Changing pattern of springtime biomass burning over Peninsular Southeast Asia (PSEA) in the recent decade

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Abstract:

The focus of this study is to present the recent changes in BB activity over PSEA by considering decadal changes, 5-year ensemble mean analysis, and long-term trends from twenty years (2001-2020) of Moderate Resolution Imaging Spectroradiometer (MODIS) active fire counts. The results revealed that overall springtime BB activity significantly decreased over the past decade (2011-2020) compared to the previous decade (2001-2010). Surprisingly, the individual monthly analysis revealed that BB activity over PSEA decreased substantially in March, whereas in April it increased significantly over the past decade (2011 to 2020). Further, 5-year ensemble means revealed, BB activity over northern PSEA in March sharply increased during 2006–2010, and moderately increased in 2011-2015 followed by a profound decrease in 2016-2020. Whereas, in April, the BB activity showed a pronounced increase in the 2011-2015 and 2016-2020 periods over northern Laos compared to the rest of PSEA. The observed changes in the BB activity are strongly reflected in the BB aerosols and gases. The MERRA-2 reanalysis total surface mass concentration-$PM_{2.5}$, BB black carbon, and MOPITT satellite observed surface carbon monoxide (CO) showed a significant decrease over northern PSEA in March and a strong enhancement was evident over northern Laos in April. Finally, the trend analysis in BB activity shows a significant increasing trend over Laos and Cambodia, and a decreasing trend was found rest of the PSEA. These findings have important implications for future BB management strategies and regional climate in the PSEA region.

Keywords: Biomass burning; Peninsular Southeast Asia; MODIS active fires; Air Pollution

1. Introduction

Air pollution is the world's most pressing environmental health crisis and a major contributor to the global burden of disease (Murray et al., 2020). It is responsible for more than 6.5 million deaths annually, the bulk of which 70% occurs in the Asia-Pacific region. In addition to health risks, air pollution poses threats to local economies, food and water security, and the climate system. (United Nations Environment Programme (UNEP), 2021). Open biomass burning (BB, including forest, grassland, peat fires, and agricultural waste burning) is one of the major sources of air pollutants and represents about 30%, 10%, 15%, and 40% of present-day global emissions of carbon monoxide (CO), nitrogen oxides (NO_x), black carbon (BC), and organic carbon (OC), respectively (van Marle et al., 2017; Hoesly et al., 2018; IPCC, 2021). Biomass burning emissions can influence air quality, radiation, global and regional climate, and ecosystems through aerosol radiative effects.

The Peninsular Southeast Asia (PSEA, including Myanmar, Thailand, Vietnam, Laos, and Cambodia), is located upstream of the East Asian summer monsoon circulation and is recognized as one of the key regions affecting the monsoon system and climate (Yang et al.,2021). PSEA is one of the hotspot regions with the most intensive biomass-burning activities in the world (Reid et al., 2013; Lin et al., 2013; Lee et al., 2016) and a major contributor of carbon emissions, and atmospheric aerosols in springtime (March-April). The open BB occurs almost every year during springtime in the PSEA due to slash-and-burn agricultural activities (Reid et al., 2013; Lin et al., 2013; Tsay et al., 2016; Huang et al., 2016; 2020; Jainontee et al., 2023) and emits a substantial amount of aerosols and trace gases into the atmosphere (Ou-Yang et al., 2022; Nguyen et al., 2022). The BB emissions are responsible for the peaks in aerosol optical depth (AOD), carbon monoxide, and black carbon during springtime over PSEA (Pani et al., 2018). The BB pollution from PSEA is often transported from its sources to the East China Sea (ECS), Taiwan, and the western North Pacific within a few days by the subtropical southwesterly jet and impacts the downwind air quality, environment, and regional climate (Lin et al., 2009; Lin et al., 2013; Chuang et al., 2015; Huang et al., 2020; Ou-Yang et al., 2022; Babu et al., 2022).

The effects of BB aerosols over the PSEA on regional air quality (Lin et al., 2009; Lin et al., 2013; Hsiao et al., 2016; Lin et al., 2017; Yang et al., 2022) and climate (Lee et al., 2016; Pani et al., 2018; Ding et al., 2021; Wang et al., 2021; Li et al., 2022) have been widely investigated based on observations and numerical modeling studies. However, the long-term spatiotemporal changes and recent trends in the BB activity over PSEA were still limited and not fully explored. For example, Huang et al. (2016) reported inter-annual variation of springtime BB in PSEA and its correlation with air quality at Mt. Lulin in Taiwan using long-term (2005–2015) satellite and global reanalysis data. They found that more (less) springtime BB activity occurred in the years 2007 and 2010 (2005, 2008, 2011, and 2015), respectively. By using 14 years (2003-2016) of MODIS data, Vadrevu et al. (2019) reported trends in BB activity in South and Southeast Asian countries and found a statistically-significant increasing trend in BB activity over Cambodia and Vietnam during the study period. Similarly, Yin et al. (2019) reported detailed seasonal patterns and tempo-spatial distributions of the different BB types in PSEA by using 16 years (2001-2016) of MODIS data. A recent Intergovernmental Panel on Climate Change (IPCC) report indicates that weather conducive to fires has become more frequent in some regions and will continue to increase with higher levels of global warming (IPCC, 2021). It is necessary to deepen the research and understanding of the recent changes in BB activity over PSEA. By considering the previously reported studies, this study for the first time investigates the detailed climatological pattern, decadal and recent changing patterns, and long-term trends in the BB activity in PSEA over the past 20 years (2001–2020).

2. Data and Methodology

2.1 MODIS active fire products

We used the latest collection of 6.1 Moderate Resolution Imaging Spectroradiometer (MODIS) active fire products as a proxy for biomass burning activity from January 2001 to December 2020 in the present study. The MODIS on board the Terra (known as Earth Observation Satellite (EOS) AM-1) and Aqua (known as EOS PM-1) satellites is a key instrument for the identification of fire activities over the globe (Giglio et al., 2018). MODIS provides information on the geographic location of the fire spot, fire radiative power (FRP), and fire count detection confidence. MODIS is one of the most important and longest available data sources of active fire hotspots, providing the global mapping of fire locations and burned areas. More details and descriptions of the MODIS fire detection algorithm can be found in Giglio et al. (2018). Each country's Standard Processing MODIS active fire/hotspot is available online (https://firms.modaps.eosdis.nasa.gov; last access: March 27, 2023).

2.2 MERRA-2 Reanalysis products

The Modern-Era Retrospective Analysis for Research and Applications, version 2 (MERRA-2) is NASA's latest reanalysis dataset and has provided data since 1980; it uses the Goddard Earth Observing System, version 5 (GEOS-5) Earth system model (Gelaro et al., 2017). It includes the assimilation of bias-corrected AOD from MODIS and Advanced Very High-Resolution Radiometer (AVHRR), non-bias-corrected AOD from the space-based Multiangle Imaging SpectroRadiometer (MISR), and ground-measured AOD from Aerosol Robotic Network (AERONET) stations (Buchard et al., 2017). We mainly utilized total surface mass concentration-$PM_{2.5}$, black carbon surface mass concentration, and biomass burning black carbon data, respectively.

