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Divergent Trends of Black and Brown Carbon Driven by Anthropogenic Emissions and Open Biomass Burning Across Asia

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Abstract. Black carbon (BC) and brown carbon (BrC) are the dominant light-absorbing carbonaceous aerosols (LACs) and contribute substantially to regional climate warming. Across Asia, heterogeneous changes in anthropogenic and open biomass burning (OBB) emissions driven by clean air policies and climate variability are reshaping LAC composition, yet how these changes alter the relative abundance and radiative roles of BC and BrC remains poorly understood. Here, using the chemical transport model GEOS-Chem combined with machine-learning attribution, we quantify the responses of BC and BrC to concurrent emission changes across East, South, and Southeast Asia during 2012–2019. We identify pronounced spatial heterogeneity in BrC/BC mass ratio trends. East Asia exhibits a significant upward trend, driven by policy-induced suppression of BC-rich anthropogenic sources alongside enhanced BrC-rich OBB from a seasonal shift in crop residue burning under open-fire regulations. In contrast, South and Southeast Asia show declining ratios attributable to residential energy transitions and wildfire variability, respectively. These asymmetric responses propagate into direct radiative forcing (DRF), with the DRFBrC/DRFBC ratio increasing from 34.1% to 41.3% in East Asia while declining elsewhere. Notably, in East and Southeast Asia, OBB amounts to up to half of anthropogenically driven radiative forcing changes. Our results demonstrate that emission mitigation can redistribute rather than proportionally reduce LAC warming, highlighting that future climate benefits will critically depend on the concurrent management of open biomass burning.

1 Introduction

Light-absorbing carbonaceous aerosols (LACs), strongly influence the radiative balance of the Earth system by directly absorbing solar radiation (Bond et al., 2013; Saleh, 2020) or indirectly altering cloud and precipitation processes (Liu et al., 2020). LACs consist of black carbon (BC), which strongly absorbs solar radiation throughout the entire spectrum (Bond et al., 2013), and brown carbon (BrC), a component of organic carbon (OC) characterized by wavelength-dependent absorption from visible to ultraviolet range (Saleh, 2020). Of the two, BC is the primary contributor to the radiative effect of LACs, with a global direct radiative forcing (DRF) due to aerosol-radiation interaction ranging from 0.21 to 0.39 W m^{-2} (Thornhill

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et al., 2021; Tuccella et al., 2020; Zhang et al., 2020), higher than that of BrC (0.03–0.22 W m^{-2}) (DeLessio et al., 2024; Drugé et al., 2022; Saleh et al., 2015; Zhang et al., 2020).

BC is a direct product of incomplete fuel combustion, with major sources from anthropogenic activities (e.g., industry, power generation, transportation, and residential combustion) and open biomass burning (OBB; e.g., forest, shrub, and crop residue fires) (Hoesly et al., 2018; Pan et al., 2020). In contrast, though sharing similar sources, primary BrC (BRpri) predominantly originates from OBB and residential solid fuel combustion (Atwi et al., 2022; Satish et al., 2020; Xiong et al., 2022). Additionally, BrC can be formed secondarily via the oxidation of volatile organic compounds (VOCs), termed secondary BrC (BRsec) (Liu et al., 2015; Siemens et al., 2022). These source-level discrepancies thus imply that BC and BrC may respond differently to profound shifts in emission regimes, driven by anthropogenic mitigation (Geng et al., 2024; McDuffie et al., 2020) and climate-sensitive wildfires (Jones et al., 2022).

