Columnar aerosol types and compositions over peninsular Southeast Asia based on long-term AERONET data

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Abstract
Aerosol chemical components such as black carbon (BC) and brown carbon (BrC) regulate aerosol optical properties, which in turn drive the atmospheric radiative forcing estimations due to aerosols. In this study, we used the long-term measurements from AERONET (Aerosol Robotic Network) to better understand the aerosol types and composition with respect to their seasonal and spatial variabilities in peninsular Southeast Asia (PSEA, here defined as Vietnam, Cambodia, Thailand, Laos, and Myanmar). Two methods (i.e., aerosol type cluster and aerosol component retrieval) were applied to determine the aerosol type and chemical composition during the biomass-burning (BB) season. AERONET sites in northern PSEA showed a higher AOD (aerosol optical depth) compared to that of southern PSEA. Differences in land use pattern, geographic location, and weather regime caused much of the aerosol variability over PSEA. Lower single-scattering albedo (SSA) and higher fine-mode fraction (FMF) values were observed in February and March, suggesting the predominance of BB type aerosols with finer and stronger absorbing particles during the dry season. However, we also found that the peak BB month (i.e., March) in northern PSEA may not coincide with the lowest SSA once dust particles have mixed with the other aerosols. Furthermore, we investigated two severe BB events in March of 2014 and 2015, revealing a significant BrC fraction during BB event days. On high AOD days, although the BC fraction was high, the BrC fraction remained low due to lack of aerosol aging. This study highlights the dominance of carbonaceous aerosols in the PSEA atmosphere during the BB season, while also revealing that transported dust particles and BrC aerosol aging may introduce uncertainties into the aerosol radiative forcing calculation.

Keywords Biomass burning · Aerosol optical properties · Aerosol composition · Black carbon · Brown carbon

Introduction
Atmospheric aerosols, either from natural sources or anthropogenic emissions, perturb Earth’s radiation budget directly by scattering and absorbing incoming solar radiation (Charlson et al. 1992; Chylek and Wong 1995; Hassan et al. 2015). Aerosol direct radiative forcing is usually negative at the top of the atmosphere (TOA) under clear sky conditions. However, it can become less negative or even positive with an increase in aerosol absorption, especially over high albedo surfaces (Boucher et al. 2013; Feng et al. 2013; Wang et al. 2007). This aerosol absorption is mainly regulated by the aerosol chemical components and their respective mass fractions. Aerosol chemical components such as sulfate, nitrate, and sea-salt are efficient light scattering components (IPCC 2013), whereas mineral dust (DU), black carbon (BC), and brown carbon (BrC) are principal absorbers of
solar radiation (Moosmüller et al. 2009). Mixing of aerosols can also change their optical and radiative properties (Forster et al. 2007). Large uncertainties in aerosol radiative forcing estimations still persist on a global as well as regional scale due to knowledge gaps in and the high spatiotemporal variability of aerosol chemical, microphysical, and optical properties (IPCC 2013). Thus, it is essential to gain a better understanding of aerosol chemical composition based on observational studies to reduce these uncertainties (e.g., Van Beelen et al. 2014).

Traditionally, aerosol chemical components can be detected through in situ measurements and offline sampling coupled with laboratory analysis, but these approaches have often focused on surface level sites and are limited in their spatial coverage (Xie et al. 2017), and are not representative of aerosol chemical composition on the global scale (Chen et al. 2019). Field campaigns are typically conducted for weeks to months, thus unable to provide long-term aerosol chemical profile patterns. Moreover, long-term measurement networks are limited to surface measurements. On the other hand, remote sensing techniques have shown enormous potential for characterizing global aerosol absorption using long-term observations of aerosol optical properties (Chen et al. 2019). Providing continuous, long-term, and readily available aerosol optical and microphysical properties, the ground-based worldwide Aerosol Robotic Network (AERONET; Holben et al. 1998, 2001) has been widely used in literature to determine aerosol optical properties over specific source regions (Chu and Ha 2016; Giles et al. 2012; Russell et al. 2010). Furthermore, several studies have also determined columnar aerosol composition based on AERONET observations over different and distinct regions (Bahadur et al. 2012; Chen et al. 2019; Esteve et al. 2012; Schuster et al. 2005; Xie et al. 2014, 2017).

