May 2023

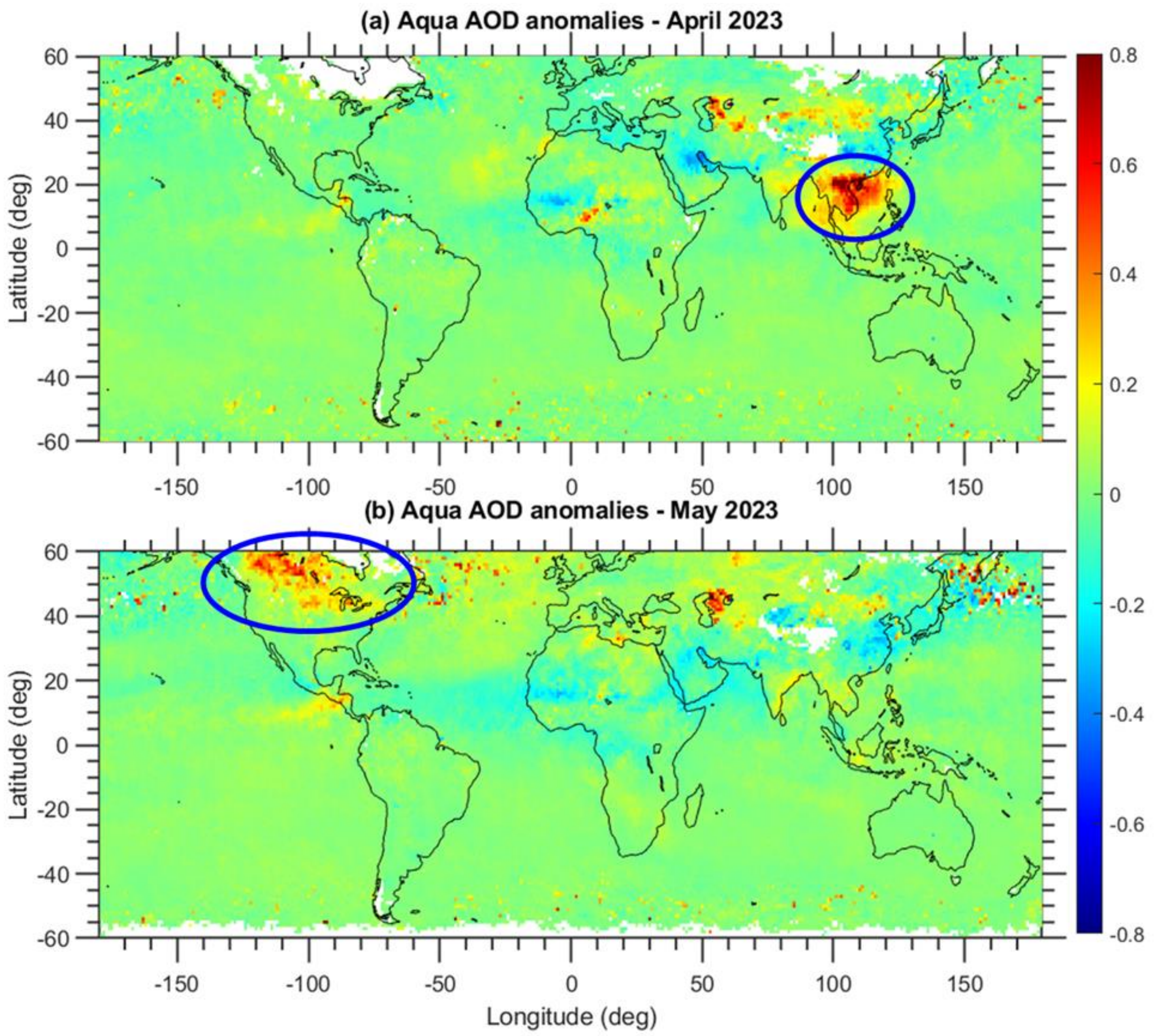


Figure 1. MODIS Aqua measured AOD anomalies in (a) April 2023 and (b) May 2023 compared to the long-term mean (2003-2022). The highlighted circles in (a) and (b) indicate the AOD anomalies over the South China Sea (SCS) and Canada regions. This figure highlights that the AOD anomalies observed by MODIS are significant and particularly pronounced over the SCS compared to the other areas globally. It illustrates the unique characteristics of April 2023 compared to long-term mean. Data visualizations produced using MATLAB 2023b (https://matlab.mathworks.com).

2. Data and Methodology

2.1 Data

This study relies entirely on publicly available data, covering the period from 2003 to 2023. We used data products from various satellite measurements, ground-based observations, and reanalysis products.

2.1.1 Satellite remote sensing measurements

Moderate Resolution Imaging Spectroradiometer (MODIS)

MODIS is a passive sensor aboard the Aqua and Terra satellites, which are in sun-synchronous orbits and cross~~a sun-synchronous orbit, and pass~~ the Equator in the morning (Aqua) and afternoon (Terra). From MODIS satellite measurements, we utilized aerosol optical depth (AOD), fire counts, fire radiative power (FRP), cloud fraction, and burned area products. We used Level 3 monthly AOD at 1∘ × 1∘ spatial resolution derived from the mean of the Dark Target and Deep Blue Combined Aerosol Products from the Terra satellite (MOD08_M3 Collection 6.1) and Aqua satellite (MYD08_M3 Collection 6.1) (Platnick et al., 2015; Buchholz et al., 2020). 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., 2019a). 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., 2019b). Additionally, we used MODIS's daily fire counts and fire radiative power (FRP) products (Giglio et al., 2006, 2016, 2018). Direct fire counts from MODIS were obtained from the Fire Information for Resource Management System (FIRMS) dataset. We selected all MODIS fire counts from the Terra and Aqua sensors with a confidence level of at least 80%. Finally, we utilized Cloud Fraction data from both the Terra and Aqua satellites.

Measurements Of Pollution In The Troposphere (MOPITT)

MOPITT is a multi-channel thermal infrared (TIR) and near-infrared (NIR) instrument operating on board the sun-synchronous polar-orbiting NASA Terra satellite. This study uses a version 9 (MOP03TM_9) gridded monthly product (Worden et al., 2010; Deeter et al., 2019). For more details on the retrieval algorithm, validation, and uncertainties in MOPITT CO, see Deeter et al. (2019).

Atmospheric Infrared Sounder (AIRS)

In addition to the MOPITT measurements, we used CO from the AIRS instrument on the NASA Aqua satellite, which provides CO at multiple vertical levels twice daily and has near-global coverage. AIRS uses wavenumbers 2183–2200 cm−1 (4.58–4.5 µm) for retrieving CO (McMillan et al., 2005). The V9 level 3 CO product, available at 1° × 1° resolution at 700 and 500 hPa levels, was utilized in the present study. AIRS sensitivity to CO is broad and optimal in the mid-troposphere between approximately 300 and 600 hPa (Warner et al., 2007, 2013; AIRS project, 2019). CO retrievals exhibit a 6%–10 % bias between 900 and 300 hPa with a root mean square error of 8%–12 % (McMillan et al., 2011). In addition to CO, we also utilized~~ ozone~~, surface temperature, and outgoing longwave radiation (OLR) data from the AIRS satellite.

Global Precipitation Climatology Project (GPCP)

The Global Precipitation Climatology Project (GPCP) Version 3.2 Satellite-Gauge (SG) Combined Precipitation Data Set was used during the study period. The data is available for download from https://measures.gesdisc.eosdis.nasa.gov/data/GPCP/GPCPMON.3.2/ (last accessed June 5, 2025).

Cloud-Aerosol LIDAR with Orthogonal Polarization (CALIOP)

The CALIOP sensor on the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observations (CALIPSO) satellite provides data on atmospheric aerosols, including aerosol layer heights and thicknesses, optical depth, aerosol type, and other optical properties (Omar et al.,2009; Kim et al., 2018). In our study, we used vertical aerosol-type images available on the CALIPSO website.

2.~~.~~1.2 Reanalysis/model products

MERRA-2 reanalysis

We used monthly mean geopotential height, wind vectors (zonal and meridional wind speeds), and, total column black carbon, organic carbon, and particulate matter from the Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2). MERRA-2 is the latest atmospheric reanalysis data produced by the NASA Global Modeling and Assimilation Office (GMAO; Gelaro et al., 2017). The horizontal resolution of the MERRA-2 reanalysis is 0.5° × 0.625°.

Global Land Data Assimilation System (GLDAS)

Monthly mean soil moisture content (10 - 40 cm underground) from the Global Land Data Assimilation System (GLDAS)_NOAH025_M v2.1 is utilized. The data can be downloaded from https://hydro1.gesdisc.eosdis.nasa.gov/data/GLDAS/GLDAS_NOAH025_M.2.1/ (last accessed: June 05, 2025).

2.1.3 Ground-based observations

AERONET

In this study, we use the latest version (V3) of Level 2.0 AERONET data from two stations: Dongsha Island (also called the Pratas Islands; Dongsha_Island, 20.70°N, 116.73°E, 5 m above sea level) and Lulin Atmospheric Background Station (LABS, 23°28′N, 120°52′E, 2,862 m; Sheu et al., 2010). These offer cloud-screened, quality-checked direct-sun AOD retrievals with uncertainties of about ±0.01 in the visible and ±0.02 in the ultraviolet range (Giles et al., 2019; Sinyuk et al., 2020).

The summary of the major data used in the present study is presented in **Table 1**.

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

2.2 Methodology

The anomalies in the various parameters for April 2023 were estimated by subtracting the April background long-term mea (2003-2022) from April 2023 value.

The magnitude of the AOD/CO enhancement in April 2023 above the long-term background was determined by comparing the average of April 2003-2022. We obtained the percentage change in AOD/CO relative to the respective background using Equation 1:

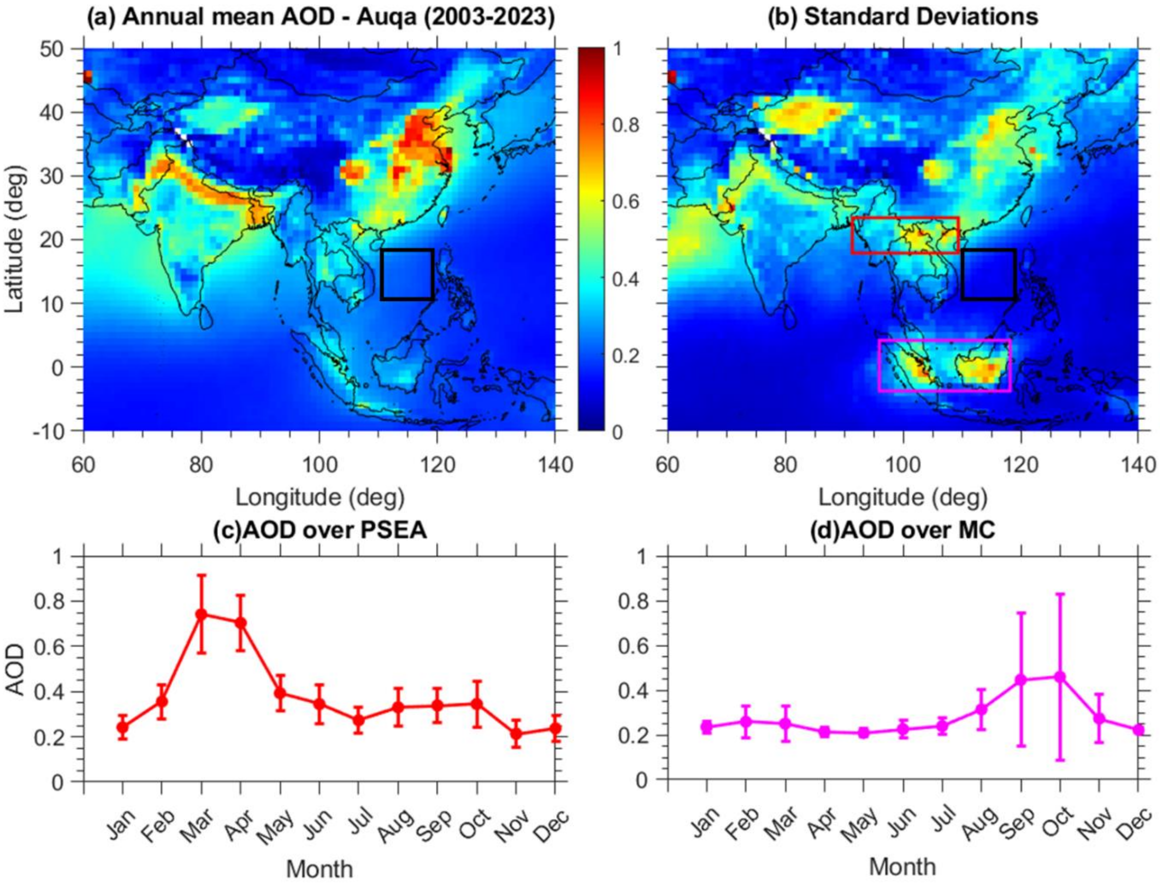
$$\text{Relative change in percentage} = \left(\frac{x_{i-\bar{x}}}{\bar{x}}\right) \times 100 \qquad \text{(Eq. 1)}$$

where x_i represents the monthly mean of April in 2023, and $\bar{x}$ is the long-term mean of April calculated using the data from 2003 to 2022.