2.3 MOPITT carbon monoxide measurements

The surface level carbon monoxide data obtained from the Measurement of Pollution in the Troposphere (MOPITT, version 8) instrument (Deeter et al., 2019) were also utilized. MOPITT is a multi-channel Thermal InfraRed (TIR) and Near InfraRed (NIR) instrument operating onboard the sun-synchronous polar-orbiting NASA Terra satellite. MOPITT V8 CO products, consisting of a CO profile at ten pressure levels, have been validated; more details about the retrieval algorithm, validation, and uncertainties of MOPITT CO can be found in Deeter et al. (2019).

Apart from the above-mentioned data, we also used the Global Precipitation Climatology Project (GPCP) Version 3.2 Satellite-Gauge (SG) Combined Precipitation Data Set (Huffman et al., 2022) and the Global Land Data Assimilation System (GLDAS) soil moisture data (Rodell et al. 2004).

2.4 Methodology

Data confidence in the MODIS fire product is specified by a numeric scale of 0 to 100%. The active fire hotspots with confidence >30% were only considered in the present analysis. For the analysis of spatial and temporal variation of BB activity, the daily active fire counts within a spatial grid of 0.5°×0.5° were aggregated and subsequently averaged for each month over the study period. Before estimating the trends in BB activity, we obtained the percentage change in BB activity relative to the respective long-term mean using Eq. 1:

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

where x_i represents the monthly (annual) mean of the individual month (year), and $\bar{x}$ is the corresponding monthly (year) long-term mean calculated using the data from 2001 to 2020. Finally, the long-term trend in BB activity throughout the observational period has been estimated using the least-square linear regression trend analysis, and the significance of the trend is tested using Mann-Kendall tests ($p < 0.05$) (Mann, 1945; Kendall, 1975).

3. Results and Discussions

3.1 Long-term mean structure of springtime Biomass Burning over Peninsular Southeast Asia

The long-term MODIS active fire counts were utilized as a proxy for the BB activity over the PSEA. **Figure 1a** shows the long-term mean annual cycle of the BB activity over PSEA obtained from MODIS active fire counts averaged between January 2001 to December 2020. Similarly, **Figure 1b** shows the long-term mean spatial distribution of BB activity from February through April over PSEA. It is evident from **Figure 1a** that BB activity increases in January through April, followed by a general decline from May through November. The maximum BB activity occurred during the springtime and the minimum BB was observed during the summer monsoon period. The BB activity in summer monsoon months is naturally suppressed due to the presence of monsoonal rains over the PSEA region. Overall, BB season over the PSEA region extends from January to April during which more than 70% of total fires are recorded with the peak during March. Further, the spatial distribution of BB activity from February to April exhibits quite interesting features over PSEA. The peak BB activity progresses northward in time, and in February, it was mostly concentrated over Cambodia. Then the BB activity progresses through Thailand, Laos, and Myanmar, peaking in March and April. It is evident from **Figure 1b** that the BB activity is higher over northern PSEA than over southern PSEA in both March and April. Overall, the greatest springtime BB activity occurs in the northern regions of Laos, Cambodia, and Thailand, eastern and western Myanmar, and lower BB activity in the central regions of Myanmar, Thailand, and northern Vietnam. The observed long-term mean structure of the BB activity from the present study is in agreement with the previously reported studies (Vadrevu et al., 2015, 2019;

Huang et al., 2020). In the following sections, we mainly focused on BB activity changes and their impacts on air quality, and emissions during March and April months only.

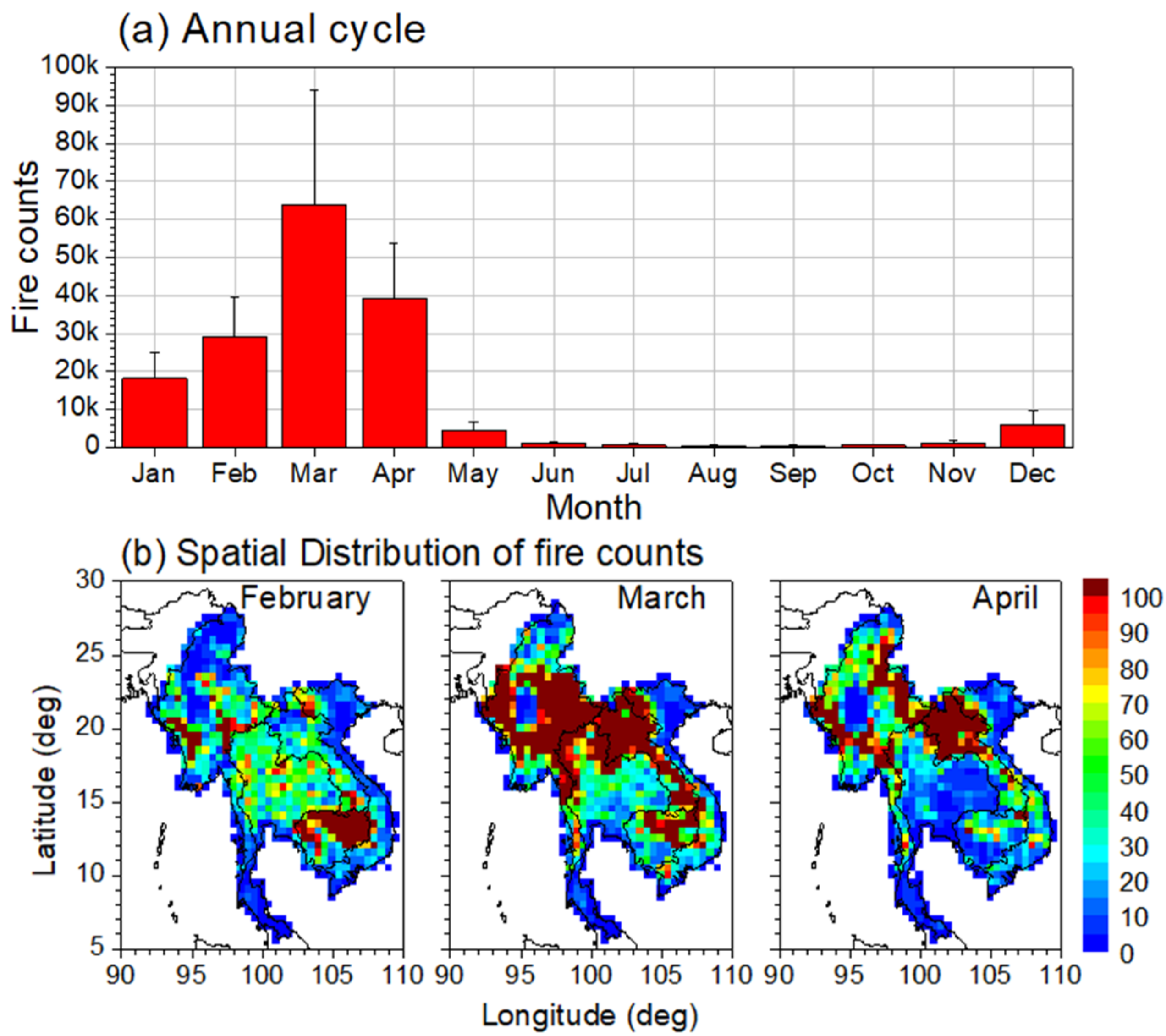

Figure 1. (a) Long-term monthly mean and (b) the spatial distribution of total fire counts in February, March, and April months over peninsular Southeast Asia (PSEA) obtained from MODIS active fire counts between 2001 to 2020. Vertical error bars shown in subplot (a) indicate ±1σ from the monthly mean.