Ever since the Seven South East Asian Studies (7-SEAS)/Dongsha Experiment (Lin et al. 2013) exposed that immense biomass-burning (BB) pollution from peninsular Southeast Asia (PSEA, here defined as Vietnam, Cambodia, Thailand, Laos, and Myanmar) is transported to adjacent oceanic regions and significantly affects the regional climate, there has been intense focus on characterizing the aerosols over northern PSEA. 7-SEAS/BASELInE (Biomass-burning Aerosols & Stratocumulus Environment: Lifecycles & Interactions Experiment) spring campaigns during 2013–2015 were conducted to primarily understand the impacts of BB emissions on surface-atmosphere energy budgets (Lin et al. 2014; Pani et al. 2016, 2018; Wang et al. 2015) over the northern PSEA region. Although the complex aerosol environment of northern PSEA, particularly during the BB season, has been extensively investigated within the 7-SEAS framework, the role of absorbing aerosols on the environment is still unclear. Therefore, the primary objective of this study is to understand the seasonal and spatial differences of aerosol optical properties in PSEA, including absorption and aerosol chemical components in BB-influenced smoke haze, by using long-term AERONET direct sun measurements and inversion products. The role of BB-derived absorbing aerosols is thoroughly investigated in this study.

### Methodology

#### Site description

Figure 1 shows the AERONET sites used in this study. In addition to 5 permanent AERONET sites, namely Son La (SL), Chiang Mai (CM), Ubon Ratchathani (UR), Silpakorn Univ (SU), and Bac Lieu (BL), we deployed one temporary site at Doi Ang Khang (DAK), during the 7-SEAS/BASELInE spring campaigns (Tsai et al. 2016). The DAK site (in northern Thailand) is a meteorological station located in the Fang District of Chiang Mai Province, and on a mountain range along the Thai-Myanmar border at an elevation of 1536 m above sea level (a.s.l.) (Wang et al. 2015). Because this site is surrounded by forest and farmland, smoke emitted from agricultural burning and forest fires have occasionally been observed near the site. Next to DAK, the CM site (in northern Thailand) is located at the meteorological station near Chiang Mai airport. The air quality of this site is mainly affected by urban emission and agricultural burning transported from the surrounding areas. The SL site (in northern Vietnam) is situated in a valley surrounded by mountains. The population of Son La is approximately 200,000 people, suggesting the SL site may receive considerable local pollutants. The UR site (in north-eastern Thailand) is located at the meteorological station near Ubon Ratchathani airport.
Agricultural burning and urban emission are the main sources of air pollution in this area. The SU site (in southern Thailand) is located at Silpakorn University in Nakhon Pathom Province, which has a population of ~920,000 people; thus, the SU site is heavily impacted by urban emissions. The BL site (in southern Vietnam) is located at Bac Lieu Province. Because the site is close to the South China Sea, the air quality is affected by oceanic particles. Here we separated the six sites into two categories: DAK, CM, and SL sites in northern PSEA, and UR, SU, BL sites in southern PSEA.

The DAK dataset spanned from January to April during 2013–2015. The datasets for the other five sites were of different lengths, but all ended on December 31, 2017. The starting date for CM, SL, UR, SU, and BL sites were January 1 in 2008, 2012, 2007, 2010, and 2006, respectively.