3. Results and Discussion

3.1 Record-breaking aerosol loading over SCS in April 2023

Aerosol optical depth (AOD) is a common metric for measuring atmospheric aerosol loading and is crucial for radiative forcing assessments (Hirsch and Koren, 2021). In this study, we use AOD data from the MODIS instruments aboard the Aqua and Terra satellites for the period. Before analyzing the unusual AOD conditions observed in April 2023, we first characterize the long-term AOD behavior over the study area using two decades of MODIS data. The spatial patterns of the long-term annual mean AOD and its associated standard deviation across the Asian region are shown in **Figures 2a** and **2b**, respectively. Additionally, the long-term monthly-mean variability of AOD over the two main ~~biomass-burning (~~BB~~)~~ regions surrounding the SCS, namely PSEA and the MC, is shown in **Figures 2c** and **2d**. The relatively low AOD levels and small standard deviations over the SCS suggest the dominance of a relatively clean marine environment. The seasonal cycle of AOD shows clear peaks linked to regional BB activities (**Figs. 2c** and **2d**). Over PSEA, AOD peaks during March–April, while over the MC, the peak occurs in September–October. These seasonal maxima align with well-known BB activity periods in these areas (Ravindra Babu and Lin, 2024; Chang et al., 2024). The fire season over the MC usually runs from August to October, whereas PSEA experiences intense BB activity from January to April, with a notable peak in March.


(a) Annual mean AOD - Auqa (2003-2023)
(b) Standard Deviations
Latitude (deg)
Longitude (deg)
50
40
30
20
10
0
-10
60
80
100
120
140
0
0.2
0.4
0.6
0.8
1
0
0.1
0.2
0.3
0.4
0.5
(c)AOD over PSEA
(d)AOD over MC
AOD
Month
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec

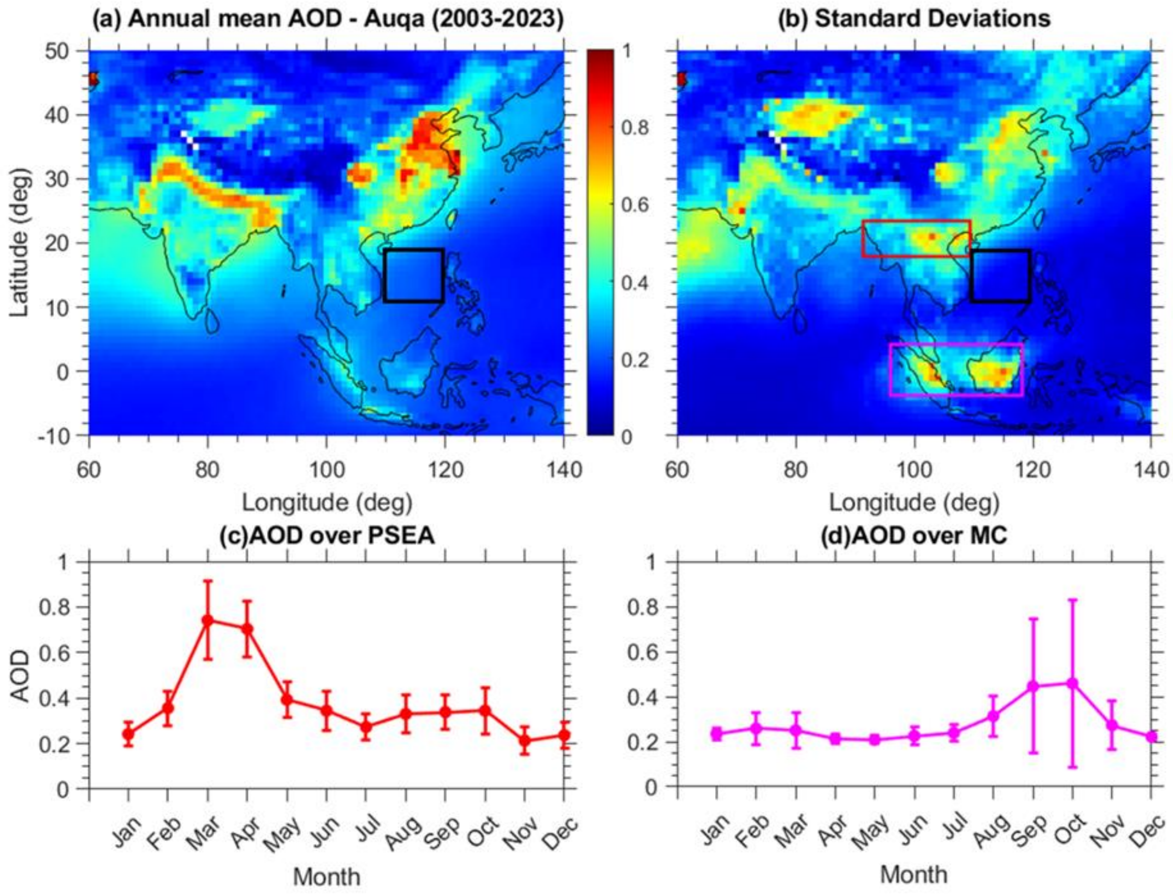
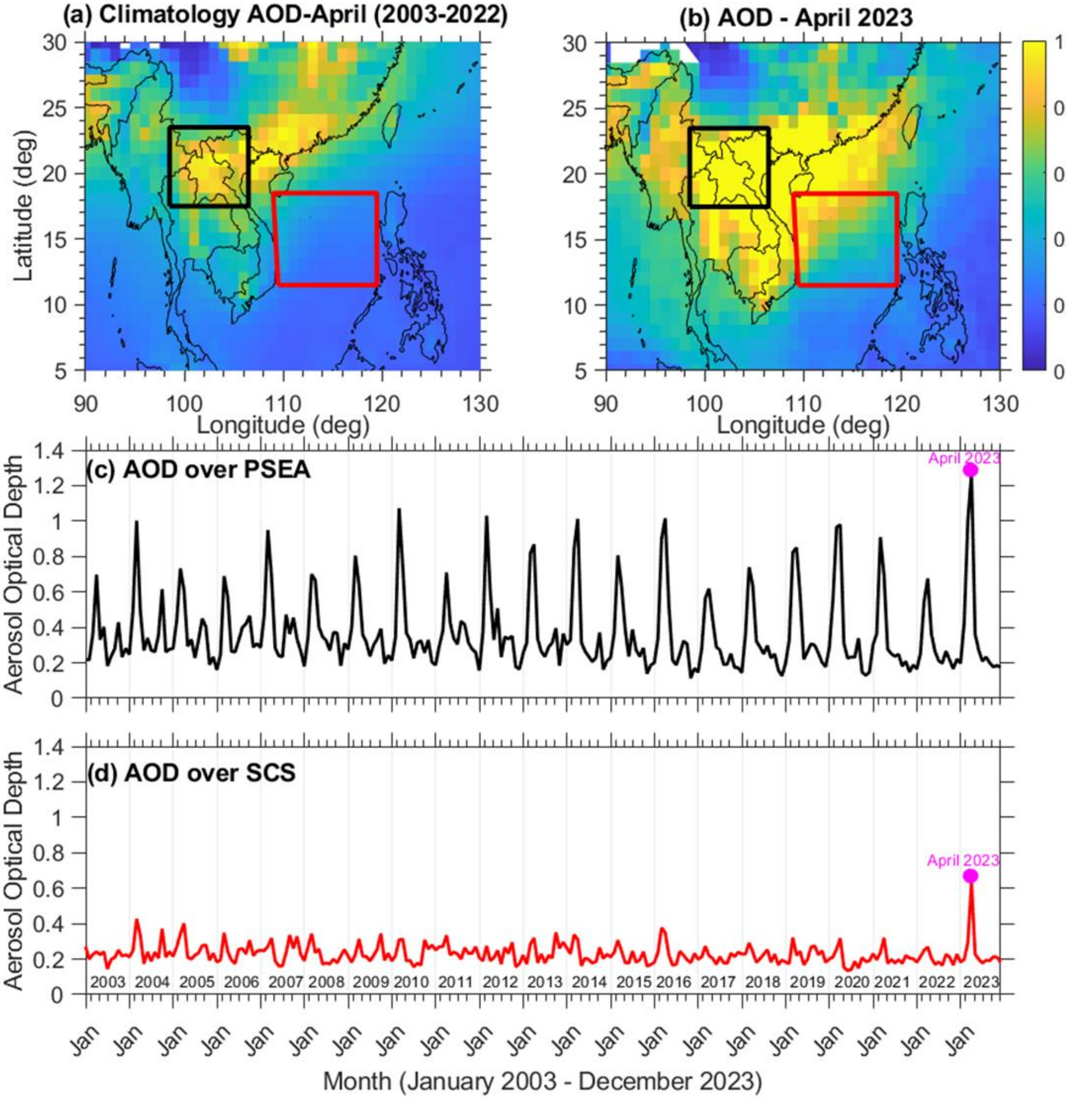


Figure 2. Climatological mean distribution of MODIS (a) Aerosol Optical Depth (AOD) and (b) respective standard deviations. The black box illustrated in both figures emphasizes the specific area of the South China Sea (SCS) that is the primary focus of this research. (11-18°N,109-119°E). The red and magenta boxes indicate the PSEA and MC, two significant biomass-burning regions near the SCS. The long-term average seasonal variation in AOD is illustrated over (c) PSEA and (d) MC.


(a) Climatology AOD-April (2003-2022)
(b) AOD - April 2023
Latitude (deg)
Longitude (deg)
30
25
20
15
10
5
90
100
110
120
130
1
0.8
0.6
0.4
0.2
0
(c) AOD over PSEA
April 2023
(d) AOD over SCS
April 2023
Aerosol Optical Depth
1.4
1.2
1
0.8
0.6
0.4
0.2
0
2003 2004 2005 2006 2007 2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018 2019 2020 2021 2022 2023
Jan
Month (January 2003 - December 2023)