3.2 Changing Pattern in Springtime Biomass Burning in Recent Decade

The spatial and temporal distribution of BB varies in the tropical region according to forest cover and crop residue burning (van der Werf et al. 2017). The long-term MODIS active fire products allow producing dense and historical time series of BB activity that can be used to assess the long-term changes in the BB activity over PSEA. To explore the spatiotemporal changes in BB activity in PSEA during the past two decades, first, we divided the study period into two periods (Decade1: 2001–2010, Decade2: 2011–2020), respectively.

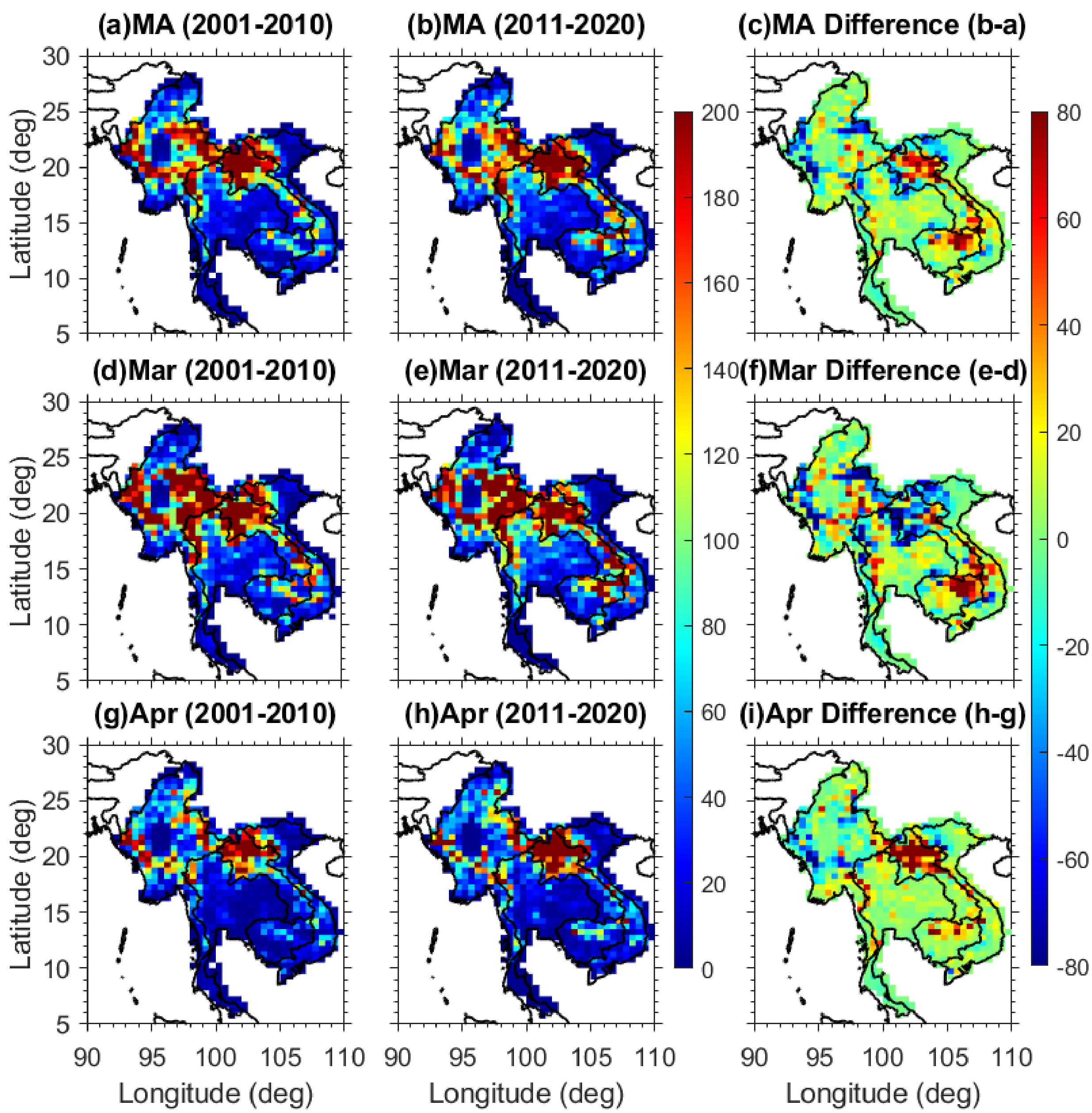

Figure 2. Decadal changes in biomass burning activity over PSEA in springtime (mean of March and April), March and April months. To generate this figure, we compared the recent decade 2011-2020 active fire counts with the previous decade 2001-2010 (difference of (2011-2020) - (2001-2010)).

The analysis was carried out for the entire springtime (mean of March and April; hereafter, MA mean) and individual March and April months, respectively. **Figures 2a-c** show the mean decadal pattern of the BB activity and the difference between Decade2 and Decade1in MA mean over PSEA. Similarly, **Figures 2d-f** and **Figures 2g-i** show the individual months of March and April. Significant enhancement (decrease) of springtime BB activity was noticed in Decade 2 compared to Decade 1 over Cambodia and Laos (Myanmar and northern Thailand) (**Fig. 2c**). Individual monthly analysis revealed distinct results between March and April in Decade 2. Comparing **Figures 2d-f** and **Figures 2g-i**, we can see that the changes in the BB activity in the recent decade were not similar in March and April. It is very clear from **Figure 2f** that during March month, the BB activity significantly decreased over most of the PSEA region except for northeastern Cambodia and southern Laos where it shows significantly increasing BB activity in Decade 2. Very interestingly, the difference between Decade2 and Decade1 BB activity in April clearly shows pronounced increasing BB activity, particularly in northern parts of Laos (**Fig. 2i**). This discrepancy suggests that the BB activity was higher in April compared to March over north PSEA during the recent decade and also increased over northeastern PSEA compared to the northwestern PSEA. This is strongly indicating the shifting of the peak BB activity over PSEA in the recent decade (2011-2020).

To see more clearly the changing pattern of BB activity in recent periods, we further investigated the BB activity by considering the 5-year ensemble mean anomaly over PSEA. To quantify the recent changes in BB activity, the 20 years of MODIS active fire data were divided into four sub-periods: 2001–2005, 2006–2010, 2011-2015, and 2016–2020. Then we obtained the fire anomalies for four sub-periods based on the background long-term mean (2001-2020) of MODIS active fires. **Figure 3a-c** shows the observed springtime (MA mean) 5-year ensemble mean active fire counts anomalies for the 2006–2010, 2011-2015, and 2016–2020 periods**.** Similarly, **Figure 3d-f** (**Fig. 3g-i**) shows the observed 5-year ensemble mean active fire counts anomalies in March (April) for the 2006–2010, 2011-2015, and 2016–2020 periods (figures for the 2001-2005 period were not shown). Quite opposite patterns were evident between 2006-2010 and 2016-2020 for the springtime BB activity (**Fig. 3a-c**). Substantial enhancement of BB activity was evident in the 2006-2010 period whereas, a significant lowering of BB activity was evident during the 2016-2020 period over the north PSEA. The BB activity changes were quite distinct in March and April over PSEA (**Fig. 3d-i**). During March, the BB activity significantly increased over northern PSEA during 2006-2010 and slightly enhanced between 2011 to 2015, and a pronounced decline was found during the 2016-2020 period. However, there was a significant increase in BB activity in the recent two periods (2011-2015 and 2016-2020) over south Laos and northeastern Cambodia (longitude: 105–107^{o}E latitude: 14–18^{o}N) during March.