AERONET measurements

AERONET deploys CIMEL Electronique CE-318 Sun-sky radiometers to measure the spectral direct-beam solar radiation as well as directional diffuse radiation along the solar almucantar (Holben et al. 1998, 2001). The direct-beam solar radiation measurements (i.e., direct sun measurement) were used to determine the columnar aerosol optical depth (AOD or \( \tau \)) in eight spectral channels (340–1020 nm) with a temporal resolution of approximately 15 min. The extinction Ångström exponent (EAE or \( \alpha \)) is another derived quantity and is typically used to describe the spectral dependence of AOD. In addition to measuring direct solar irradiance, the sun-sky radiometer measures the sky radiance at four wavelengths (440, 675, 870, and 1020 nm) along the solar almucantar (i.e., at a constant solar zenith angle, with varied azimuth angles). For quality control, the solar zenith angles were restricted to > 50° (i.e., in early morning and late afternoon) and a minimum AOD (440 nm) of 0.02 (Sinyuk et al. 2020). Sky radiance measurements were used to retrieve additional columnar aerosol properties including the volume size distribution, phase function, real and imaginary components of the refractive index (RI), particle effective radius (\( \text{eff} \)), single-scattering albedo (SSA), and the asymmetry factor (g), which are typically computed using AERONET inversion algorithms (Dubovik et al. 2000).

Aerosol type classifications

Two methods (i.e., aerosol type cluster and aerosol component retrieval) have been applied to determine the aerosol type and chemical composition during the BB season. We adopted the aerosol type cluster method from Giles et al. (2012), which used average values of the aerosol optical properties across 19 source-specific areas and delineated four aerosol types (i.e., dust, urban/industrial, biomass burning, and mixed) based on a cluster analysis. In our study, the cluster analysis was mainly based on extinction AE and SSA, as shown in cf. Figure 11(c) of Giles et al. (2012).

For the aerosol component retrieval, we used the aerosol composition model described in Li et al. (2013) and Xie et al. (2017). Xie et al. (2014) tested three different internal mixing models (Maxwell–Garnett, Bruggeman, and volume average mixing), and determined that Bruggeman was more suitable for dust events, Maxwell–Garnett was better for haze events, and volume average mixing was the best choice for clean air situations (low aerosol loading). Then, Xie et al. (2017) pointed out that, due to the aerosol hygroscopic growth process, the relation between water and other components must be considered, which was most similar to the assumptions in the Maxwell–Garnett model. Considering the biomass-burning aerosol components and the weather condition in PSEA, we selected the Maxwell–Garnett mixing assumption for our study. The aerosol composition model established in this study includes BC, BrC, DU, ammonium sulfate-like (AS), and aerosol water content (WA). We constrained the Maxwell–Garnett (MG) model with aerosol optical property data from AERONET and solved it as a cost function (Fig. 2). The forward model describes the simulation of refractive indices from aerosol composition and mixing states. The dielectric functions are calculated using the following relations (Bohren and Huffman 1998), and a look-up table of refractive indices of typical aerosol components is provided in Table 1.

\[
\varepsilon_j = (n_j + k_j i)^2
\]

\[
\varepsilon_m = (n_m + k_m i)^2
\]

We calculated the MG dielectric function \( \varepsilon_{\text{MG}} \) by using the dielectric functions of components and derived the real refractive index (\( n_{\text{MG}}^{\text{cal}} \)) and imaginary refractive index (\( k_{\text{MG}}^{\text{cal}} \)) of the mixture from the MG dielectric function (Bohren and Huffman 1998; Xie et al. 2017):

\[
\varepsilon_{\text{MG}} = \varepsilon_m \left[ 1 + \frac{3 \sum f_j (\varepsilon_j - \varepsilon_m) / (\varepsilon_j + 2 \varepsilon_m)}{1 - \sum f_j (\varepsilon_j - \varepsilon_m) / (\varepsilon_j + 2 \varepsilon_m)} \right]
\]

\[
n_{\text{MG}}^{\text{cal}} = \sqrt{|\varepsilon_{\text{MG}}| + \text{real}(\varepsilon_{\text{MG}})/2}
\]

\[
k_{\text{MG}}^{\text{cal}} = \sqrt{|\varepsilon_{\text{MG}}| - \text{real}(\varepsilon_{\text{MG}})/2}
\]