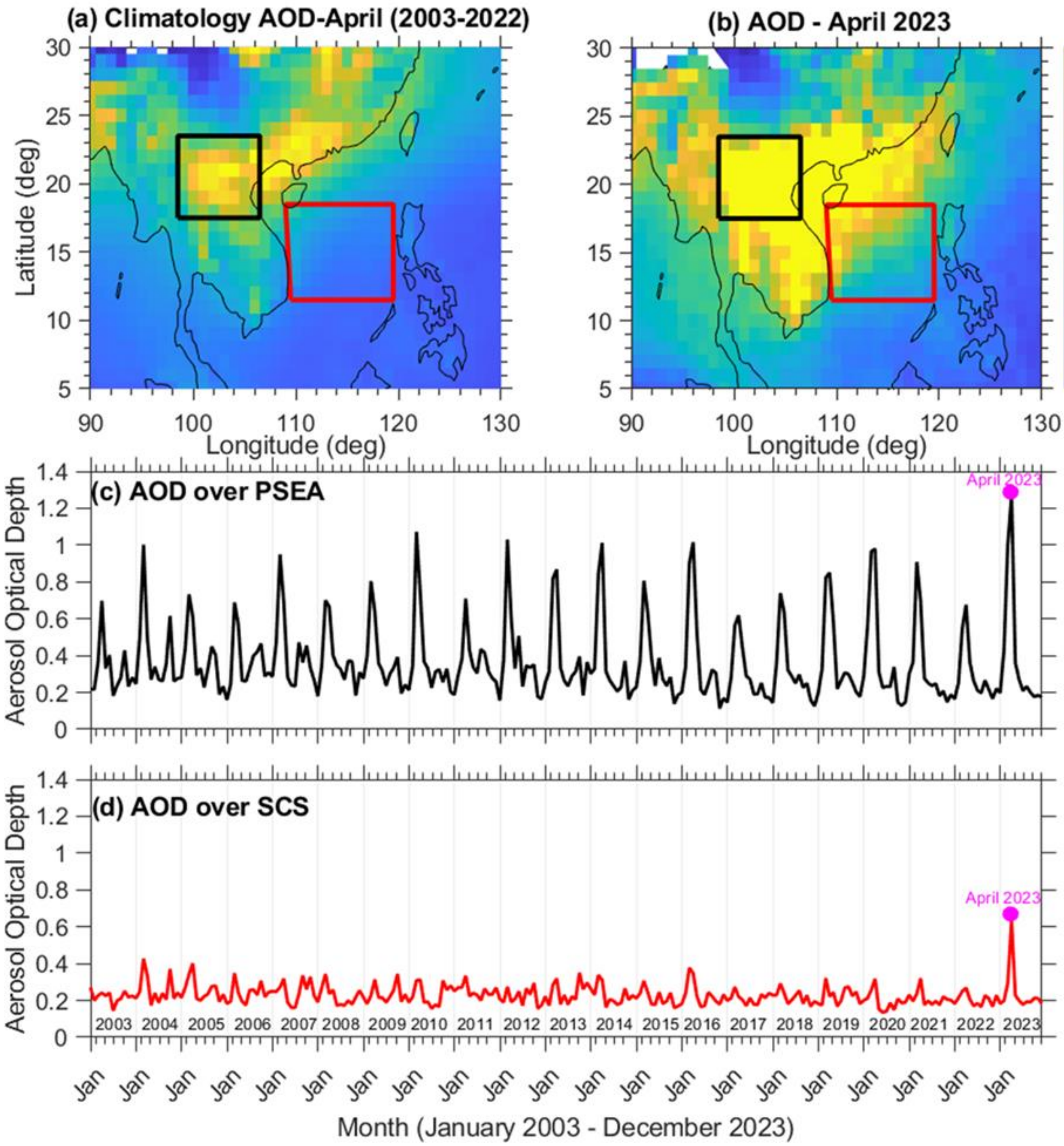


Figure 3. Spatial distribution of (a) Inter-annual (2003 to 2022) monthly average AOD values for April. (b) Monthly AOD values for April 2023. A notable increase in AOD values is observed over the Peninsular Southeast Asia (PSEA) and the South China Sea (SCS). AOD distribution averaged in April over the past two decades showed a belt of high aerosol loading extending from northern Laos to the southern coast of China. During April 2023, extreme AOD values were observed across the entire PSEA, extending to coastal South China and the SCS. (c) Time series of average monthly mean AOD values over the northern PSEA (17-23°N, 99- 106°E), and (d) over the SCS (11-18°N,109-119°E) from January 2003 to December 2023. The magenta dot in subplots (c) and (d) marks the AOD values during April 2023.

To emphasize the anomalous conditions in April 2023, we present the spatial distribution of April AOD over the study region for both the long-term average and April 2023. The long-term average April AOD for 2003–2022 and the corresponding April 2023 AOD distribution are shown in **Figures 3a** and **3b**. Moreover, the time series of monthly mean AOD from 2003 to 2023 over northern PSEA (17–23°N, 99–106°E) and the SCS (11–18°N, 109–119°E) are displayed in **Figures 3c** and **3d**. The AOD distribution in April over two decades indicates high aerosol loading from northern Laos to coastal South China (15-25°N, 100-120°E). In April 2023, extreme AOD values extended from PSEA to South China and SCS, with the highest values centered between northern Laos and the SCS. Record-breaking AOD levels were observed for the area averaged over the SCS in April 2023, showing a nominal increase in northern PSEA (**Fig. 3c**). However, the highest AOD value for northern PSEA in April 2023 correlates with record AOD over the SCS. Long-term monthly mean AOD from Aqua and Terra (2003–2023) exhibited a strong correlation of 0.97, confirming the consistency and reliability of these observations (**Fig. S1a** in the Supplement). To assess the magnitude of the increase, we estimated the percentage change in AOD by comparing April 2023 with the long-term April average from 2003 to 2022.

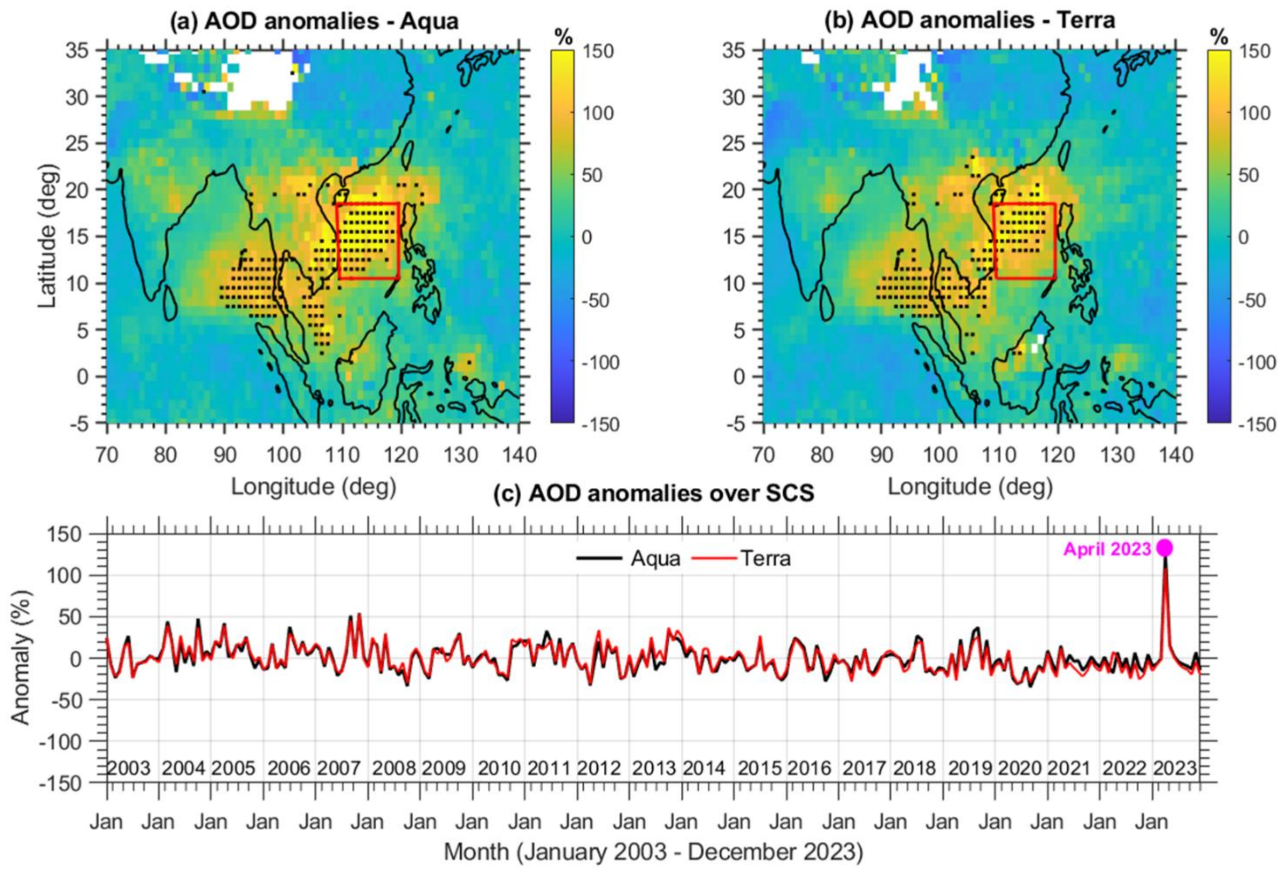


Figure 4. Spatial distribution of the change (%) in Aerosol Optical Depth (AOD) values during April 2023 compared with the inter-annual April average (2003-2022). (a) AOD anomalies are obtained from the MODIS Aqua and (b) from the MODIS Terra satellite. The black dots indicate that the anomalies exceed 4σ of the long-term mean. (c) Time series of area-averaged AOD anomalies expressed in percentage change over the South China Sea (SCS) domain from the Aqua (black line) and Terra (red line) satellites. The most pronounced enhancement occurred over the SCS, where April AOD anomalies exceeded 4σ above the long-term mean.

Figures 4a and 4b illustrate the spatial extent of AOD anomalies, shown as percentage changes, based on data from MODIS Aqua and Terra satellites. In April 2023, there was a widespread and unexpected increase of about 150% across most of the SCS and southern Bay of Bengal (BoB), with anomalies surpassing roughly 4 standard deviations. The area-averaged AOD anomalies (%) over the SCS, indicated by the black line for Aqua and the red line for Terra, reveal that the April 2023 peak was the highest on record compared to data from 2003 to 2023, emphasizing the extreme AOD intensity that month. These satellite observations were also supported by ground-based measurements from AERONET. The only operational AERONET remote station downwind of PSEA BB~~biomass burning~~, with over a decade of continuous AOD measurements (**Fig. S2a** in the Supplement), within the SCS region is located on Dongsha Island (also known as Pratas Island, 20.70°N, 116.73°E; 5 m a.s.l.). Analysis of monthly mean AOD data from Dongsha Island indicates that April 2023 had the highest AOD value during the observational period from January 2009 to December 2023 (**Fig. S2c** in the Supplement). AERONET comparisons show strong correlations with MODIS AOD: 0.86 for Aqua and 0.87 for Terra (**Fig. S3** in the Supplement), supporting the reliability of the satellite observations. Because AOD is a column-integrated measure, it does not provide information on the vertical distribution of aerosols. To address this limitation, we further analyzed vertical distribution images of aerosols from the Cloud-Aerosol Lidar and Infrared Pathfinder Satellite Observation (CALIPSO), which reveal pronounced enhancements in smoke aerosol over the SCS (**Fig. 5**). Elevated smoke layers were also observed over the southern BoB in April 2023, predominantly within the mid-troposphere at altitudes of approximately 2-5 km. Consistent with these CALI~~S~~PSO 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% (**Fig. S4** in the Supplement). The most pronounced enhancements occur between 700 and 600 hPa, closely matching the altitude range identified by CALIPSO. The concurrence of satellite (MODIS and CALIPSO) and reanalysis data points to a severe pollution episode in April 2023 over and surrounding regions of the SCS, characterized by an elevated aerosol layer indicative of long-range-transported ~~biomass-burning~~BB smoke. Notably, the SCS is a relatively clean remote marine region with limited local aerosol sources. In such environments, enhanced aerosol loading is typically associated with long-range transport of pollutants from surrounding continental regions (Pani, 2023). Given the potential influence of long-range pollution transport, we further analyzed variations in carbon monoxide (CO), a widely used tracer of ~~biomass-burning~~BB emissions due to its relatively long atmospheric lifetime (~1–2 months) and strong association with incomplete combustion (Ravindra Babu et al., 2023). We investigated CO changes across the study region using measurements from the MOPITT and AIRS satellites, which together provide more than two decades of continuous CO observations. CO data at 700 and 500 hPa from both satellites were analyzed for the period 2003–2023, with the 500 hPa level representing the altitude of maximum sensitivity for CO retrievals (Buchholz et al., 2021).

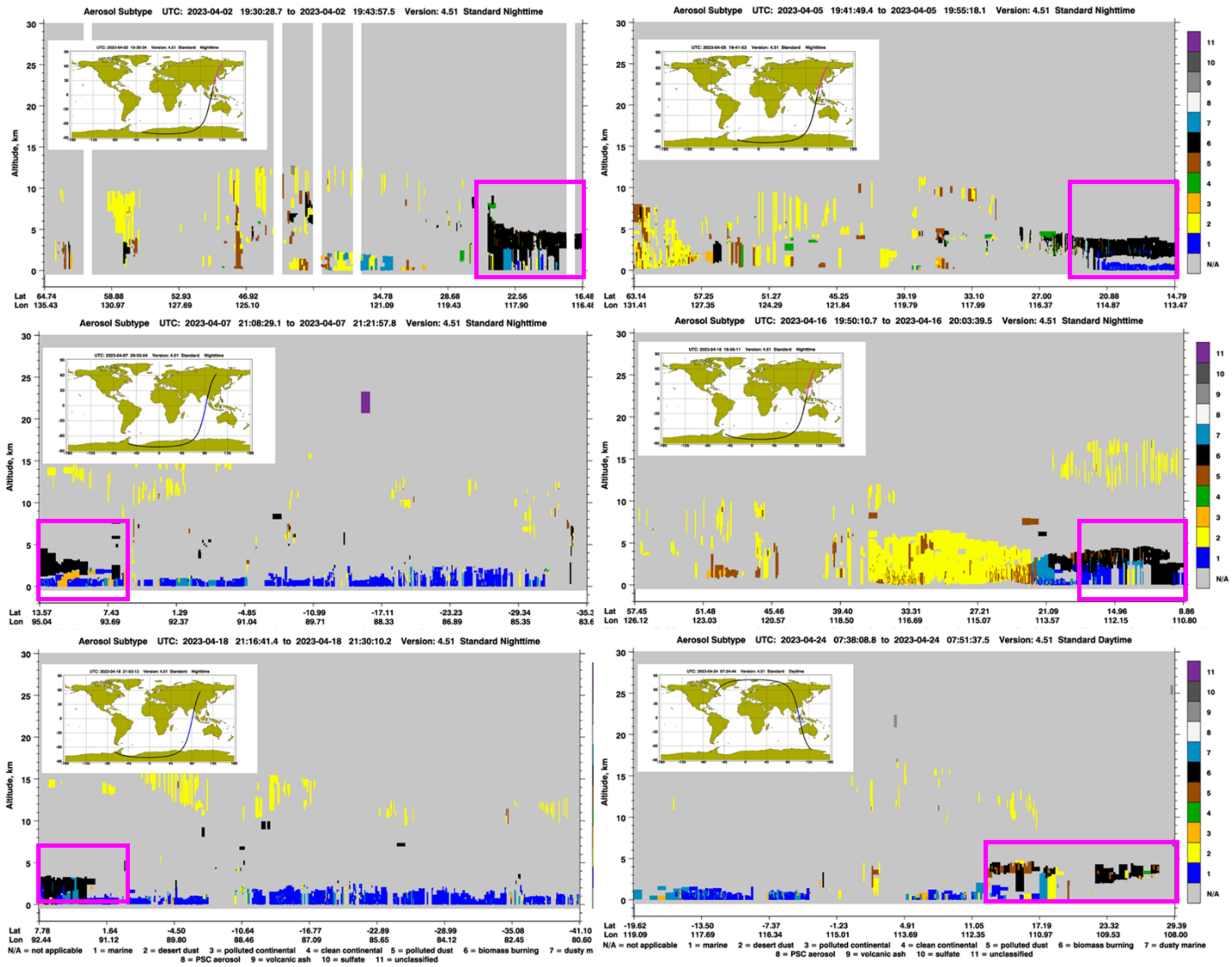


Figure 5. Aerosol subtype images obtained by the CALIPSO observations during various days in April 2023. The highlighted magenta box indicates elevated smoke over the South China Sea (SCS) and the southern Bay of Bengal. Smoke aerosol is shown in black.