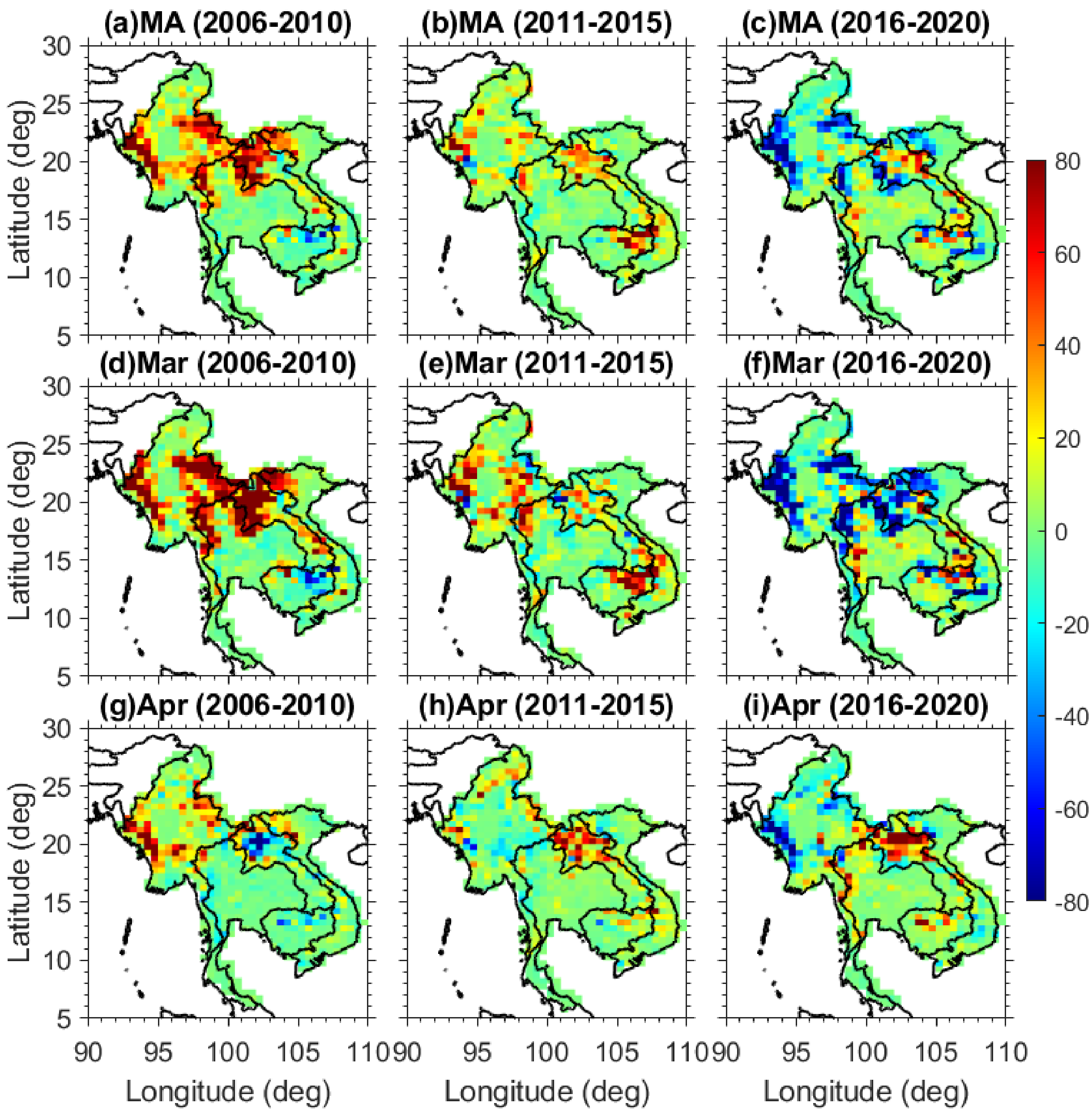

Figure 3. Observed MODIS active fire count anomalies compared to the long-term mean (2001-2020) in (a) 2006–2010, (b) 2011–2015, and (c) 2016–2020 for springtime (mean of March and April). The subplots d-f and g-i are the same as subplots a-c, but for the individual months of March and April, respectively.

In contrast to March, quite interesting changes were observed in BB activity during April in recent periods over PSEA. For example, Myanmar shows increased BB activity during 2006-2010, whereas it shows significantly decreasing BB activity during the recent 2016-2020 period. Similarly, northern Laos exhibited lowered BB activity during the 2006-2010 period. However, significant enhancement of BB activity was evident over northern Laos (longitude: 100–105^{o}E latitude: 18–22^{o}N) in recent two periods (2011-2015 and 2016-2020) compared to the remaining regions in the PSEA. In conclusion, the dipole pattern of increasing (decreasing) BB activity over southern PSEA (northern PSEA) during March and increasing (decreasing) BB activity over northeastern PSEA, particularly Laos (northwestern PSEA) during April was noticed in recent two periods (2011-2015 and 2016-2020), respectively. Overall, it is clear from **Figures 2** and **3** that compared to the remaining regions in the PSEA, Laos, and Cambodia become hotspot regions for peak BB activity in the recent decade. These changes in the BB activity in the recent period may affect local air quality, carbon emissions, and regional climate. It may be worthwhile to investigate further how these unusual changes in BB activity reflect on the distribution of BB aerosols and carbon gases over the PSEA during recent periods. Hence, we further examined the total surface mass concentration-$PM_{2.5}$, BB-black carbon, and carbon monoxide changes that are associated with the change of BB activity in recent periods over PSEA. The detailed results are further discussed in the following sections, respectively.

3.3 Impact of Changing BB Pattern on BB Aerosols and Carbon Emissions

It is well known that BB emissions are major sources of aerosols, greenhouse gases, and particulate matter over PSEA during the respective peak BB season. For example, it is reported that the contribution of non-BB AOD was usually lower than that of BB AOD during the springtime at Chiang Mai Met Station (18.77^{o}N, 98.97^{o}E, 312 m a.s.l) (Pan et al., 2020) and at Chiang Mai University (CMU; 18.795°N, 98.957°E, 373 m a.s.l.) (Pani et al., 2018) Thailand in northern PSEA. Recently, Thao et al. (2022) found that open BB was the largest emission source in PSEA, contributing 57% to the $PM_{2.5}$ concentrations during the peak BB period in March 2012. For the same period (March 2012), Thao et al. (2022) estimated open BB emission contributes 70% to $PM_{2.5}$ concentrations in Laos, followed by Myanmar (69%), Cambodia (54%), Thailand (47%), and Vietnam (31%). Even some studies based on simulations found that BB aerosols accounted for up to 90 % of the near-surface $PM_{2.5}$, BC, and OC concentrations over the BB source regions of north PSEA (Li et al., 2022). Overall, it is clear that BB activity is a major source of air pollutants, particulate matter, carbon emissions, and carbonaceous aerosols over PSEA during springtime.