Asia, as one of the largest source regions of LACs globally, has undergone pronounced and spatially heterogeneous shifts in emission regimes over the past decade, particularly in East, South and Southeast Asia. This makes it a natural laboratory for examining how divergent anthropogenic and OBB trajectories reshape LACs. In East and South Asia, LACs' sources are dominated by anthropogenic activities, with China and India accounting for nearly 50% of global anthropogenic carbonaceous aerosol emissions (McDuffie et al., 2020; Xu et al., 2021). In both regions, OBB is also predominantly from human agricultural activities (Gong et al., 2025; Yin, 2020). Since 2013, East Asia, especially China, has achieved substantial reductions in both anthropogenic emissions and harvest-season open burning, driven by stringent air pollution controls and straw burning bans (Geng et al., 2024; Kurokawa and Ohara, 2020; You et al., 2026). Meanwhile, South Asia has seen relatively modest changes, as the rollout of clean energy and open burning controls has faced socioeconomic and infrastructural constraints (Bhuvaneshwari et al., 2019; Roy, 2024). Southeast Asia, by contrast, stands out as a wildfire-prone region (Pan et al., 2020; Yadav et al., 2017), with anthropogenic emission intensities considerably lower than those in East and South Asia (Kurokawa and Ohara, 2020). Emissions of LACs in this region are primarily from natural open burning, which is highly sensitive to climate variability and thus exhibits strong interannual fluctuations (Chen et al., 2017; Yin et al., 2021).

Therefore, East, South, and Southeast Asia represent three real-world emission trajectories: policy-driven, near-baseline transition and climate-sensitive, respectively. These heterogeneous trajectories are likely to drive regionally distinct responses of BC and BrC. Both observational and modeling studies have demonstrated that BC is generally expected to decline under policy controls over Asia (Liu et al., 2022a; Pathak et al., 2024; Xie et al., 2025; Zheng et al., 2025), while the response of BrC remains poorly constrained. An unresolved question is therefore whether anthropogenic mitigation together with OBB variability reshapes LACs uniformly, or instead alters the relative abundance and radiative importance of BC and BrC across regions.

To address this question, we investigate emission-driven changes in the BrC/BC mass ratio across Asia from 2012 to 2019 and identify the key contributors using the chemical transport model GEOS-Chem combined with Shapley Additive exPlanations (SHAP). We then quantify how these changes affect the contributions of BC and BrC to the DRF of LACs.

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This provides insight into how evolving emission patterns alter the balance of abundance and radiative forcing between these two species, with implications for targeted mitigation strategies. This paper is organized as follows. Section 2 describes the model setup and observational data. Section 3 presents model evaluation, analyzes BrC/BC trends, and discusses the underlying drivers. Section 4 presents the conclusions.

2 Methodology

2.1 Model and simulation

2.1.1 Model description

The GEOS-Chem model (version 13.2.0, http://10.5281/zenodo.5500536) was used in this study to simulate aerosol mass for 2012 to 2019 after a 4-month spin up. The simulation was run at a resolution of 2°×2.5°with 47 vertical layers driven by MERRA2 assimilated meteorology. The study area comprises East, South, and Southeast Asia and their surroundings (Fig. S1).

Anthropogenic emissions were taken from the Community emissions Data System (CEDS, v2021_04_21 release; Hoesly et al., 2018), while emissions of gaseous species in China were overwritten by Multi-resolution Emission Inventory for China (MEIC) version 1.3 (Zheng et al., 2018). The SO_2 emission from MEIC is scaled up by a factor of 1.5 (Koukouli et al., 2018). OBB emissions were taken from Fire Energetics and Emissions Research (FEER) version 1.0 (Ichoku and Ellison, 2014). The injection height was treated by distributing OBB emissions uniformly within the boundary layer, following Pan et al. (2020). Biogenic emissions were calculated online by MEGAN version 2.1 (Guenther et al., 2012).

2.1.2 Simulation of BC and BrC

In GEOS-Chem, the parameterizations of BC and primary OC follow Park et al. (2003). The formation of secondary OC (SOC) is based on an irreversible scheme with fixed yields (Kim et al., 2015). We isolated the BrC from OC. Both BRpri and BRsec were considered.

Two dominant sources of BRpri, OBB and residential solid fuel combustion, were included; and their emissions were obtained via multiplying OC emissions (from inventories) by the mass ratio M_{BRpri}/M_{OC}. This ratio was derived by linking BRpri emission to its absorption, based on an empirical relationship between combustion efficiency and absorption Angstrom exponents (Jo et al., 2016). Details are provided in Text S1 and Table S1. This approach estimates the global BRpri emissions at 5.40 Tg C yr^{-1} for OBB and at 3.18 Tg C yr^{-1} for residential sources, in good agreement with bottom-up estimates (Xiong et al., 2022; Table S2). For BRsec, we considered only SOC formed from anthropogenic aromatic VOCs (AVOC) to be light-absorbing, as treated previously (Xu et al., 2024; Zhang et al., 2020); while SOC from other sources (e.g., biogenic VOCs), due to its negligible absorption (Liu et al., 2015), was not considered.