The observed CO anomalies from the two satellites are shown in **Fig. 6**, revealing significantly elevated CO concentrations over the SCS in April 2023, reaching up to 3σ above the 2003–2022 climatology. Although MOPITT displays more spatially concentrated anomalies than AIRS, both datasets consistently show positive CO anomalies at both pressure levels, indicating a substantial increase in mid-tropospheric CO during this period. For MOPITT CO retrievals, primary sources of uncertainty include limitations in vertical sensitivity and potential retrieval biases (Sayer et al., 2014; Wei et al., 2019). However, the observed enhancements (>3σ) are supported by independent AIRS CO measurements, reinforcing the robustness of the detected anomalies. The comparison between MOPITT and AIRS CO at 500 hPa over the SCS further shows a strong positive correlation (R ≈ 0.89; **Fig. S1b** in the Supplement). Furthermore, the spatial distribution of CO anomalies closely resembles that of AOD anomalies (**Fig. 4**). Further, the area-averaged anomalies of AOD and 500 hPa CO over the SCS in April during 2003-2023 exhibit a strong positive correlation (R = 0.81; **Fig. 7**~~**S5** in the Supplement~~), suggesting that long-range transport of pollution plays an important role in modulating aerosol variability in this region. The bubble chart further highlights the exceptional severity of the April 2023 event compared with previous years (**Fig. 7**~~**S5** in the Supplement~~). Because CO is primarily produced by incomplete combustion, elevated concentrations far from major traffic or industrial sources strongly suggest ~~biomass burning~~BB and wildfire emissions. The strong similarity between the spatial distributions of CO and AOD anomalies suggests that the increased aerosol loading was driven by BB in April 2023. This indicates that smoke was likely transported from surrounding regions toward the SCS and the BoB, which are located near major BB~~biomass burning~~ hotspots, including the MC and PSEA. The MC fire season typically occurs from August to October, whereas PSEA experiences a ~~biomass burning~~BB season from January to April, peaking in March (**Fig. 2**). These seasonal characteristics strongly suggest that the elevated AOD levels observed over the SCS in April 2023 were likely linked to ~~biomass burning~~BB activity in PSEA. Overall, the April 2023 event is notable for its exceptional intensity and extensive spatial coverage. The MODIS AOD anomalies were approximately four times higher than the long-term mean across much of the SCS and the southern BoB during April 2023. ~~We suggest that this episode represents a rare, previously unreported extreme aerosol-loading event, distinct from the springtime biomass-burning transport events over the PSEA region documented in earlier studies.~~ Such anomalously high aerosol loading over the SCS may have important implications for regional climate and hydrological cycle, highlighting the need for further investigation into the underlying drivers and physical mechanisms responsible for this event.

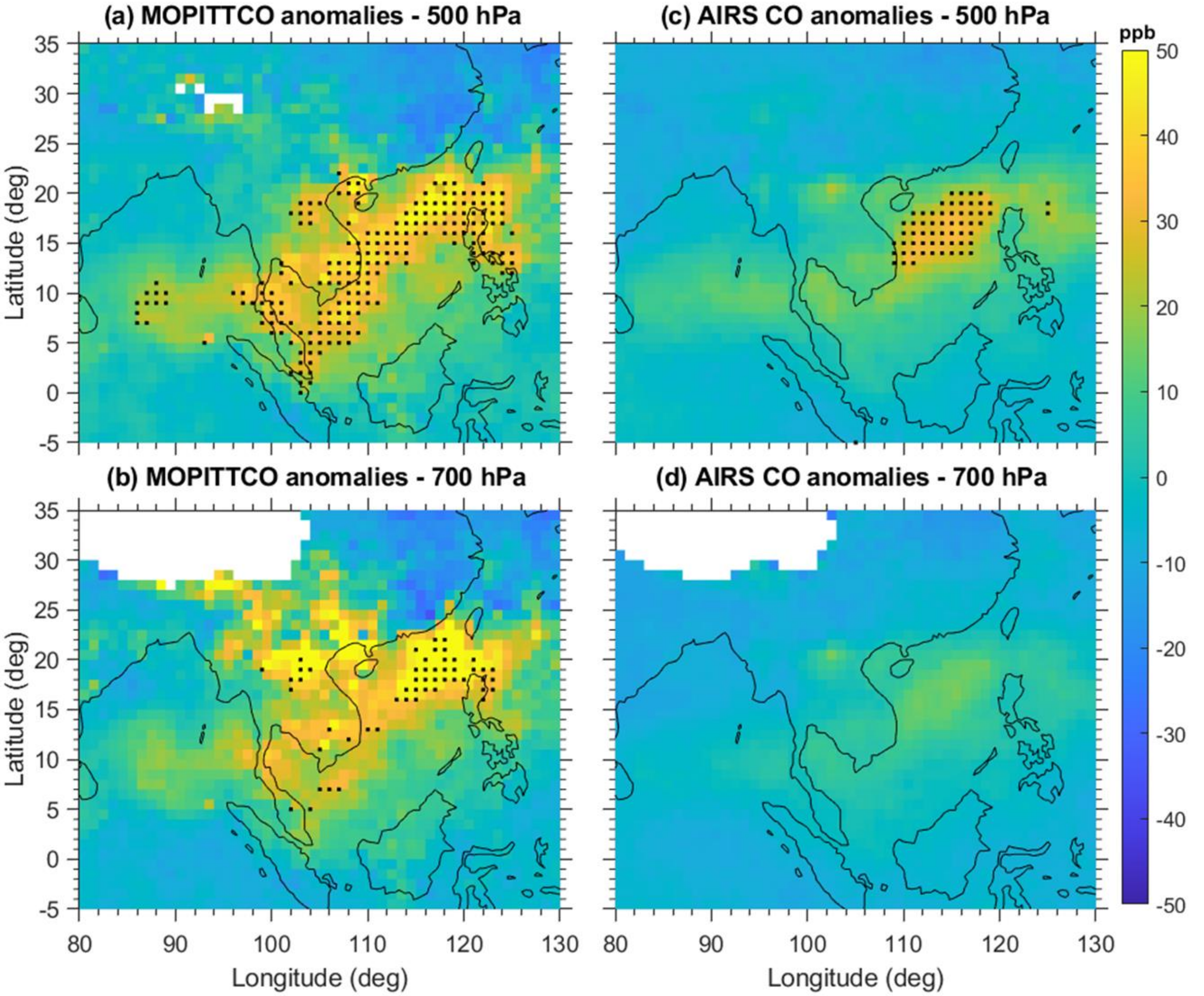


Figure 6. Spatial distribution of carbon monoxide (CO) anomalies in April 2023 at (a) 500 hPa and (b) 700 hPa from MOPITT satellite measurements. Panels (c) and (d) show the corresponding CO anomalies at 500 hPa and 700 hPa derived from AIRS satellite observations. Anomalies are calculated relative to the long-term April mean for 2003–2022. Black dots indicate regions where anomalies exceed the 3σ significance threshold.

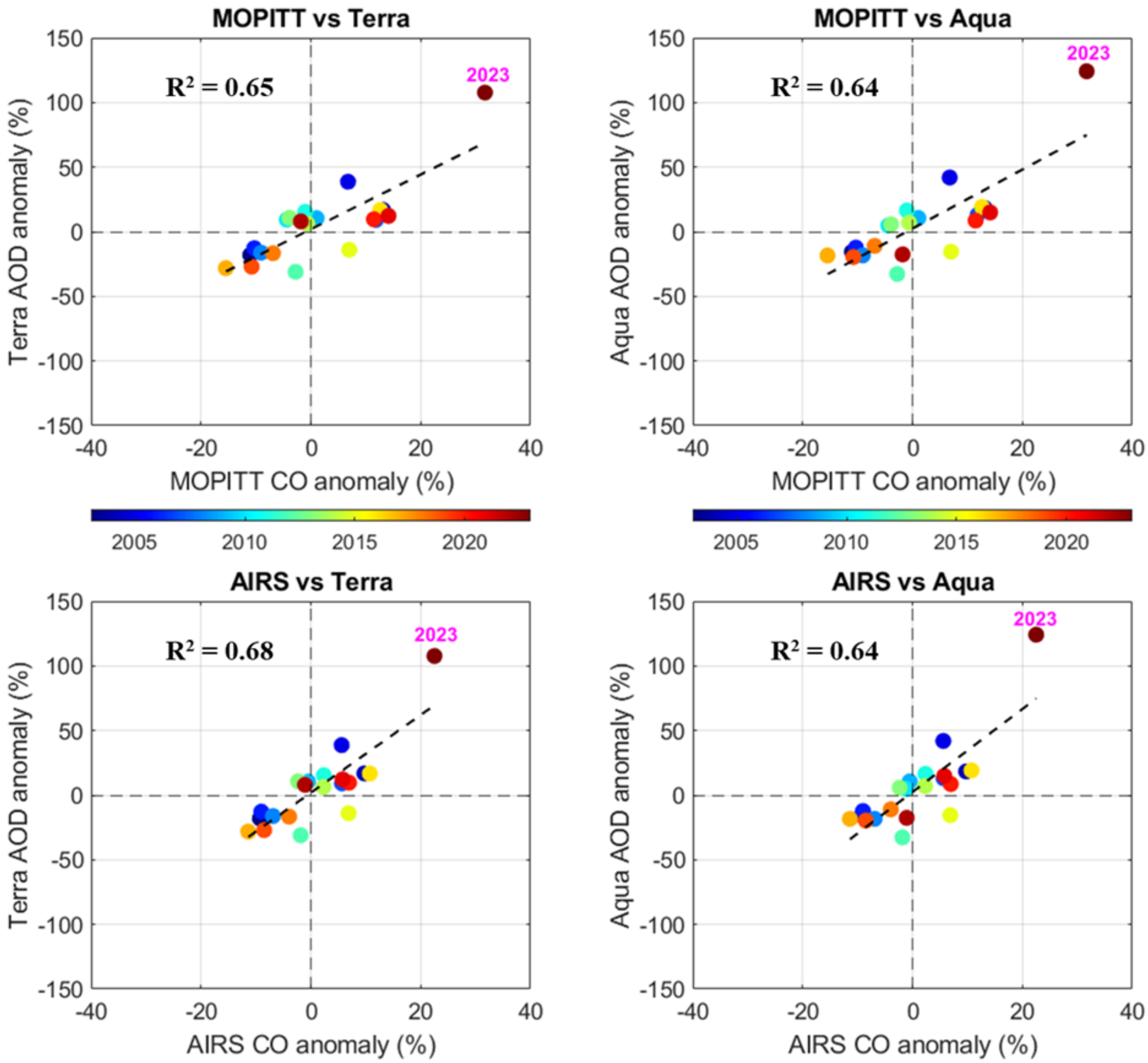


Figure 7. Bubble plot of the AOD and CO anomalies (April) over the South China Sea (SCS) during 2003–2023. To panels for MOPITT and MODIS (Terra and Aqua), whereas the bottom panels are for AIRS and MODIS observations. The average coefficient of determination (R^2) is ~0.65, corresponding to a correlation coefficient (R) of 0.81, indicating a statistically robust association between CO and AOD over the SCS.