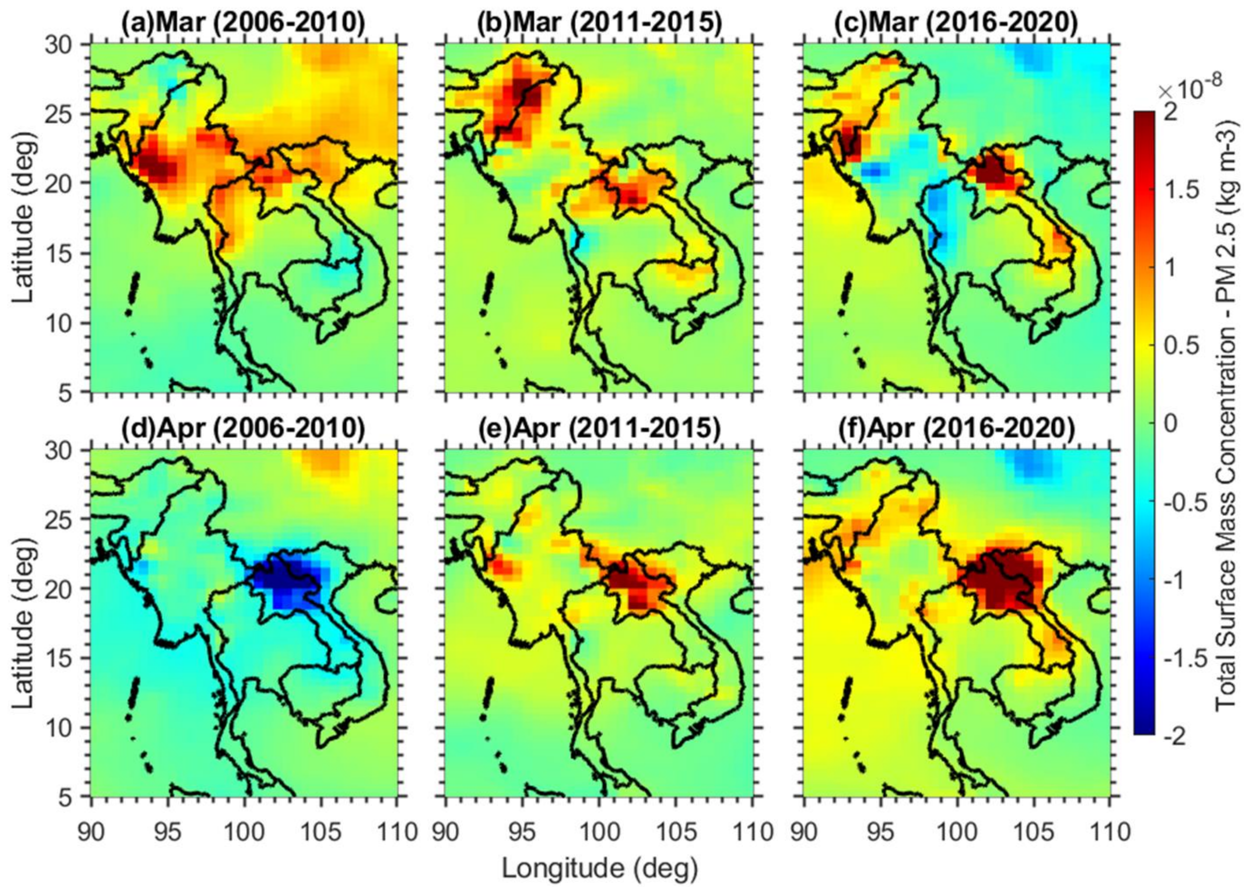

Figure 4. MERRA-2 reanalysis measured total surface mass concentration-PM 2.5 anomalies compared to the long-term mean (2001-2020) in (a) 2006–2010, (b) 2011–2015, and (c) 2016–2020 for March month. The subplots d-f are the same as subplots a-c, but for the month of April, respectively.

We analyzed MERRA-2 reanalysis total surface mass concentration-$PM_{2.5}$, BB black carbon, and MOPITT satellite observed surface carbon monoxide (CO) data from 2001-2020 during springtime to investigate whether similar patterns exist relative to the recent unusual changing pattern in BB activity. A similar 5-year ensemble mean analysis was applied to each BB aerosol ($PM_{2.5,}$ and black carbon) and CO, as shown in **Fig. 3**. The 5-year ensemble mean anomaly compared to the background long-term mean (2001-2020) in the MERRA-2 measured total surface mass concentration- $PM_{2.5}$ and BB black carbon are shown in **Figures 4-5**, respectively. Similarly, the surface CO anomalies obtained from MOPITT data are shown in **Figure 6**. In 2006–2010 during March, the $PM_{2.5}$ concentrations, BC, and surface CO in northern parts of PSEA increased substantially. Whereas, in 2016-2020, the opposite pattern was noticed as observed in the BB activity shown in **Figure 3**, respectively. Interestingly, during April significant positive anomalies in the elevated BC (CO) and higher $PM_{2.5}$ are observed over northern Laos in recent two periods (2011-2015 and 201l-2020) and lowered in 2006-2010, coinciding with the BB anomalies seen in **Fig. 3**. The rapid increase in BB activity in April over northern Laos might be one of the possible causes of enhanced aerosol loading over this region. The observed increased and decreased $PM_{2.5}$, BC, and CO over PSEA in recent decade, strongly supports the observed changes in the BB activity over the PSEA. Overall, the substantial changes in the BB activity and BB aerosols changes show good agreement over PSEA. Overall, it is clear from the present study that there are significant changes in the BB activity over PSEA in the recent decade and Laos become one of the major hotspot regions for the peak BB activity and BB emissions in the recent decade.