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The optical calculations of BC and BrC (adopting treatments of scattering OC) were based on the aerosol optical scheme in GEOS-Chem (Martin et al., 2003), with following modifications. The refractive index of BC was updated to 1.95 + 0.79i at 550 nm (Bond and Bergstrom, 2006). The imaginary refractive index of BRpri and BRsec (Table S3) were obtained from field observations of OBB (Kirchstetter et al., 2004) and laboratory measurements of aromatic SOC (Liu et al., 2015), respectively. Given the significant variability in BrC photobleaching rates (Qiu et al., 2024, 2026; Wong et al., 2017), this process was not considered in our study. Both BrC and scattering OC were converted to organic matter using a factor of 2.1 (Park et al., 2003).

2.1.3 DRF calculation

Shortwave DRF of BC and BrC were estimated under clear-sky condition using the shortwave component of Rapid Radiative Transfer Model for GCMs (RRTMG_SW, https://github.com/AER-RC/RRTMG_SW). Here, DRF refers to radiative forcing directly induced by the aerosol-radiation interaction (IPCC, 2021). This model simulates the net solar flux at the top of atmosphere (TOA) across 14 spectral bands ranging from 0.2 to 12.2 μm (Iacono et al., 2008). The BrC absorption-induced DRF was calculated as the difference between two RRTMG_SW runs, one with BrC absorption (including BRpri and BRsec) and one without. In other words, the effect of BrC scattering was not considered. The BC DRF was calculated in the same way, except that the small effect of its scattering was included.

2.2 Trend analysis

Trends in BC, BrC and the BrC/BC ratio were derived from monthly simulation outputs using Seasonal-Trend decomposition with Loess (STL) (Cleveland et al., 1990) combined with linear regression. Specifically, the time series data were first decomposed into trend (T_t), seasonal (S_t), and residual (R_t) components using STL. Linear regression was then performed on T_t, with the slope representing the long-term trend. This approach is advantageous as it isolates long-term trend from seasonal fluctuations and short-term anomalies, and has therefore been widely used in atmospheric sciences (Biswal et al., 2025; Li et al., 2014; Xu et al., 2023a). It enables a robust assessment of long-term changes in the mass and DRF of BC and BrC, along with their corresponding BrC/BC ratios.

2.3 Random forest and SHAP analysis

A random forest (RF) statistical model, coupled with Shapley Additive exPlanations (SHAP), was used to investigate the contributors of BC, BrC and their mass ratio. RF captures the non-linear responses of these target variables to emissions and meteorology, while SHAP provides feature attribution. This approach is widely used to attribute multiple predictors in atmospheric science (Dai et al., 2023; Hou et al., 2022; Wang et al., 2024).

Here, we first built the RF models separately for each target variable (i.e., BC, BrC, and the BrC/BC ratio) with the following inputs: meteorological variables (temperature, pressure, relative humidity, 10 m wind components) from GEOS-Chem, and emissions of BC, BRpri and AVOC (precursors of BRsec) from inventories. The dataset was randomly split into

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training (80%) and testing (20%) sets. The RF model was trained on the training set, with hyperparameters optimized by 10-fold cross-validation to maximize the mean R^2. The optimized model was then evaluated on the unseen test set. Subsequently, SHAP was used to interpret the contributions of anthropogenic and OBB emissions, and meteorology.

2.4 Observations

Surface observations over East, South and Southeast Asia were collected for model evaluation. Locations of observational sites are shown in Fig. S1. The mass concentrations of BC and OC were compiled from short-term observations at multiple sites (Table S4) and long-term monitoring in Beijing (Ji et al., 2019; Sun et al., 2022), Nanjing (Abulimiti et al., 2025) and Fukue (Kanaya et al., 2020). Here, OC denotes the sum of BrC and scattering OC due to lacking direct measurements of BrC concentration. These data were used to evaluate the model performance in simulating BC and OC concentrations and their long-term variations. In addition, the absorption of OC measured at 365–370 nm was collected to evaluate the simulated BrC absorption, including short-term site observations (Table S5) and long-term observations in Nanjing (Chen et al., 2019; Xie et al., 2020; Text S2).