3.2 Transport and Source Attribution of the April 2023 Aerosol Event

From the previous section, it is clear that most aerosols are free-troposphere-dominated and located primarily in the ~2-5km region over the SCS. To determine the source regions responsible for elevated aerosol concentrations over the SCS in April 2023, backward air-mass trajectories were computed using the NOAA HYSPLIT model. Trajectories were initialized at

15°N, 115°E, at 3 km above sea level, corresponding to the altitude range (2-~~–~~5 km) of the elevated aerosol layer observed in CALIPSO and MERRA-2 profiles. Daily 72-hour trajectories (**Fig. ~~7a~~8a**) indicate that air masses arriving over the SCS predominantly originated from northern PSEA. When overlaid on the monthly mean MODIS AOD (**Fig. ~~7b~~8b**), these trajectories reveal transport pathways that coincide with regions of high aerosol loading, ~~confirming~~ strongly suggesting that long-range transport of PSEA BB smoke ~~from northern PSEA~~ likely transported to the SCS. ~~was the primary mechanism delivering BB emissions to the SCS.~~ To examine the BB activity during April 2023, MODIS fire counts and burned area (BA) data were used. The spatial distributions of MODIS fire counts and ~~burned area (~~BA~~)~~ for April 2023 (**Figs. ~~8a~~9a–b**) show that BB activity was overwhelmingly concentrated in northern PSEA, particularly in northern Laos and adjacent regions of Myanmar and Thailand. Minimal fire activity and BA were observed over the MC and southern China; therefore, these regions were ~~therefore~~ excluded from source-region calculations. Analysis of inter-annual variability in April BB activity over PSEA from 2003 to 2023 (**Figs. ~~8c~~9c–d**), considering only fire detections above the 80% confidence level, indicates substantial year-to-year fluctuations. Notably, April 2023 recorded the highest burned area (~2.27 Mha) over the 21-year period, highlighting the exceptional intensity of BB activity that month.

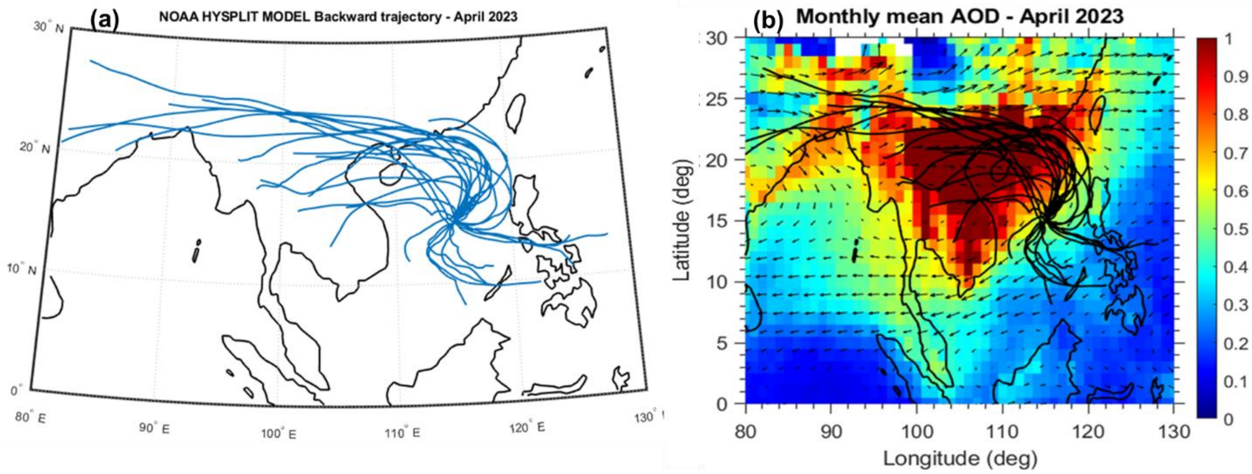


Figure ~~7~~8. (a) Daily 72-h NOAA HYSPLIT backward trajectories ending at 12:00 UTC at a representative location (15°N, 115°E) over the South China Sea (SCS) at 3 km altitude for April 2023. (b) Same as (a), but overlaid on the monthly mean MODIS aerosol optical depth (AOD) for April 2023.

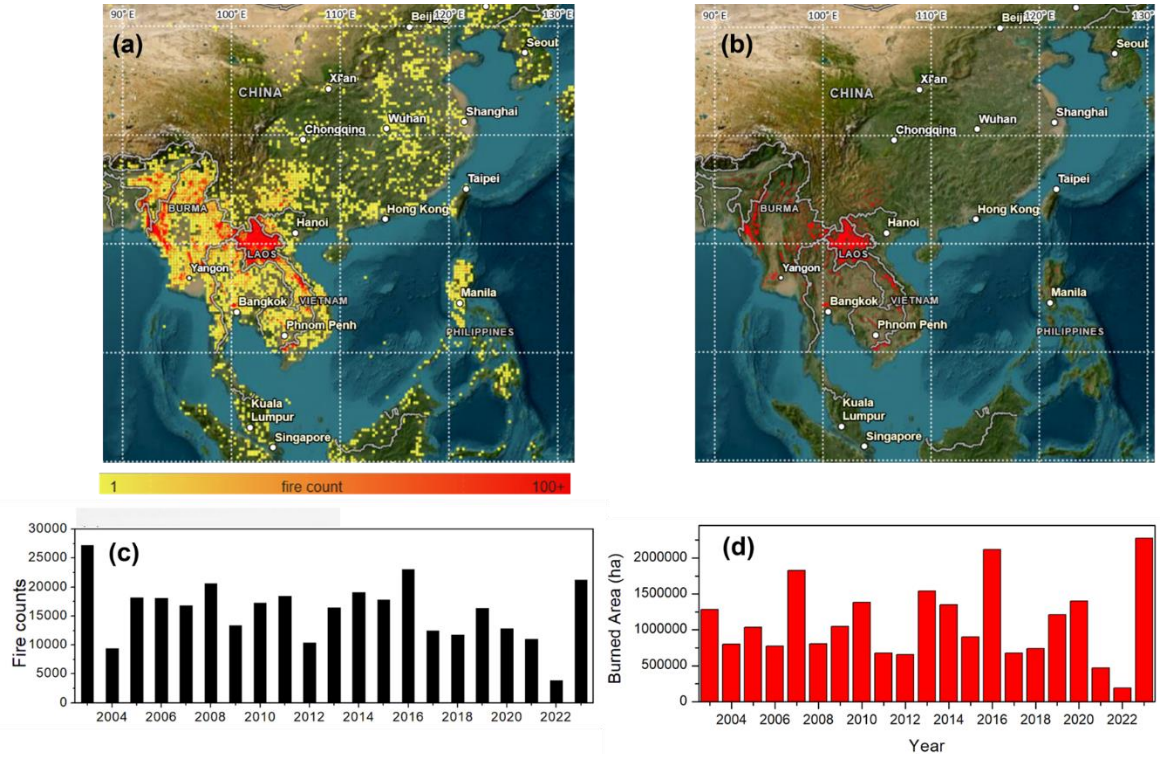


Figure ~~8~~9. Spatial distribution of the (a) MODIS fire counts, (b) MODIS Global Burned Area Product in April 2023. Inter-annual variability in (c) Fire counts, and (d) Burned Area over Peninsula Southeast Asia in April from 2003 to 2023. (Source: https://firms.modaps.eosdis.nasa.gov/). For inter-annual variability in fire counts, we considered those above the 80% confidence level.

Country-level statistics (**Table 2**) further highlight the dominant contribution from Laos, which accounted for 11,877 fires (56.0%), 1.53 × 10^6 MW of fire radiative power (FRP; 63.5%), and 1.08 × 10^6 ha of burned area (47.7%). Notably, the BA observed in April 2023 represents the highest monthly value in the available dataset (2002–2023; **Fig. ~~S6~~ S5** in the Supplement). Approximately 60% of Laos is forested (**Fig. ~~S7~~ S6** in the Supplement), with much of this forest located in northern Laos where the majority of fires occurred during April 2023 (**Fig. ~~8a~~9a**). Myanmar contributed the second-largest share, with 7,054 fires (33.3%), 7.78 × 10^5 MW of FRP (32.3%), and 9.15 × 10^5 ha of burned area (40.3%). Thailand, Vietnam, and Cambodia contributed comparatively smaller burned areas of 1.21 × 10^5 ha, 1.30 × 10^5 ha, and 2.20 × 10^4 ha, respectively. In total, 21,198 fires across PSEA produced approximately 2.41 × 10^6 MW of FRP in April 2023. These results strongly suggest that intense BB activity over northern PSEA, likely contributed substantially to the exceptional aerosol loading observed over the SCS in April 2023. ~~These results indicate that intense BB activity over northern PSEA, particularly northern Laos, was the primary~~

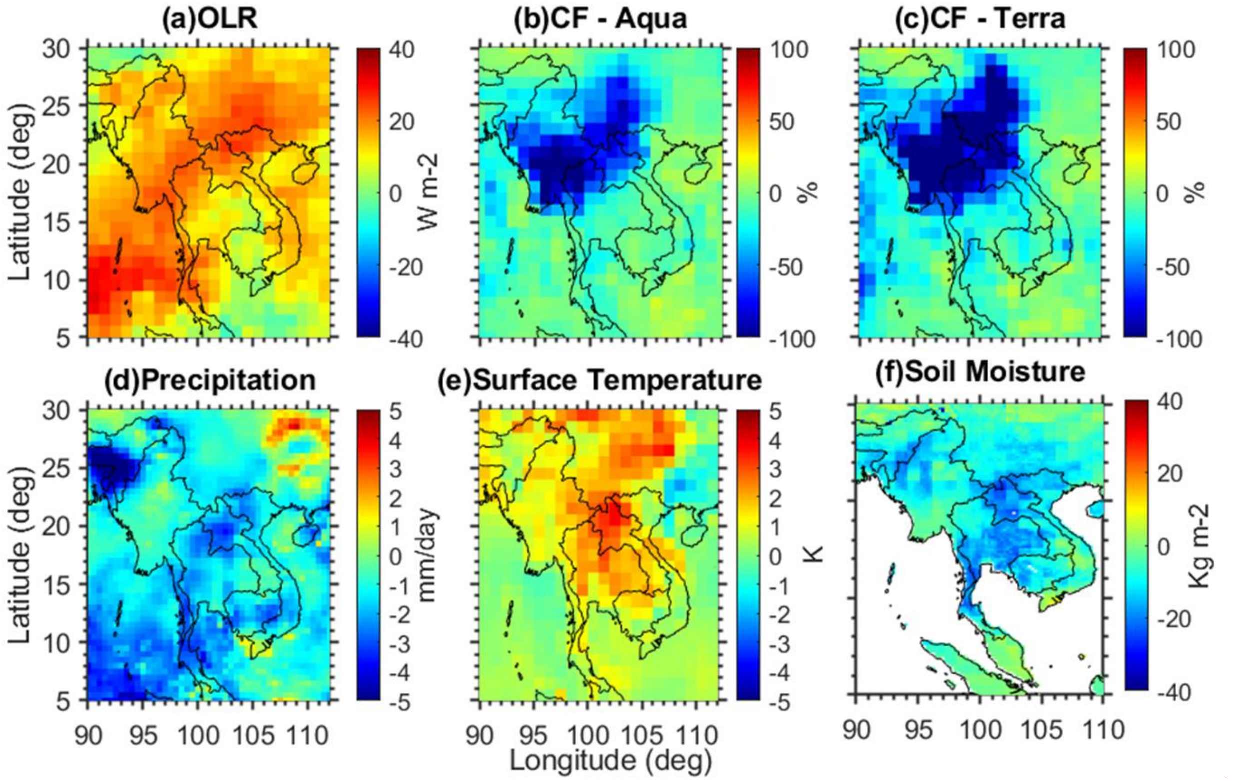
~~source of the exceptional aerosol loading observed over the SCS in April 2023.~~ However, two key questions remain: (i) what factors triggered the anomalously strong fire activity in Laos during April 2023, and (ii) why were BB aerosols transported unusually far southward across the SCS and into the southern BoB, rather than following the more typical transport pathways toward Taiwan and the north western Pacific? To address these questions, we next examine the large-scale meteorological and dynamical circulation conditions prevailing during April 2023.

Table 2. MODIS total fire counts, the corresponding total accumulated fire radiative power (FRP), and the burned area (BA) observed over peninsular Southeast Asia (PSEA) and each country within PSEA in April 2023. The percentage contribution of each country to the total number of fires, the total FRP, and the BA of PSEA is shown in brackets.