where \( f_j \) indicates the volume fraction of the \( j \)th component in the mixture; \( \varepsilon_j \) and \( \varepsilon_m \) are the dielectric functions of the \( j \)th component (BC, BrC, DU, AS) and the aerosol water
content (AW), respectively. Note that the complex refractive index spectra, especially for BC and BrC, are still quite uncertain in the current aerosol optics research, and vary widely across studies (shown in Table S1). The total modeling residual between model \( n_{\text{cal}}^{\text{MG}} \) and observation \( n_{\text{obs}}^{\text{MG}} \) was quantified by a cost function \( \chi^2 \) based on the least-squares principle:

\[
\chi^2 = \sum \frac{(n_{\text{cal}}^{\text{MG}} - n_{\text{obs}}^{\text{MG}})^2}{\sigma(n)^2} + \sum \frac{(k_{\text{cal}}^{\text{MG}} - k_{\text{obs}}^{\text{MG}})^2}{\sigma(k)^2}
\]

where the superscript cal and obs denote modeled (calculated from the forward model) and observed (derived from AERONET measurements) parameters, respectively. The real and imaginary parts of the refractive index are weighted by a factor \( \sigma(n) \) and \( \sigma(k) \) in the cost function equation to give parameters with higher accuracies and greater contributions. The standard deviations of refractive indices used in this study are 0.04 \( \sigma(n) \) and 0.5 \( \sigma(k) \) (Xie et al. 2017).

Xie et al. (2017) show generally good consistency between remotely estimated and measured components (e.g., correlation coefficients for BC, BrC, AS, and PM\(_{2.5}\) were 0.78, 0.8, 0.82, and 0.88, respectively). Finally, we obtained the fraction of aerosol components by minimizing the cost function \( \chi^2 \). In Fig. 3, we show the comparison results between the retrievals and aerosol chemistry measurements from February 22 to April 8, 2013. The aerosol chemistry data was adopted from a previous study (Lee et al. 2016). According to aerosol chemistry observation, the retrieval aerosol types underestimated BrC and overestimated DU. Overall, the correlation coefficient between component retrieval and chemical sampling was 0.6 at DAK.

### Table 1

| Aerosol component | RI (440 nm) | RI (670 nm) | RI (870 nm) | RI (1020 nm) | \( \rho (\text{g cm}^{-3}) \) |
|-------------------|-------------|-------------|-------------|--------------|----------------|
| BC                | 1.85–0.71i  | 1.85–0.71i  | 1.85–0.71i  | 1.85–0.71i   | 2.0            |
| BrC               | 1.57–0.063i | 1.55–0.003i | 1.54–0.001i | 1.54–0.001i  | 1.8            |
| DU                | 1.54–0.008i | 1.52–0.005i | 1.51–0.003i | 1.51–0.003i  | 2.6            |
| AS                | 1.535–10\(^{-7}\)i | 1.525–10\(^{-7}\)i | 1.52–10\(^{-7}\)i | 1.53–10\(^{-7}\)i | 1.76 |
| WA                | 1.33–0i     | 1.33–0i     | 1.33–0i     | 1.33–0i      | 1.0            |
Results and discussion

Long-term variability at 6 AERONET sites

BB aerosols are the predominant type of aerosol over PSEA during spring months (Wang et al. 2007; Punsompong et al. 2021). As shown in Fig. 4, the long-term data analysis revealed that the monthly mean aerosol optical depth (AOD) was higher in the months of March and April than in the rest of the months, as observed by all AERONET sites in the region. This finding indicates the influence of regional BB activities, as is also shown by the FMF trends. Fine-mode particles (particle size approximately < 1 μm) are mainly caused by the increase of aerosol loading over PSEA. Due to the spatial differences of geography, land use patterns, and weather regimes, the AERONET sites in northern PSEA show a higher AOD compared to that of southern PSEA. In comparison to the yearly-mean aerosol optical properties, lower single-scattering albedo (SSA) and higher fine-mode fraction (FMF) values in February and March suggested the domination of smaller and stronger absorbing particles during this period. This result is consistent with in situ and satellite measurements described by 7-SEAS field deployments (Lin et al. 2014; Wang et al. 2015). Interestingly, we found that the peak BB month (i.e., March) in northern PSEA may not coincide with the lowest SSA. The possible reasons for the cause are discussed in the following sections.