3. Results and Discussion

3.1 Model evaluation

We first evaluated the simulated BC and OC mass concentrations against observations across East and Indo-Southeast Asia. See Sect. 2.4 for details of observations. The model reproduced the observed levels well, with normalized mean biases (NMB) within ±0.25 (Figs. 1a–1b). Notably, it also successfully captured the long-term trends of BC and OC at urban sites (Beijing and Nanjing), as well as the BC trend at the background site Fukue (OC was not available) (Figs. S2a–S2e). The model thus reliably captures concentration trends in various environments, from emission-dominated urban areas to transport-influenced background sites. Furthermore, in the absence of BrC mass concentration data, we evaluated the model by comparing the simulated BrC absorption ($B_{abs,BrC}$) with OC absorption measurements (details in Sect. 2.4). The simulated $B_{abs,BrC}$ at 370 nm showed good agreement with observed values (NMB: –0.11; Fig. 1c), and its long-term trend in Nanjing was consistent with local observations (Fig. S2f).

Overall, the simulated results demonstrate reasonable accuracy in both the magnitudes and long-term trends of BC and OC concentrations, along with BrC absorption, providing a reliable basis for subsequent analysis of trends in BrC/BC ratios and their radiative forcing implications.

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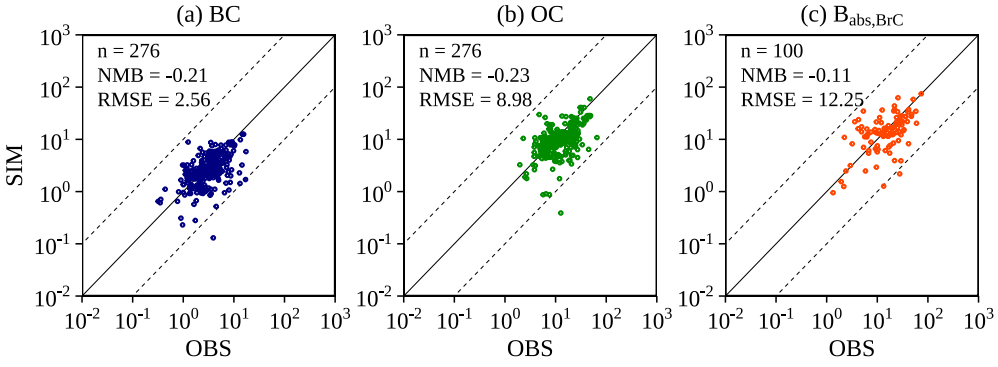

Figure 1. Comparison between simulations (SIM) and observations (OBS): (a) BC and (b) OC mass concentrations (unit: μg m^{-3}), (c) BrC absorption ($B_{abs,BrC}$) at 370 nm (unit: $M \cdot m^{-1}$). Number of data (n), normalized mean bias [$NMB = \sum(SIM - OBS) / \sum OBS$] and root mean squared error [$RMSE = \sqrt{(\sum(SIM - OBS)^2 / n)}$] are shown inset.

3.2 Spatiotemporal trend of BrC/BC

During 2012–2019, the trends in BrC/BC mass ratio exhibited distinct spatial heterogeneity across Asia, particularly in East, South and Southeast Asia (Fig. 2a, regions outlined by blue rectangles), despite their comparable mean ratios (Fig. S3). This distinct pattern highlights the divergent responses of BC and BrC to localized variations in anthropogenic emissions and OBB activities.