Country	**Total Fires**	**Fire Radiative Power (MW)**	**Burned Area (ha)**
PSEA	21198	2407283	2272099.89
Country	Total Fires	FRP	BA
Cambodia	242 (1.14%)	13402 (0.5%)	21959.5 (0.97%)
Laos	11877 (56.02%)	1530000 (63.5%)	1084050 (47.71%)
Myanmar	7054 (33.27%)	777970 (32.32%)	915175.7 (40.27%)
Thailand	1322 (6.24%)	50276 (2.1%)	120573.7 (5.31%)
Vietnam	703 (3.32%)	35634 (1.5%)	130340.7 (5.74%)

3.3 Large-scale meteorological and dynamical circulation anomalies in April 2023

In this section, we examine the meteorological and large-scale dynamical circulation anomalies associated with the April 2023 event. **Figure ~~9~~ 10** presents the spatial distribution of anomalies in key meteorological parameters during April 2023 relative to the 2003–2022 climatological mean. As shown in **Figure ~~9~~10**, ~~anomalies in~~ Outgoing Longwave Radiation (OLR) anomalies indicate suppressed convective activity over PSEA during April 2023. Reduced convection was accompanied by negative precipitation anomalies, elevated surface temperatures, and pronounced soil moisture (SM) deficits. These conditions are spatially consistent with the regions of enhanced fire counts and ~~burned area~~BA observed by MODIS over northern Laos (**Fig. ~~8~~9**). Long-term SM anomalies over northern Laos reached exceptionally low values in April 2023, representing the lowest levels in the past two decades (**Figs. ~~S8a~~S7a–b** in the Supplement). To further examine the persistence of these conditions, we analyzed the temporal evolution of SM anomalies during 2021–2023. The results show maximum positive anomalies in March 2022 and a transition to strong negative anomalies by April 2023, indicating a prolonged drought from winter 2022 to April 2023 (**Fig. ~~S8c~~ S7c** in the Supplement). We further assessed the relationship between SM anomalies and fire activity over Laos. Standardized fire anomalies and SM anomalies (**Fig. ~~S9~~ S8** in the Supplement) reveal a significant inverse relationship: reduced SM is associated with enhanced fire activity. In April 2023, extreme negative SM anomalies coincided with strong positive fire anomalies, highlighting the role of severe surface drying in promoting intense ~~biomass-burning~~BB activity. A similar co-occurrence of anomalously low SM and elevated fire activity is also evident in 2016, a year previously identified as having intensified regional burning. These findings provide additional observational evidence that ~~soil moisture~~SM deficits are linked to enhanced fire activity over PSEA. Previous studies have shown that negative SM anomalies can promote positive geopotential height anomalies in the upper troposphere, which tend to reinforce local high-pressure conditions and enhance surface warming (e.g., Fischer et al., 2007; Dong et al., 2023). Motivated by this mechanism, we next examine the large-scale dynamical circulation patterns during April 2023 to understand how atmospheric dynamics may have contributed to the observed meteorological anomalies and the anomalous transport of ~~biomass-burning~~BB aerosols.


(a)OLR
(b)CF - Aqua
(c)CF - Terra
(d)Precipitation
(e)Surface Temperature
(f)Soil Moisture
Latitude (deg)
Longitude (deg)
W m-2
%
mm/day
K
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30
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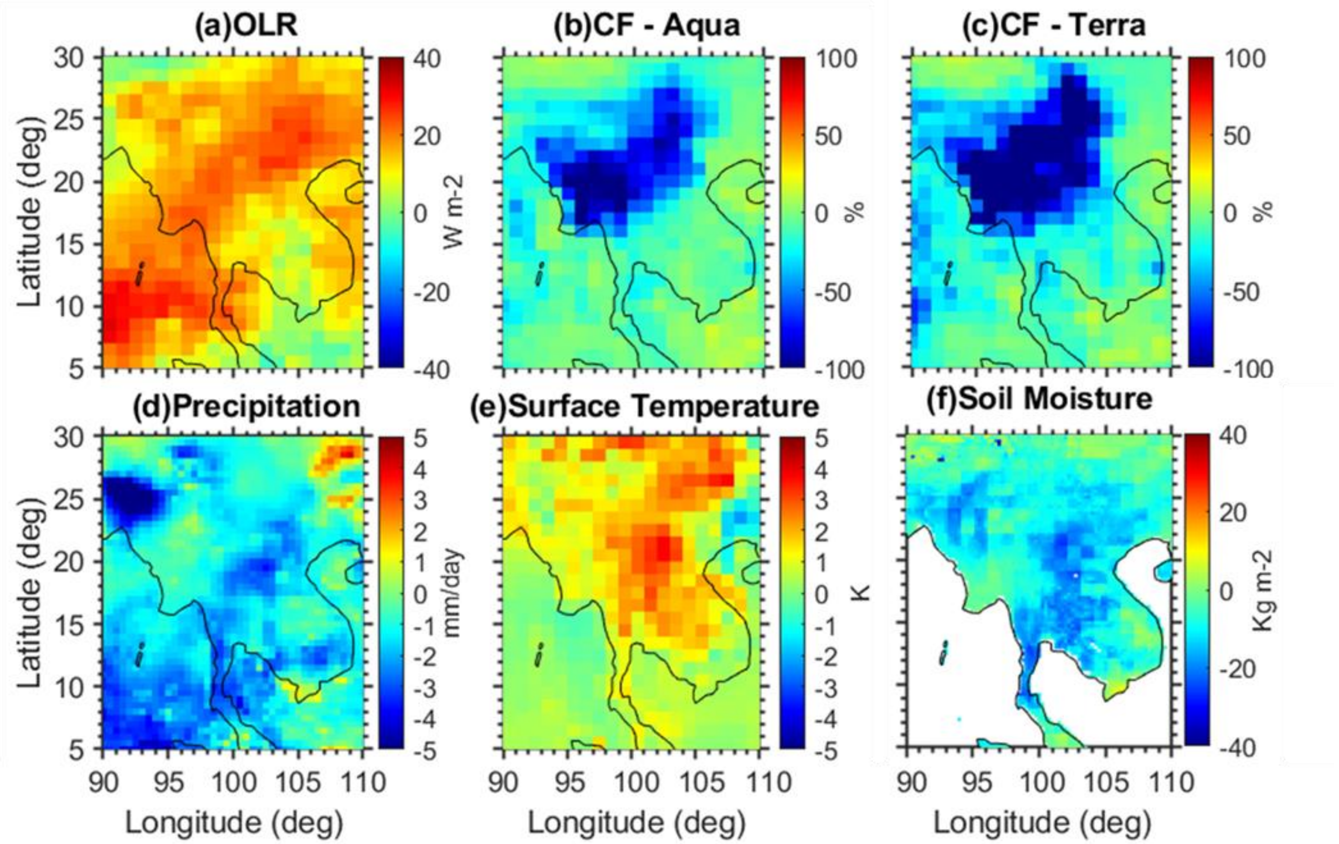
(a)OLR
(b)CF - Aqua
(c)CF - Terra
(d)Precipitation
(e)Surface Temperature
(f)Soil Moisture
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Figure ~~9~~10. Surface and atmosphere conditions in April 2023. April anomalies in 2023 compared to the 2003-2022 climatological period for (a) Outgoing Longwave radiation (OLR), (b) cloud fraction (CF) from Aqua, (c) cloud fraction from Terra, (d) precipitation, (e) Surface Temperature, (f) soil moisture (10 - 40 cm underground). OLR and surface temperatures are obtained from AIRS satellite measurements. CF data from MODIS Aqua and Terra. Soil moisture is obtained from the GLDAS Noah Land Surface Model L4 monthly 0.25 x 0.25 degree V2.1. Precipitation data is obtained from the Global Precipitation Climatology Project (GPCP) Version 3.2.