According to the climate classification by Yen et al. (2013), the PSEA climate could be identified as three seasons: wet season (May to October), dry and cold season (November to January), and dry season (February to April). Figure 5 shows an M-shaped (i.e., fine and coarse modes) particle size distribution for three seasons derived from AERONET observation at the 6 sites during the
study period. Fine-mode particles are generally produced from anthropogenic activity, while coarse mode particles are mainly derived from natural sources. The BL site exhibited less seasonal variation. Except for BL, the rest of the sites showed a pronounced quantity of particle number, especially for fine-mode particles, during the dry season when large amounts of fine BB particles are released into the atmosphere. The weather regimes coupled with land use activities predominate drive the regional variability of aerosols in the dry season. Particle size distributions in wet and dry-and-cold seasons showed a similar pattern at the three eastern sites (i.e., SL, UR, and BL), where coarse mode and fine particles were similar, which was also supported by the FMF values shown in Fig. 4. On the other hand, CM and SU revealed a higher fraction of coarse mode particles in the wet season. The long-range transport of dust particles from the semi-arid regions over northwest India (e.g., Pani et al. 2016) may have influenced the columnar aerosol loading at CM and SU. Overall, the difference in land use patterns, geographic location, and weather regimes may have caused the aerosol variability over PSEA.

**Dominant aerosol type in dry season**

Aerosol types for each AERONET site in dry season were further discussed using the aforementioned cluster analysis method (Giles et al. 2012). Based on current research results (Lin et al. 2014; Wang et al. 2015), the predominant aerosol type in the dry season is BB; however, site-to-site variation occurs due to the mixing with local pollutants. Figure 6 shows the scatterplot of SSA and EAE. We used 0.1 as the resolution of EAE and 0.01 as the resolution of SSA, and each contour represented the number density of data points. According to Giles et al. (2012), the cluster analysis can be applied to categorize aerosols into four types: dust, urban/industrial, biomass burning, and mixed. The ideal range to represent each aerosol type is marked with an oval and dust type was ignored in Fig. 6 due to its EAE value being low than 0.5 and out of figure range.

As shown in Fig. 6, the CM and SU sites have a higher number of data points. The scatter distribution of CM and SU appeared to be similar, but CM showed more data distributed at lower SSA value. The cluster group with lower SSA might suggest the influence of local anthropogenic pollution. Among the 6 AERONET sites, DAK was selected as representative of a BB near-source region. The cluster analysis results for DAK showed a large area with a number density up to 3.5%, suggesting this was a common optical property of BB aerosols in the dry season. However, this aerosol characteristic was different than the typical aerosol type values suggested by Giles et al. (2012), which defined a representative range based on worldwide selected AERONET sites. Regarding BB, they applied data from Africa savanna or grassland areas, which might have inherently different characteristics from the BB in PSEA. BB aerosols observed at DAK showed generally lower EAE, and much lower EAE for a higher SSA range, as compared to Giles et al. (2012). We suspect
that dust particles transported at higher levels might have contributed to the columnar aerosol loading and caused the difference. A similar distribution pattern to DAK was also found for SL and UR. According to BL site cluster analysis, a mixed aerosol type with low absorbance was determined during the dry season in southern PSEA.

**Aerosol chemical components over northern Thailand in dry season**

To gain a better understanding of a mixture of BB aerosols over northern Thailand, we further applied the aerosol refractive index to retrieve various aerosol components. Table 2 shows the fraction of aerosol components in each month at CM. The AERONET level 2.0 data was used for the aerosol component determination (Table 2), but the level 1.5 data was used during July to September, due to lack of the data points. A large fraction of absorbing aerosols was observed in February (BC ≈ 7% and BrC ≈ 43%) and March (BC ≈ 5% and BrC ≈ 38%), reflecting the signature of BB aerosols. DU contributed a major fraction in aerosol components throughout the year, especially from May to December, which includes the wet season and a low aerosol loading period. The dust particles may have been transported from Thar Desert or even Middle Eastern deserts via westerlies within the free troposphere to PSEA. Road dust and farming dust from local emissions could also have caused a high DU fraction. More detailed studies should be performed to clarify the sources of dust in the future. AS usually indicates local industrial or city emissions. The fraction of AS was low in each month, except for July and August, when the lowest AOD was observed (Fig. 4b). We suggest that a high AS fraction in July and August was due to steeply lower contributions from BB and DU.