East Asia, representing a policy-driven regime, experienced a statistically significant positive trend of +0.021 yr^{-1} ($p < 0.05$; Fig. 2b), corresponding to a relative increase of 14.3% when compared to its multi-year mean BrC/BC of 1.03. This reflects a systematic rise in the relative contribution of BrC to total LACs concentrations under stringent air pollution controls. By contrast, South (near-baseline transition regime) and Southeast Asia (climate-sensitive regime) showed negative trends of −0.006 and −0.013 yr^{-1}, respectively (both $p < 0.05$; Figs. 2c–2d). Relative to their multi-year mean BrC/BC of 0.92 (South Asia) and 0.97 (Southeast Asia), these trends translate to relative reductions of 4.6% and 9.4%, respectively. These contrasting results arise from the different emission trajectories across these three regions, whose underlying drivers will be discussed in detail below using trend and SHAP analysis. The optimized hyperparameters and performance metrics of RF statistical models, which were built to support the SHAP analysis, are presented in Table S6.

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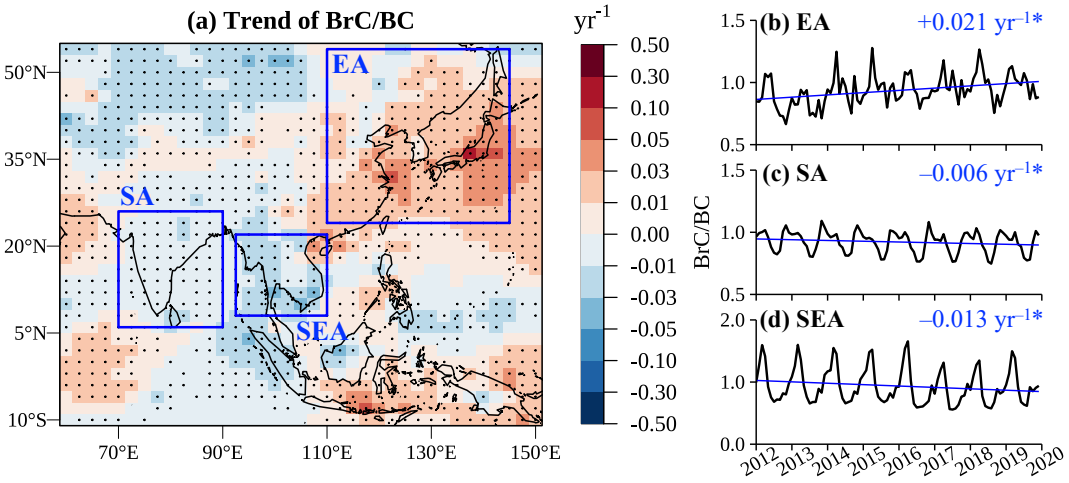

Figure 2. (a) Trends in the BrC/BC mass ratio across Asia for 2012–2019, with dots indicating statistical significance ($p < 0.05$). East Asia (EA), South Asia (SA) and Southeast Asia (SEA) are outlined by blue rectangles. (b-d) Regional mean BrC/BC (black) and corresponding trend (blue), with slope and statistical significance ($p < 0.05$, denoted by *) shown inset.

3.2.1 East Asia

We first examine East Asia, where the BrC/BC ratio increased despite reductions in both BC and BrC concentrations. This upward trend was driven by a disproportionately faster decline in BC (−0.037 μg m^{-3} yr^{-1}) compared to BrC (−0.011 μg m^{-3} yr^{-1}) (Fig. 3a; see Figs. S4a–S4b for time series and source-specific trends). This disparity reflects an unintended consequence of targeted controls on anthropogenic emissions and agricultural open burning.

On one hand, clean air actions targeting fossil fuel used in industry and power generation (Geng et al., 2024; Zheng et al., 2018) have reduced BC more rapidly than BrC. We estimated a rapid decline of −0.049 μg m^{-3} yr^{-1} in anthropogenic BC (Fig. S4a), consistent with the observed trend of –0.06 μg m^{-3} yr^{-1} in China from 2007 to 2019 (He et al., 2023). In contrast, the decline in anthropogenic BrC (i.e., the sum of BRsec and residential BRpri) was considerably slower (−0.039 μg m^{-3} yr^{-1}; Fig. S4b), owing to the relatively weaker reduction in residential combustion and VOC emissions (Geng et al., 2024; Li et al., 2023).