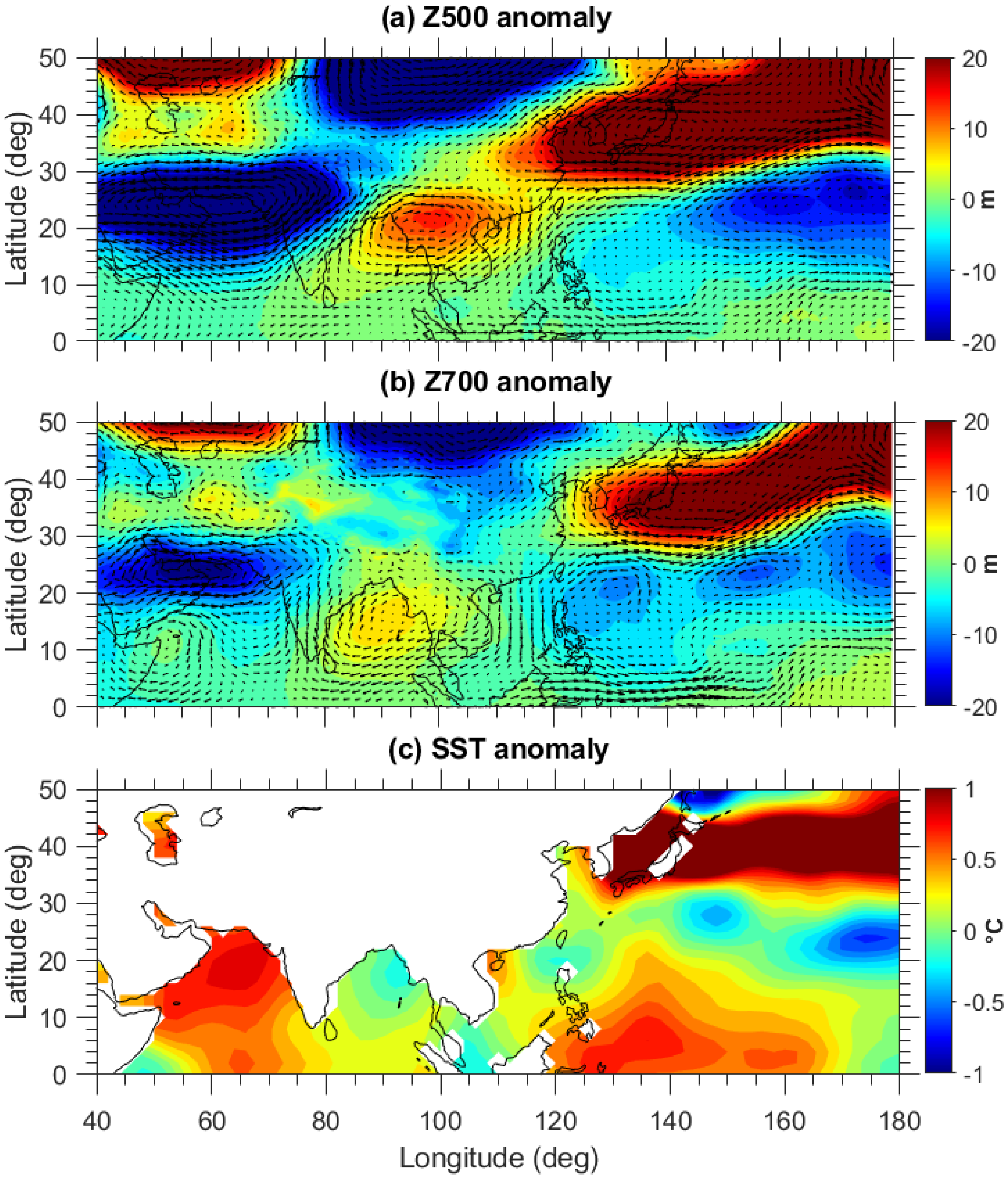


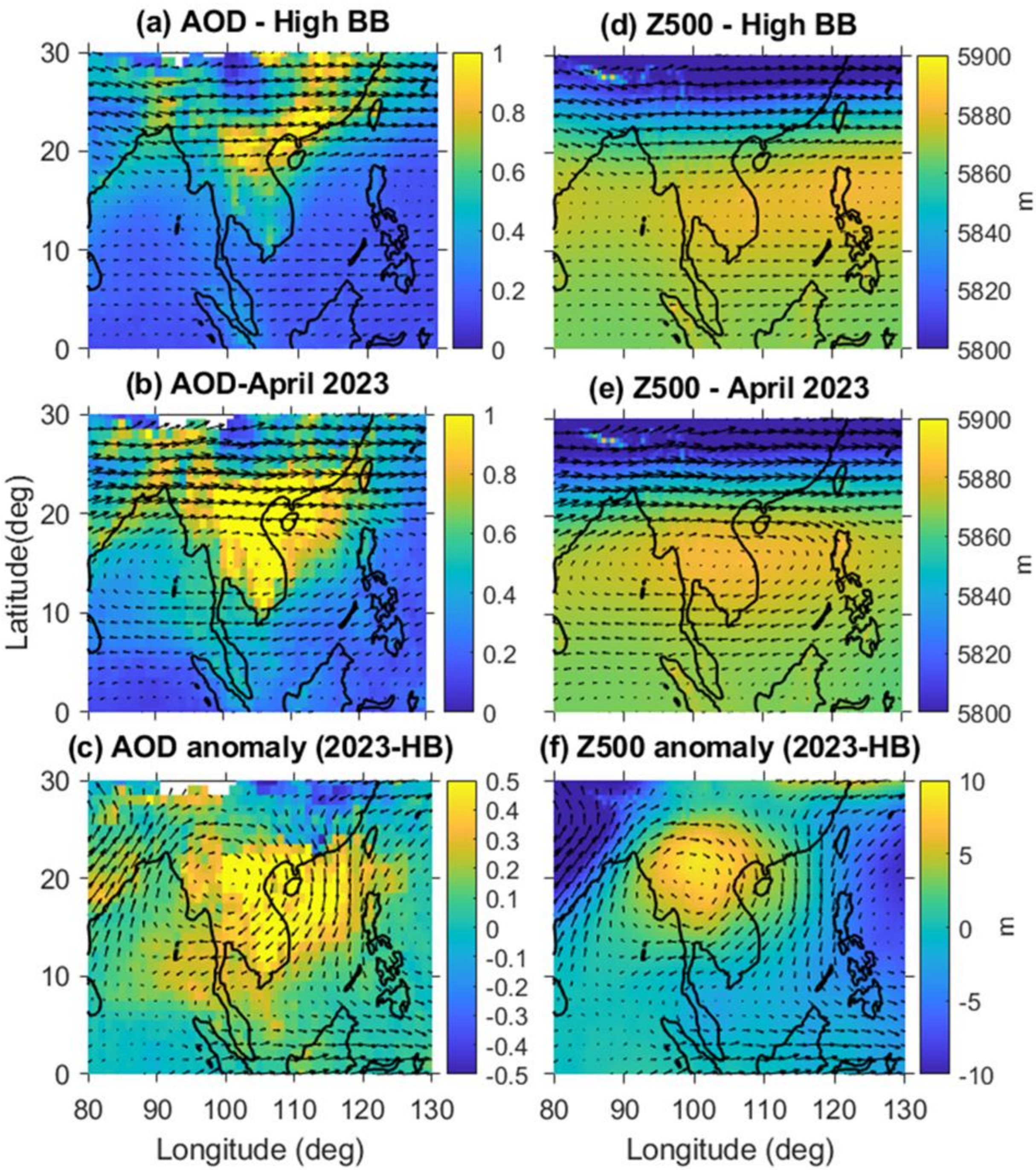
Figure ~~10~~11. Spatial distribution of (a) 500 hPa geopotential height (Z500), (b) 700 hPa geopotential height (Z700), and (c) Sea Surface Temperature (SST) anomalies in April 2023. The anomalies are calculated by subtracting the April 2023 monthly mean from the April climatology for the period 1991 to 2020. The wind anomalies for the respective pressure levels are overlaid in Z500 and Z700 anomalies. The geopotential height and wind data are from the MERRA-2 reanalysis, while SST data are from the NOAA Extended Reconstructed SST V5.

Our analysis focuses on geopotential height and horizontal wind fields at the 700- and 500-hPa levels. The geopotential height fields (Z700 and Z500) in April 2023 show clear departures from the April climatology (1991-2020) (**Figs. ~~S10~~S9–~~11~~ 10** in the Supplement). At 700 hPa, the climatological high-pressure system over the Indian region extended eastward toward PSEA, while at 500 hPa, the western Pacific subtropical anticyclone shifted westward to lie directly over PSEA. Geopotential height anomalies relative to the 1991–2020 mean (**Fig. ~~10a~~11a-b~~–b~~**) reveal a pronounced anti-cyclonic circulation (positive anomalies) centered over northern PSEA (~20°N, 100°E) at 500 hPa. Similar anti-cyclonic anomalies are also evident in the Z700 field over the BoB. At the same time, significant cyclonic anomalies (negative geopotential height anomalies) are observed over the Arabian Sea and the WNP at both levels. These geopotential height anomaly patterns are broadly consistent with the observed sea surface temperature (SST) anomaly distribution. Positive SST anomalies are evident over the Arabian Sea, whereas negative SST anomalies occur over the BoB (**Fig. 11**). Positive SST anomalies are also observed over the WNP warm pool region, where negative geopotential height anomalies are present. Collectively, these patterns suggest a low–high–low (L–H–L)-like wave train extending from the Arabian Sea to the WNP warm pool region. These findings are consistent with those of Liu et al. (2026), who proposed that enhanced convection over the Horn of Africa and Arabian Peninsula (HAAP) generated downstream Rossby wave propagation across South Asia and mainland Southeast Asia, contributing to anomalous upper-level cyclonic circulation over South Asia and anti-cyclonic circulation over the Indochina Peninsula (ICP) and southern China. However, their analysis was primarily based on upper-tropospheric (~300 hPa) circulation fields. Although our analysis focuses on mid-tropospheric circulation anomalies at 700 and 500 hPa, the observed patterns are broadly consistent with a vertically coherent large-scale circulation response during spring 2023. These circulation anomalies, particularly mid-tropospheric anti-cyclone that suppressed convection over PSEA, are consistent with positive OLR anomalies and reduced precipitation (**Fig. ~~9~~10**).

Subsidence associated with the anti-cyclonic circulation promoted clear-sky conditions (**Fig. ~~9~~10**) and surface warming, which, together with severe soil moisture deficits, created favorable conditions for intense ~~biomass burning~~BB across northern Laos. Liu et al. (2026) further showed that upper-tropospheric convergence and dynamical subsidence associated with this wave pattern contributed to persistent heat and drying over the ICP during spring 2023, potentially supporting the lower- and mid-tropospheric anti-cyclonic anomalies identified here. The circulation pattern also altered regional transport pathways. The combined influence of the WNP cyclone, the BoB anticyclone at 700 hPa, and the PSEA anticyclone at 500 hPa modified the background flow over Southeast Asia. Meridional wind anomalies (**Figs. ~~S12b~~S11b–c** in the Supplement) show persistent northerly flow over the SCS, enabling southward transport of smoke from northern PSEA toward the SCS and into the southern BoB. ~~This pathway contrasts with the climatological transport route that typically advects smoke toward Taiwan and the northwestern Pacific.~~ Zonal wind anomalies further indicate weakened mid-latitude westerlies and locally reversed easterlies near Japan and Taiwan associated with a strong anti-cyclonic anomaly (**Figs. ~~S12a~~S11a–b** in the Supplement), suppressing the typical eastward transport of smoke. Consistent with this, AOD observations from the high-altitude mountain background station, namely Lulin Atmospheric Background Station (LABS) obtained through AERONET show no notable enhancement in April 2023 (**Fig. ~~S13a~~ S12** in the Supplement), indicating reduced smoke transport toward the northwestern Pacific. AERONET comparisons show strong correlations with MODIS AOD: 0.83 for Aqua and 0.84 for Terra (**Fig. ~~S14~~ S13** in the Supplement), further supporting the reliability of the satellite observations as shown in the Dongsha data. Overall, the anomalous circulation pattern, characterized by a BoB anticyclone and a WNP cyclone, redirected BB plumes from northern PSEA toward the SCS and southern BoB, producing the exceptional aerosol loading observed in April 2023.

A key question is whether April 2023 ~~represents~~ was an exceptional ~~biomass burning (~~BB~~)~~ year relative to PSEA, or ~~if~~ whether similar conditions have occurred in other high-BB years. High-BB years were identified using standardized fire anomalies derived from April MODIS fire counts following the method of Vadrevu et al. (2019). For this analysis, April fire counts from 2003–2023 were standardized relative to the 2003–2022 climatology over northern PSEA (17–23°N). Years with anomaly values exceeding 0.5 were classified as high-BB years (**Fig. S14**), including 2003, 2006, 2008, 2010, 2014, 2015, 2016, and 2023. Composite analyses of MODIS

AOD, 500 hPa geopotential height (Z500), and wind vectors were conducted to characterize typical aerosol and circulation patterns during high-BB conditions. **Figure 12a–c** presents the spatial distributions of composite AOD for high-BB years, AOD during April 2023, and their anomalies, respectively, while **Fig. 12d–f** shows the corresponding Z500 and wind vector fields. Relative to the high-BB composite, April 2023 exhibited substantially higher AOD across PSEA, the SCS, and the southern BoB, indicating enhanced regional aerosol loading. The Z500 field further showed pronounced positive anomalies over northern PSEA, reflecting a stronger, more spatially coherent anti-cyclonic circulation than under typical high-BB conditions. Correspondingly, wind anomalies revealed enhanced northerly flow over the SCS during 2023, suggesting strengthened meridional aerosol transport. An additional comparison between April 2016 and April 2023 (**Fig. S15** in the supplement) showed similar spatial patterns, including enhanced AOD over southern PSEA. However, the magnitude and spatial extent of the AOD enhancement were greater in 2023. The AOD anomaly between 2023 and 2016 further revealed pronounced increases over the SCS and southern BoB, coinciding with enhanced northerly anomalies. Overall, these results suggest that anomalous circulation conditions in 2023 likely amplified aerosol transport and accumulation beyond those typically associated with high-BB years.



~~High BB years were identified using standardized fire anomalies from MODIS fire counts, with years exceeding 0.5 classified as high BB (**Fig. S9** in the Supplement). Composites of MODIS AOD, 500 hPa geopotential height, and wind vectors were constructed to represent typical circulation and aerosol patterns during high BB periods. Comparison with April 2023 shows notable differences: 2023 featured a stronger, more spatially coherent anti-cyclonic high over PSEA and substantially higher AOD, indicating unusually intense aerosol loading. This suggests that circulation anomalies in 2023 amplified aerosol accumulation and transport beyond typical high BB conditions (**Fig. S15** in the Supplement).~~**Figure 12**. Spatial distribution of MODIS aerosol optical depth (AOD), MERRA-2 500-hPa geopotential height (Z500), and wind vectors during April. (a) Composite AOD for high biomass-burning (BB) years, (b) AOD in 2023, and (c) AOD anomalies between 2023 and the composite high-BB years. Panels (d–f) show the corresponding composites for Z500 and associated wind vectors for (d) high-BB years, (e) 2023, and (f) anomalies between 2023 and the high-BB composite, respectively.

Another question is whether inter-annual variability associated with climate oscillations, such as the El Niño–Southern Oscillation (ENSO), influenced BB activity and circulation in 2023. SST anomalies ~~linked to~~associated with ENSO strongly modulate Indo-Pacific circulation and hydro-~~-~~climate, with El Niño events typically enhancing springtime fires ~~via~~ through drought, reduced precipitation, and suppressed moisture transport (Yin, 2020; Zhu et al., 2021; Zheng et al., 2023). We constructed composites of MODIS AOD and 500-hPa wind vectors for El Niño–ensuing and La Niña–ensuing Aprils during 2003–2022 (**Fig. S16** in the Supplement). The results reveal higher AOD over northern PSEA and coastal South China during El Niño-ensuing Aprils, accompanied by a stronger anti-cyclonic system over PSEA extending from the BoB, consistent with enhanced aerosol accumulation. In contrast, Aprils following La Niña show weaker circulation and lower AOD. April 2023 occurred during the transition from a triple-dip La Niña to a developing El Niño, deviating from typical ENSO-fire patterns. This unusually large-scale background is consistent with Liu et al. (2026), who noted that the extreme spring 2023 heat event over the ICP differed fundamentally from canonical ENSO-linked events, as severe regional warming and subsidence developed despite antecedent La Niña conditions.

Overall, systematic analysis of MODIS fire counts, burned area (BA), HYSPLIT back trajectories, and MERRA-2 large-scale circulation fields, we conclude that the extreme aerosol event in April 2023 was shaped not only by BB activity but also by anomalous large-scale circulation patterns. These findings highlight the combined influence of BB emissions and background meteorological conditions in producing the exceptional smoke event.

~~The anomalous anti-cyclonic and cyclonic circulations over the BoB and western North Pacific in April 2023 are notable (**Fig. 10**), though their detailed dynamics are beyond the scope of this study. Preliminary analysis revealed that SST warming over the western Pacific warm pool and mid-latitude North Pacific, together with cooling over the central-eastern equatorial Pacific, likely induced a Matsuno-Gill-type response, while warming in the Arabian Sea and cooling in the BoB aligned with geopotential height anomalies, promoting drought, intensified BB, and southward~~

~~smoke transport toward the SCS and southern BoB (**Fig. 10c**; Gill, 1980; Zeng and Sun, 2022). Overall, the extreme aerosol event in April 2023 was shaped not only by intense biomass burning but also by anomalous large-scale circulation linked to ocean–atmosphere variability, highlighting the combined role of local and climate-scale drivers in exceptional smoke events.~~

4. Summary and Conclusions

In April 2023, record-breaking aerosol loading was observed over the South China Sea (SCS). By integrating multiple satellite measurements (MODIS, MOPITT, AIRS, and CALIPSO), the MERRA-2 reanalysis, and NOAA HYSPLIT back-trajectory analysis, we systematically investigated the sources, transport pathways, and large-scale dynamical conditions associated with this extreme event. MODIS observations indicate an approximately 150% increase in aerosol optical depth (AOD), relative to the long-term mean (2003-2022). This enhancement was accompanied by pronounced increases in carbon monoxide (CO) in the mid- to lower troposphere (700–500 hPa) as observed by MOPITT and AIRS, consistent with long-range transport of combustion-related pollution. The simultaneous increases in AOD and CO over the remote ocean support the influence of transported biomass-burning (BB) emissions from surrounding source regions. Analysis of MODIS fire counts and burned area revealed a significant enhancement in BB activity over northern PSEA and negligible BB activity over South China and the Maritime Continent. Furthermore, NOAA HYSPLIT back trajectories indicate that most air masses over the SCS originate from the northern PSEA. Together, fire counts, BA, and HYSPLIT trajectory analysis suggest that enhanced BB activity over northern PSEA likely contributed to the exceptional aerosol loading over the SCS in April 2023. Meteorological conditions characterized by suppressed convection, reduced precipitation, elevated surface temperatures, and decreased soil moisture likely promoted increased BB activity. These conditions were associated with a pronounced high-pressure (anti-cyclonic) anomaly over PSEA, as indicated by positive geopotential height anomalies at 500 hPa (**Figure 11a**).