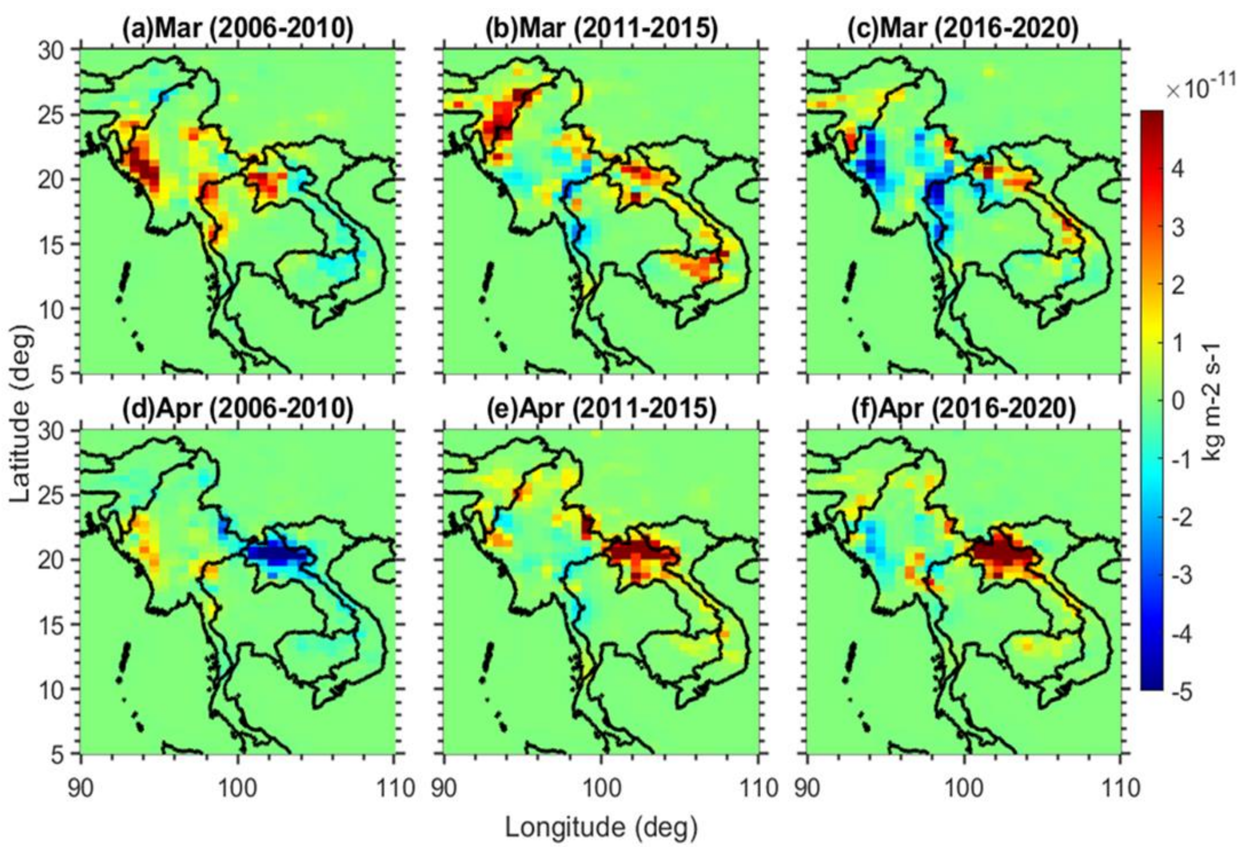

Figure 5. MERRA-2 biomass burning black carbon anomalies compared to the long-term mean (2001-2020) in (a) 2006–2010, (b) 2011–2015, and (c) 2016–2020 for March month. The subplots d-f are the same as subplots a-c, but for the month of April, respectively.

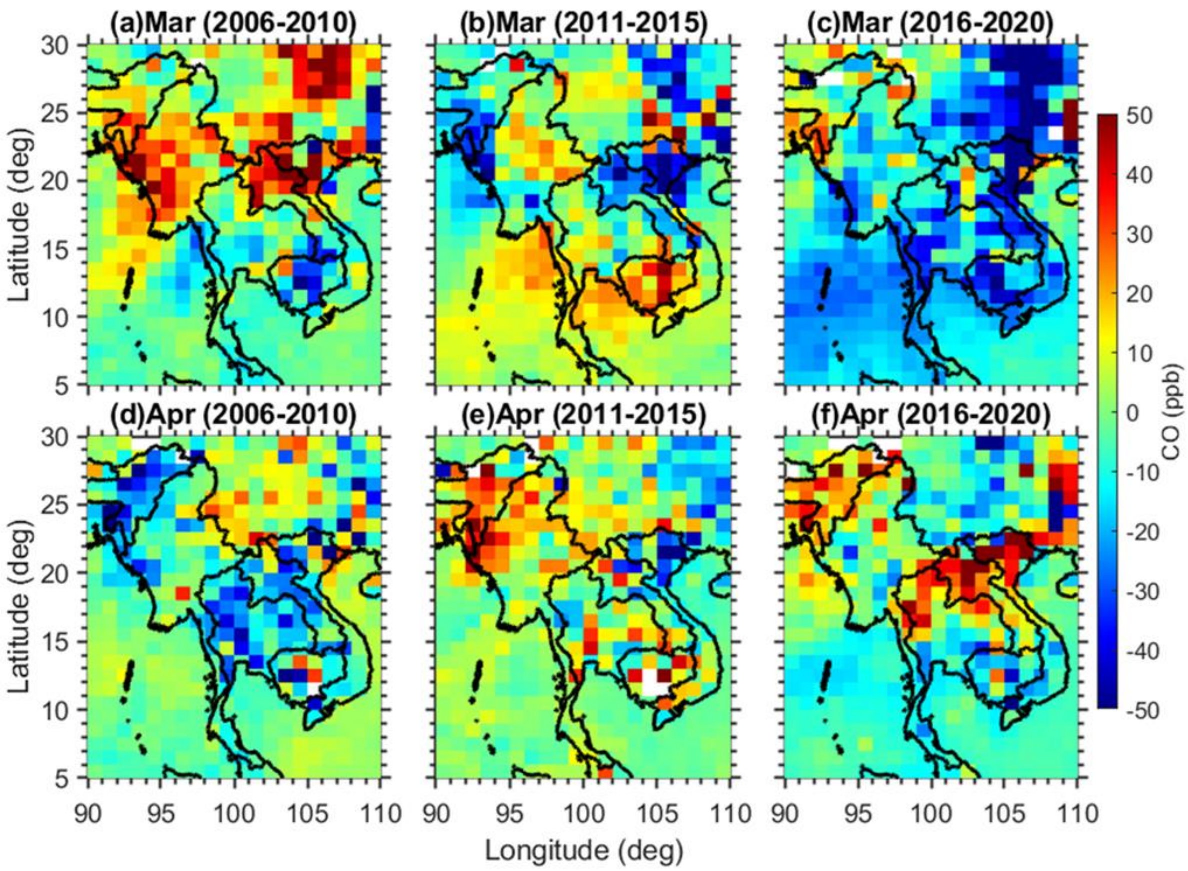

Figure 6. MOPITT observed surface carbon monoxide anomalies compared to the long-term mean (2001-2020) in (a) 2006–2010, (b) 2011–2015, and (c) 2016–2020 for March month. The subplots d-f are the same as subplots a-c, but for the month of April, respectively.

3.4 Role of Meteorological conditions on recent changes in the BB activity over PSEA

The springtime BB activity over PSEA is mostly due to anthropogenic and human origin (Vadrevu et al., 2019). However, the local meteorological (precipitation and temperature) conditions and atmospheric circulations also can have an impact on changing the BB activity (Huang et al., 2016; Vadrevu et al., 2019; Huang et al., 2020). A previous study by Vadrevu et al. (2019) suggested that precipitation has a significant correlation compared to the temperature with monthly fire counts over PSEA. They concluded that precipitation can explain more variations in fires than temperature and precipitation could be explained 40% of fire variations in Thailand, 41% in Vietnam, and 38% in Cambodia, respectively. Hence, we investigated the precipitation changes in the recent period (2016-2020) over PSEA to see the plausible link between substantial changes in the BB activity over PSEA. We utilized precipitation data from the Global Precipitation Climatology Project (GPCP) Version 3.2 Satellite-Gauge (SG) Combined Precipitation Data Set (Huffman et al., 2022). As Soil moisture is also one of the major drivers of BB activity (Hou and

Orth, 2020), we also investigated soil moisture changes over PSEA from the Global Land Data Assimilation System (GLDAS) data (Rodell et al. 2004). Precipitation and soil moisture anomalies are defined as a deviation from the long-term mean of springtime (2001–2020).