On the other hand, the unexpected increase in agricultural open burning partially offset these anthropogenic reductions, with a greater effect on BrC than BC (Fig. 3a), thus further widening the disparity in their decline rates. Open burning of crop residue accounts for 60%–80% of total OBB emissions in East Asia, especially in northeastern China (Gong et al., 2025; Liu et al., 2022b; Wang et al., 2020). Altough straw burning bans in China have effectively reduced harvest-season burning (Wang et al., 2020; You et al., 2026), satellite observations reveal that open burning still intensifies in winter and spring (Dong et al., 2024; Wang et al., 2020; You et al., 2026). Our simulations captured this seasonal feature (Figs. S5a–S5b), consistent with satellite-retrieved burned area (Chen et al., 2023). Due to its lower combustion efficiency, which favors BrC emission over BC (Wang et al., 2022), the OBB-driven increase in BrC (+0.023 μg m^{-3} yr^{-1}; Figure S4a) was approximately

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twice that of BC (+0.011 μg m^{-3} yr^{-1}; Fig. S4b). This growing contribution of OBB to BrC is further supported by a latest inventory (Zhou et al., 2026).

Consequently, reduction of anthropogenic emissions under air quality regulations, together with concurrent rise in OBB emissions driven by the seasonal redistribution of agricultural burning in response to open-fire restriction policies, results in greater relative BrC abundance in East Asia. The former suppresses BC-rich emissions, whereas the latter enhances BrC-rich emissions, as revealed by SHAP analysis (Figs. S6a–S6b). The meteorological influence was also investigated, which turned out to be relatively minor (Figs. S6a–S6b). Among these, OBB emissions driven by human agricultural activities serve as a more critical factor, with far higher importance of BRpri emissions from OBB than other factors (Fig. 3d). These findings highlight the importance of season-specific strategies for managing agricultural open burning.