The variation of aerosol chemical components in the dry season is further discussed. The highest BC and BrC fractions were observed in February when the dry season started. The pronounced increase of BC and BrC reasonably reflected the lowest DU, AS, and WA fractions in February as compared to other months. In March, although the AOD was higher (Fig. 4b) the sum of BC and BrC fractions was lower compared to February. We

| Table 2 | Fraction (%) of the aerosol component in each month at Chiang Mai (CM) |
|--------|---------------------------------------------------------------|
|        | Jan  | Feb  | Mar  | Apr  | May  | Jun  | Jul  | Aug  | Sep  | Oct  | Nov  | Dec  |
| BC     | 3.1  | 6.6  | 5.4  | 1.2  | 0.4  | 0.0  | 0.8  | 2.1  | 1.7  | 0.2  | 0.4  | 0.8  |
| BrC    | 41.3 | 42.8 | 37.8 | 40.1 | 27.2 | 1.6  | 14.1 | 21.8 | 21.6 | 25.1 | 27.7 | 35.4 |
| DU     | 26.5 | 24.3 | 28.5 | 30.6 | 40.3 | 56.4 | 37.8 | 35.6 | 37.3 | 41.3 | 42.9 | 33.8 |
| AS     | 17.8 | 16.3 | 17.6 | 16.7 | 19.6 | 24.2 | 30.8 | 28.9 | 23.5 | 18.1 | 18.2 | 17.6 |
| WA     | 11.1 | 9.7  | 10.4 | 11.1 | 12.2 | 17.5 | 16.2 | 11.3 | 15.7 | 15.0 | 11.5 | 12.1 |
further calculated the ratio of BC fraction to (BC + BrC) fraction and found that values (~0.13) are close in both months, suggesting the BB characteristics are similar. A higher DU fraction was determined in March. The contribution of dust particles may have modulated the aerosol composition, as well as aerosol optical properties in the peak BB month of March.

Aerosol optical properties and chemical components during BB events

In this section, we further investigated the detailed spatiotemporal variation of aerosol optical properties and chemical components during two severe BB events (i.e., March 19–23, 2014, and March 8–12, 2015) observed at CM and DAK sites. AOD values reached 3 and 2.5, respectively, in these two events (Fig. 7). We identified several common characteristics of event development. Regarding daily variation, the AOD increased steadily with decreasing EAE before reaching event peak days (i.e., March 21, 2014, and March 10, 2015); after the event peak day, AOD decreased but EAE stayed in the low-value range (1.4–1.6). A lower EAE value indicated relatively large particles, which might be due to particle aging, mixture, and growth during a long-lasting event. Both sites illustrated strong diurnal patterns but with time shifts due to station elevation and geographic location differences. CM showed a higher AOD value than DAK in the early morning, but then shifted in the afternoon as the AOD value became higher at DAK than at CM. According to the mountain and valley breeze effect, the BB aerosols which were produced during the previous day would have been trapped in the Chiang Mai valleys by the nocturnal stable boundary layer until early morning. Higher AOD at DAK in the afternoon was due to fresh BB plumes from nearby sources and pre-existing BB aerosols lifted from the valley to the mountain site via planetary boundary layer development. A relevant discussion about the diurnal patterns also can be found in our previous publication (Wang et al. 2015).