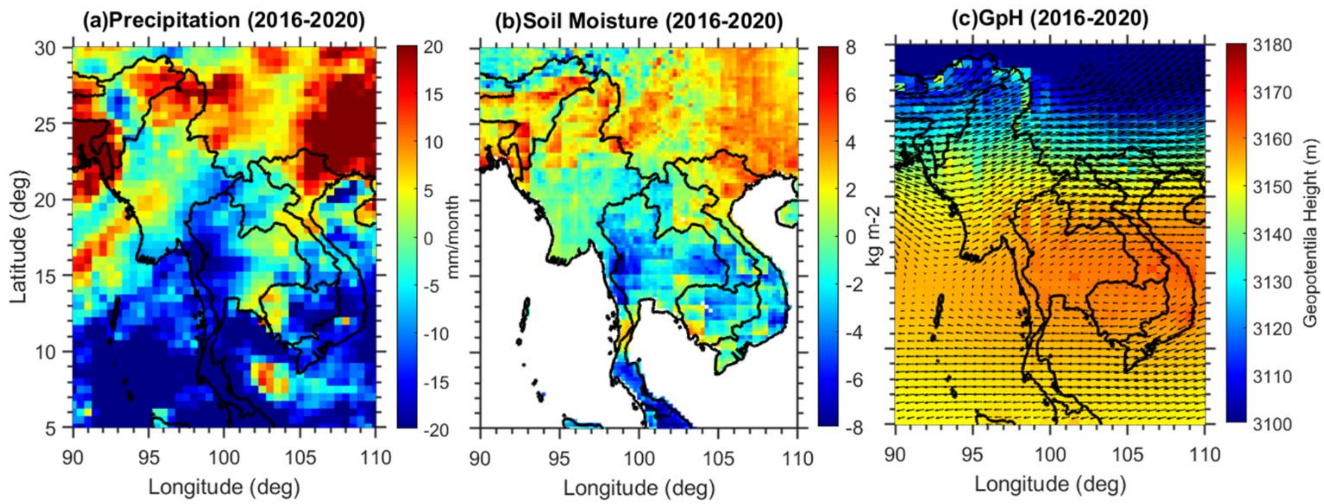

Figure 7. Springtime (average of March-April) (a) Combined satellite-gauge precipitation anomalies and (b) Soil moisture anomalies observed during 2016-2020 compared to the long-term mean (2001-2020). Subplot (c) shows MERRA-2 reanalysis measured 700 hPa winds along with Geopotential Height observed during the 2016-2020 period.

Figures 7a and **7b** show the precipitation and soil moisture anomalies compared to the long-term mean (2001-2020) in the 2016-2020 period over PSEA. The precipitation and soil moisture increased over Myanmar during the 2016-2020 period. The enhanced precipitation and soil moisture over Myanmar is consistent with the decreased BB activity in the 2016-2020 period. Similarly, less precipitation and decreased soil moisture are observed over Cambodia and Thailand during the 2016-2020 period, consistent with the observed BB activity shown in **Fig. 3**. The lowered precipitation and drier soil over Cambodia and Thailand are in line with the observed anticyclone circulation and increased geopotential height during the 2016-2020 period (**Fig. 7c**). This anticyclone over southern PSEA (particularly over Cambodia and Thailand) can induce local downdraft, suppresses springtime precipitation (**Fig. 7a**) and provide favorable conditions (reducing cloud cover and strong incoming solar radiation) for BB activity. There are some additional factors, such as land use change (Reid et al., 2013), government control policies, and shifting cultivation that might be involved in the recent changes in BB activity PSEA. For example, the decrease in BB activity during March in Thailand from 2016 may have been partially caused by Thailand's new air pollution control measures (Yabueng et al., 2020). Whereas, the significant enhancement of peak BB activity in April (particularly during 2011-2015 and 2016-2020) over northern Laos might be due to the increase in the shifting cultivation in Laos in recent years. Shifting cultivation is one of the major drivers of forest degradation in Laos (Messerli et al., 2009). Our findings on the profound increase in BB activity in Laos in recent periods (2011-2015 and 2016-2020) are partially supported by a recent study by Chen et al. (2023). Based on Landsat time series images from 1991 to 2020 on Google Earth Engine, Chen et al. (2023) monitored the shifting of cultivation across Laos. They found that the area of slash-and-burn activities in Laos increased in the 2015–2020 period. It can be noted that the results of Chen et al. (2023) are based on annual maps from Landsat images but our results from the present study are primarily based on springtime (March and April) BB activities determined from the number of daily MODIS active fire counts, respectively. It is also noted that our results are significantly distinct from the findings of Chen et al. (2023) that a significant increase of BB activity was observed over the northern Laos region in April compared to March. For instance, the detailed inter-annual variability of springtime BB activity over PSEA and the effects of various climate teleconnections such as El Niño-Southern Oscillation (ENSO) and Indian Ocean Dipole (IOD) were excluded from the study. The plausible relationship between various climate teleconnections and springtime BB activity over PSEA may be considered in future communication, respectively.

3.5 Long-term Trends in Springtime BB Activity over PSEA

Finally, we estimated the long-term trends in BB activity over PSEA. To identify the spatial pattern in BB activity trend from MODIS active fires over PSEA, we have performed spatial trend analysis by using linear regression and detected its corresponding significance level based on the MK method. As the detection confidence of MODIS active fires ranges from 0-100%, above 30% is considered to have better accuracy (Giglio et al., 2018). Therefore, first, we performed a trend analysis for the MODIS active fires that are having more than 30% confidence levels. The greater than 80% confidence levels in the MODIS fires can represent the intense BB activity hence we also did trend analysis separately for the MODIS fire counts that have greater than 80% confidence levels.