Large-scale circulation analyses further reveal a free-tropospheric pattern featuring an eastward-shifted Bay of Bengal (BoB) anticyclone and a western North Pacific (WNP) cyclone (**Figure 11b**). These circulation features significantly modified regional flow over the SCS by reversing the prevailing meridional winds from southerly to northerly anomalies. In addition, the coexistence of a subtropical anticyclone over the northwestern Pacific and the WNP anomaly generated easterly wind anomalies around Taiwan. Together, these anomalous circulation patterns altered BB smoke transport pathways and facilitated aerosol accumulation over the SCS in April 2023. A schematic summary of the physical mechanisms is provided in **Figure 13**.

~~In April 2023, we observed an unprecedented increase in aerosol loading over the South China Sea (SCS), which had not been recorded during the two-decade MODIS satellite measurements period from 2003 to 2023. Satellite observations revealed ~150% increase in AOD (MODIS), approximately four times higher than the long-term mean, alongside significant enhancements in CO (MOPITT and AIRS) at the 700 and 500 hPa levels. This study investigates the causes, physical mechanisms, and atmospheric dynamics underlying this extraordinary aerosol event. Analyses of satellite data (MODIS, MOPITT, AIRS, and CALIPSO), NOAA HYSPLIT back trajectories, and MERRA-2 reanalysis products indicate that intense biomass-burning activity over northern Peninsular Southeast Asia was the primary driver of the record-breaking aerosol loading over the SCS in April 2023. Our results further reveal that this BB activity was amplified by exceptional meteorological conditions associated with unusually large-scale dynamical circulation patterns. A dominant anti-cyclonic anomaly over PSEA suppressed convection, leading to subsidence, elevated surface temperatures, and drought conditions that fueled fires, particularly in Laos and Myanmar, which contributed most to the regional BB emissions. A schematic summarizing these drivers and mechanisms is presented in **Figure 11**.~~

~~Climatologically, two anti-cyclones are typically situated over the WNP and the Indian Ocean, producing predominantly southwesterly and southerly winds over the SCS. These southerly winds generally transport BB smoke from PSEA to downwind regions such as Taiwan and the WNP. In April 2023, however, the WNP anticyclone transformed into a cyclone, while the Indian Ocean anticyclone shifted eastward over the BoB near PSEA. The resulting northerly flow over the SCS, combined with easterly anomalies near Taiwan, blocked transport toward the northwestern Pacific and redirected smoke from PSEA to the SCS and BoB. This circulation shift, driven by the combined WNP cyclone and BoB anticyclone, highlights the critical role of large-scale atmospheric dynamics in determining BB smoke pathways. These findings improve understanding of transboundary pollution and can inform regional monitoring efforts over PSEA.~~

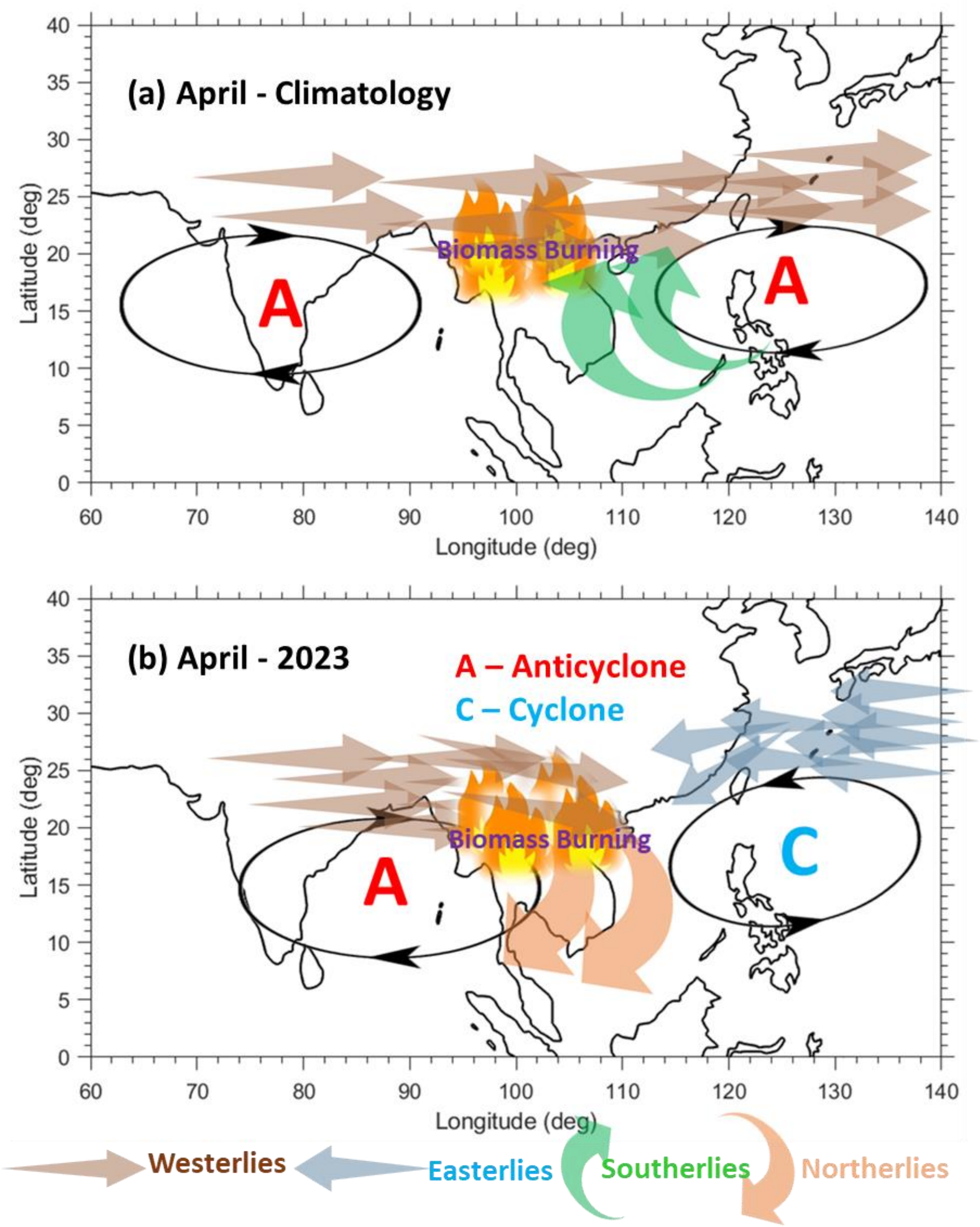


Figure 13. Schematic diagram illustrating the physical mechanisms responsible for the record-breaking aerosol loading over the South China Sea (SCS) in April 2023. The diagram summarizes the anomalous circulation and transport pathways governing biomass-burning (BB) smoke distribution. Here, 'A' denotes an anticyclone anomaly and 'C' denotes a cyclone anomaly. Horizontal arrows represent subtropical free-tropospheric westerlies and easterlies, while green and brown arrows indicate southerly and northerly winds, respectively. Top panel: The climatological conditions in April (1991-2020), characterized by the Bay of Bengal (BoB) and

western Pacific anticyclones, as well as prevailing southwesterly and southerly winds over the SCS that favor typical smoke transport toward Taiwan and the western North Pacific (WNP). Bottom panel: April 2023 conditions, featuring a WNP cyclone, and an eastward-shifted BoB anticyclone. These anomalies generated persistent northerly winds over the SCS and redirected BB plumes toward the SCS and the southern BoB. Strengthened easterlies around Taiwan further inhibited eastward transport, resulting in exceptional aerosol accumulation over the SCS in April 2023.

While this study focuses on the sources, transport pathways, and dynamical drivers of the record aerosol event, its broader impacts remain to be quantified. In particular, aerosol–radiation interactions associated with elevated AOD may significantly affect regional radiative forcing, atmospheric heating profiles, and the hydrological cycle. Future work will quantify the radiative impacts of these extreme aerosol concentrations and assess their implications for regional climate. Additionally, elevated BB emissions of CO and other precursors may enhance tropospheric ozone formation, a topic that warrants further investigation. Notably, mainland Southeast Asia experienced an extreme heatwave in April 2023, with record-high temperatures (Zachariah et al., 2024; Lyu et al., 2024). While previous studies attribute this event to anthropogenic climate change, strengthened high-pressure systems, and land–atmosphere coupling, our results suggest that BB aerosols and associated greenhouse gas emissions may also have contributed to the regional heat anomaly. Key outstanding questions include how BB-derived greenhouse gases influence regional radiative trapping and how elevated aerosol concentrations modify surface radiation, cloud processes, and precipitation. Addressing these questions is essential for understanding compound climate extremes in PSEA and surrounding regions. In conclusion, this study highlights the combined role of BB emissions and large-scale dynamical conditions in shaping smoke transport over Southeast Asia, providing deeper insights into the mechanisms governing extreme regional aerosol events.

~~While the present study focuses on the record-breaking aerosol loading, its sources, transport pathways, and dynamical drivers, the broader impacts of this extreme event remain largely unexplored. In particular, aerosol-radiation interactions associated with such unusually high AOD could substantially affect regional energy balance, atmospheric heating profiles, and the hydrological cycle over adjacent regions. Future research will aim to quantify the radiative forcing of these extreme aerosol concentrations and assess their broader atmospheric impacts. Additionally, the exceptional increase in CO and other BB emissions may have strong implications for tropospheric ozone formation, which will also be investigated. Interestingly, PSEA experienced an extreme heatwave in April 2023, with record-high temperatures (Zachariah et al.,~~

~~2024; Lyu et al., 2024). Previous studies have attributed this heatwave to climate change (Zachariah et al., 2024), as well as strengthened high-pressure systems, moisture deficits, and strong land–atmosphere coupling (Lyu et al., 2024). Our results suggest a plausible contribution from biomass-burning aerosols and associated greenhouse gases to this heatwave. Key questions for future investigation include: How do greenhouse gases released by record-breaking BB activity influence regional heat trapping? What is the impact of elevated aerosol concentrations on surface radiation, cloud formation, and precipitation patterns? Addressing these questions will be critical to understanding the exceptional conditions in PSEA and surrounding regions, including the combined effects of BB aerosols and greenhouse gas emissions on regional climate extremes.~~

Code and data availability

This study exclusively utilized publicly available datasets, and no new observational data were generated. All data required to evaluate the conclusions of this study are included in the paper and/or the Supplementary Information. Most figures presented in this study were generated using MATLAB R2020a. All datasets used in the study are freely available for download from their respective websites. ~~**Data availability**~~

MODIS data available from https://modis.gsfc.nasa.gov/data/dataprod/mod08.php. The AIRS and MOPITT CO data can be downloaded from https://disc.gsfc.nasa.gov/datasets/AIRS3STM_7.0 (AIRS project, 2019) and https://asdc.larc.nasa.gov/project/MOPITT/MOP02J_8 (NASA, 2023a). MERRA-2 data are available online through the NASA Goddard Earth Sciences Data Information Services Center (GES DISC; https://disc.gsfc.nasa.gov; NASA, 2023b). The MODIS fire and burned area products can be downloaded from https://firms.modaps.eosdis.nasa.gov/active_fire/ (NASA, 2023c). Daily CALIPSO vertical distribution images of various aerosol types were obtained from https://www-calipso.larc.nasa.gov/products. The NOAA HYSPLIT back trajectories are retrieved from https://www.ready.noaa.gov/HYSPLIT.php. /

Author Contributions

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Competing interests

The authors declare no competing interests.

Acknowledgements

We acknowledge the National Science and Technology Council of Taiwan for supporting the research under grant 114-2111-M-008-030. The authors thank NASA and NOAA for providing MOPITT, MODIS, CALIPSO and AIRS satellite data. We thank NASA's Global Monitoring and Assimilation Office (GMAO) for providing the Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) data.

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