Figure 8 shows the MODIS fire counts during the BB event days. The total numbers of daily fire count were calculated within the 2° × 2° domain around DAK and CM. As a result, the daily fire counts were significantly higher in the event peak days (i.e., March 21, 2014, and March 10, 2015) or in the afternoon the day before. More fresh BB aerosols were expected to be observed on the event peak days. Furthermore, the daily variation of retrieval aerosol components is shown in Fig. 9. At DAK, results show a higher BC fraction on the event peak days, implying abundant fresh aerosols emitted from nearby sources. Interestingly, the BrC fraction tended to be lowest on the event peak days, although the BrC fraction significantly increased the next day. This variation of BC/BrC ratios was due to the emission phase. The initial flaming burning phase (i.e., on event peak days) emits mostly BC, while the smoldering phase on the ensuing days emits mostly BrC (e.g., Chen et al. 2006, 2007). A similar feature had also been observed for levoglucosan (a well-known chemical tracer for BB) surface concentrations.

Fig. 7 The AOD and AE variations during the two selected events at a DAK and b CM stations
Fig. 8 Fire counts obtained from MODIS instrument onboard Terra and Aqua satellites during the two selected BB events. The daily fire count was calculated within the $2^\circ \times 2^\circ$ domain around (a) DAK and (b) CM.

Fig. 9 Aerosol components retrieved from AERONET data during the two selected BB events at (a) DAK and (b) CM stations.
An improved aerosol composition model that includes BC, BrC, DU, AS, and aerosol water uptake (AW) could effectively describe the variability of the aerosol aging and transport processes in PSEA. However, both the aerosol type classification method and chemical component retrieval method are dependent on inversion products and the modeling assumptions. In this study, we selected the Maxwell–Garnett mixing assumption for the aerosol component retrieval, which could yield different results with other mixing assumptions (e.g., Bruggeman and volume average mixing assumption) (Dey et al. 2006; Xie et al. 2014, 2017). The aerosol refractive index was similar for the DU and BrC aerosols existing in the region for 2–3 days, which was proven by a gradual increase of AOD and a decrease of EAE. On the event peak day, the BrC fraction reached its lowest value whereas AS had increased. Significant amounts of fresh BC and BrC aerosols were emitted on the event peak day; however, only BC particles immediately reflected a high fraction on that day. BrC aerosols displayed a large fraction on the next day.

Concluding remarks

In this study, we investigated the aerosol type and optical properties in terms of seasonal to spatial variabilities over peninsular Southeast Asia (PSEA) based on the long-term measurements from 6 sun photometer AERONET (Aerosol Robotic Network) sites. The role of absorbing aerosols (BC and BrC) related to biomass-burning (BB) activities in northern Thailand was studied. To quantify aerosol characteristics, an aerosol type classification method and an aerosol chemical component retrieval method were applied. Furthermore, applying a case analysis (March 19–23, 2014, and March 8–12, 2015), the characteristic aerosol types and chemical components during BB events were also depicted in this study. Those results are summarized as follows:

- AERONET sites in northern PSEA show a higher AOD compared to southern PSEA, where the different weather regimes and land use activities drive the regional variability of aerosol in the dry season (February to April).
- BB aerosols are the predominant type of aerosol over PSEA in February to March. Lower single-scattering albedo (SSA ≈ 0.82) and higher fine-mode fraction (FMF ≈ 0.95) values imply particles are finer and stronger absorbing during this period. The retrieved aerosol mass indicated high fractions of absorbing aerosols (BC ≈ 5% and BrC ≈ 40%). However, we also found that the high AOD month (i.e., March) in northern PSEA may not coincide with the lowest SSA once dust particles have mixed with the other aerosols. The contribution of dust particles can modulate aerosol compositions, as well as aerosol optical properties in the peak BB month of March.
- The long-range transport of dust particles from the Thar Desert could have an influence on columnar aerosol loading over PSEA. The dust particles may transport from upwind deserts via westerlies through the free troposphere to PSEA.
- According to the BB event analysis, on the high AOD day, the BC fraction was higher due to fresh emissions from flaming burning, whereas the BrC concentration showed a lower value and then increased in the ensuing days due to smoldering, burning, and photochemical aging. Therefore, a lowest SSA value might not occur at event peak day.
- This study provides a new insight on how transported dust particles and BrC aerosol aging in northern PSEA can change the columnar aerosol optical properties and aerosol type, as well as aerosol chemical components. Therefore, when one wants to perform a radiative forcing calculation for this region, those factors should be carefully considered.
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