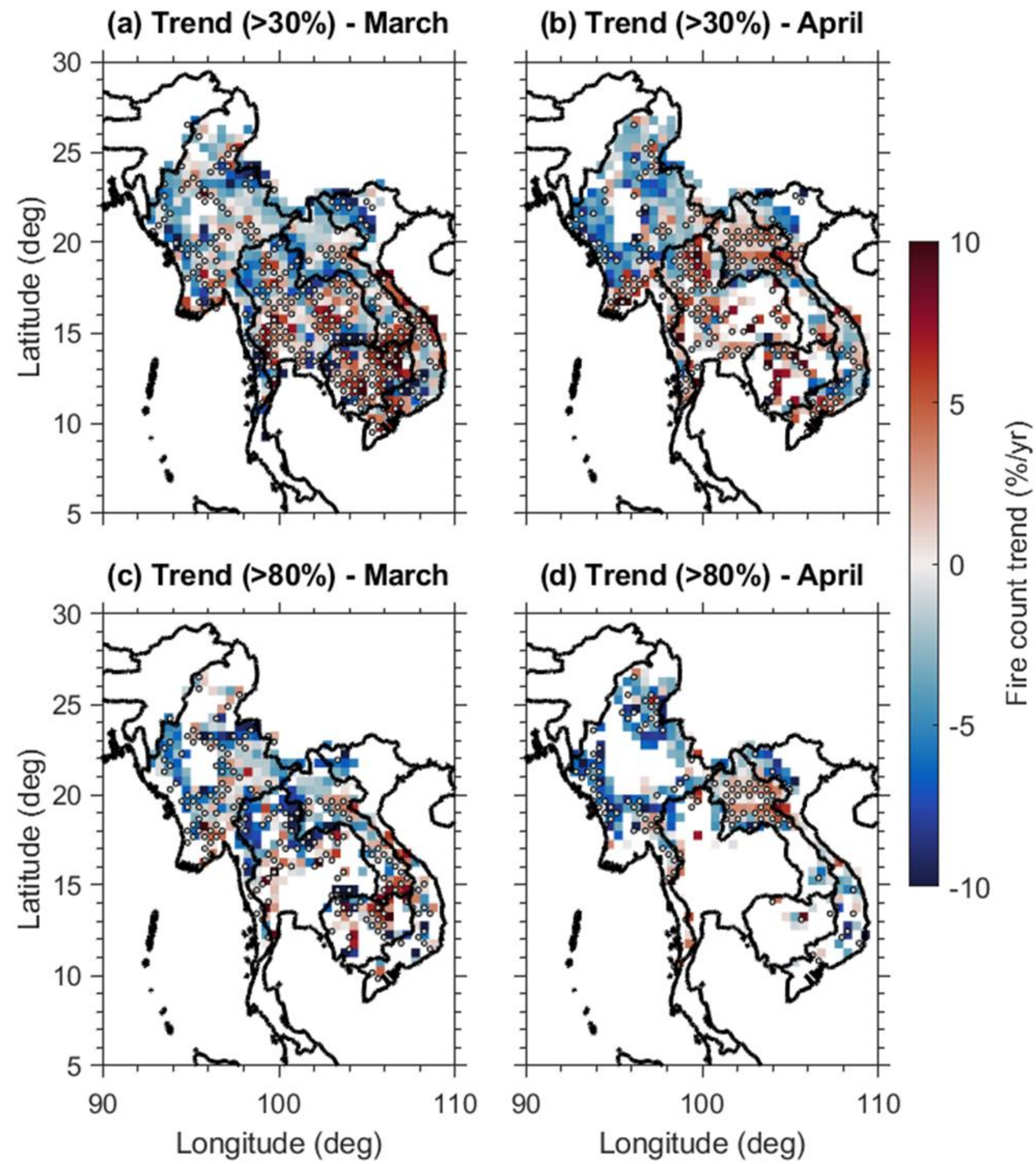

Figure 8. Long-term trends in the fire activity based on >30% fire counts over PSEA in (a) March, and (b) April. The subplots c and d are the same as subplots a and b, but the trends are based on >80% fire counts. The dots represent the statistical significance of the estimated trends at 99% (0.01 significance level).

The trend analysis results for the period 2001-2020 are shown in **Fig. 8**, where the pixels at a 99% significant level ($p < 0.01$) are marked with dots. **Figures 8a** and **8c** (**Figures 8b** and **8d**) show the observed percentage change in the BB activity trend for March (April). The trend analysis revealed a significant increasing trend in BB activity during April that was primarily concentrated in northern Laos. Whereas in March, most of the increasing trend was located over northeastern Cambodia, respectively. Overall, northeastern Cambodia during March and northern Laos during April, have increased BB activity by over 10% in the past two decades. The increasing trend in the BB activity over northern Cambodia during March from the present study is in line with the results of Vadrevu et al. (2019), who also find a statistically significant increasing trend in the fire activity over Cambodia from the 2003-2016 period. It is noted that we estimated the BB trends based on individual March and April months in the present study whereas Vadrevu et al. (2019) estimated the trends based on annual scales by considering an entire country average of total fire counts. It is also noted the substantial increasing trend in BB activity over northern Laos, particularly in April was not reported in Vadrevu et al. (2019). It is also noted that a significant decreasing trend in BB activity was evident largely aggregated in Myanmar and northern Thailand during March. It is clear from the decadal changes (**Fig. 2**), the 5-year ensemble mean BB activity changes (**Fig. 3**), and long-term trends (**Fig. 8**) that a shift in the distribution of peak BB activity from March to April was evident over northern PSEA and Myanmar/northern Thailand to northern Laos in the recent decade (2011-2020). Given the strong importance of springtime BB aerosols on climate, our present results can contribute significantly further to understanding the long-term changes in BB activity and associated emissions over PSEA.

4. Summary and Concluding Remarks

Peninsular Southeast Asia (PSEA), particularly the northern part (or region) is confronted with the problem of air pollution due to widespread biomass burning activity in nearly every dry season from January to April which has profound effects on tropospheric chemistry and composition in the East Asian periphery. We have used long-term MODIS active fire counts to characterize the long-term trends in biomass burning activity and its recent changing pattern over the PSEA for the past two decades (2001-2020). We also investigated the impact of observed BB activity changes on BB aerosols and carbon gases by utilizing MERRA-2 reanalysis products and MOPPIT satellite measurements of surface carbon monoxide. The monthly distribution shows the greatest BB activity during the dry season from January to April, with its peak in March. Results from the present study highlight the BB activity distribution, pattern, and recent trends in PSEA which are important in addressing the regional BB activity and emission issues in PSEA. The major findings obtained from the study are summarized below:

- Decadal analysis reveals a significant decrease in BB activity in March in most PSEA regions over the past decade (2011-2020) and a significant increase in BB activity in April in northern Laos.
- Five-year ensemble means anomalies in the BB activity reveals, both decreasing and increasing BB activity in PSEA were evident in the recent five-year period (2016-2020), with a dominance of decreasing (increasing) BB activity over Myanmar and northern Thailand (Laos) in both March and April.
- In March, statistically significant decreasing BB activity was found over Myanmar and northern Thailand, whereas, increasing BB activity was evident over northeastern Cambodia and south Laos.
- In April, BB activities increased significantly over Laos in the most recent 5-year period (2016-2020) and the stronger increase was evident over northern Laos.
- During 2006–2010, northern PSEA experienced the most severe BB activity, with the highest mean $PM_{2.5}$ concentrations in most regions. By contrast, during 2016–2020, BB activity was at its lowest over northern PSEA, with the lowest mean $PM_{2.5}$ values.
- BB aerosol ($PM_{2.5}$ and BC) and carbon monoxide (CO) showed a significant increase in northern Cambodia and northern Laos over the past decade.
- Long-term trend analysis revealed a significant increasing trend in PSEA that was primarily concentrated in Laos during April and Cambodia during March.

In light of the end of the MODIS instruments, our present work based on two decades of data can give an overall overview of the spatial distribution of BB activity and its recent changes along with the long-term trends over PSEA. Our study also highlighted that Laos has become a hotspot region for the rapid increase of BB emissions. Based on recent world air quality reports, there is a severe lack of ground-level monitoring of outdoor ambient $PM_{2.5}$ in Laos (World Air Quality Report, 2021/ https://www.iqair.com/newsroom/WAQR_2021_PR). Also, it was reported that the highest health risk rates per 100,000 populations due to open BB to human health were found in Laos when compared to the rest of the PSEA region (Thao et al., 2022). Similarly, the results obtained from the present study also suggest more effective measures should be taken to control BB emissions and stringent policies should be introduced to control the increasing trend of BB activity in Laos. Overall, our results will help address the issues of BB activity management and pollution, air quality monitoring, and mitigation in the PSEA region. We strongly believe that the present results can significantly contribute to a better understanding of spatial and temporal distributions of BB activity and BB aerosol changes over the PSEA.

Competing Interest

The authors declare that they have no conflict of interest.

Data availability

The MODIS fire products can be downloaded from https://firms.modaps.eosdis.nasa.gov/active_fire/. MOPITT CO data can be downloaded from https://asdc.larc.nasa.gov/project/MOPITT. MERRA-2 data are available online through the NASA Goddard Earth Sciences Data Information Services Center (GES DISC; https://disc.gsfc.nasa.gov).

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