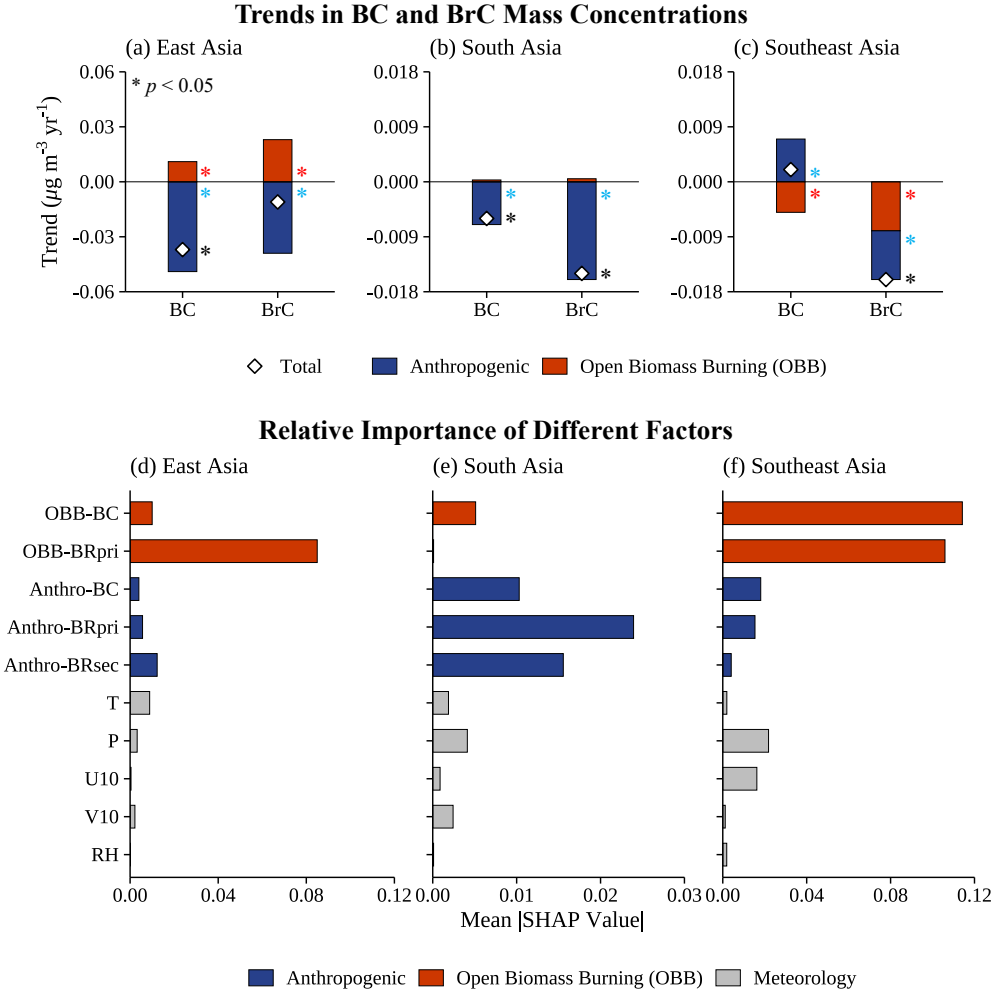

Figure 3. (a-c) Regional Trends in BC and BrC mass concentrations. Anthropogenic BrC is the sum of BRsec and residential BRpri. Asterisks (*) denote the statistical significance ($p < 0.05$) for total (black), anthropogenic (skyblue) and OBB (red) sources. (d-f) Relative importance of emissions (anthropogenic and OBB) and meteorological variables (T: temperature; P: pressure; U10: 10 m zonal wind; V10: 10 m meridional wind; RH: relative humidity).

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3.2.2 South Asia

Despite modest overall emission reductions, South Asia exhibited a declining BrC/BC ratio, driven primarily by asymmetric decreases in anthropogenic BC and BrC (Fig. 3b). In contrast to East Asia, air quality management in South Asia has targeted residential combustion through the promotion of clean household fuels (Roy, 2024). Residential biofuel combustion, the dominant contributor to ambient $PM_{2.5}$ in South Asia (approximately 52%–68%; Reddington et al., 2019), emits BrC preferentially over BC due to its lower combustion efficiency. As a result, the growing use of clean cooking fuels (Gould and Urpelainen, 2018; Roy, 2024) has led to a much larger reduction in BrC (-0.016 μg m^{-3} yr^{-1}; Fig. S4c) than in BC (-0.007 μg m^{-3} yr^{-1}; Fig. S4d), thereby driving the BrC/BC mass ratio downward. This is consistent with a recent modeling study, which similarly found a larger decline in OC than BC driven by residential combustion reductions (Chatterjee et al., 2023). Nevertheless, the adoption of these policies remains challenging due to high costs, weak supply chains, and a habitual reliance on traditional fuels (Roy, 2024; Sharma and Dash, 2022). Therefore, the anthropogenically driven declines in BC and BrC over South Asia are much smaller than those in East Asia (Figs. S4a–S4d).

Moreover, trends in OBB-emitted BC and BrC were negligible and statistically insignificant (Figs. 3b and S4c–S4d). Similar to East Asia, the dominant source of OBB in South Asia is crop residue burning (Yin, 2020). However, due to high costs and difficulties in crop residue collection (Bhuvaneshwari et al., 2019), agricultural open burning remains at stable emission levels without significant declining trends (Majumdar, 2023; Yin, 2020). Consequently, only minor declines were simulated for OBB-emitted BC and BrC in South Asia.

The SHAP analysis also highlights the key role of anthropogenic emissions in modulating BC and BrC mass concentrations and their ratio in South Asia, with their importance exceeding those of open burning and meteorology (Figs. 3e and S6c–S6d). Our results indicate that reductions in residential emissions, even relatively modest, could induce a clear shift in the BrC/BC mass ratio in South Asia. These findings further imply that the BrC/BC mass ratio is more sensitive to source-specific emission changes than to the overall magnitude of emission reductions.

3.2.3 Southeast Asia

Southeast Asia also exhibited a decreasing BrC/BC ratio, resulting from a slightly increasing BC and a decreasing BrC (Fig. 3c). In this wildfire-prone region, both BC and BrC are strongly susceptible to climate-driven variability in natural open burning. Tropical wildfires are highly sensitive to the El Niño/Southern Oscillation (ENSO) (Chen et al., 2017). El Niño events intensify regional drought and promote fire activity, while La Niña events bring anomalously wet conditions that suppress OBB emissions. This ENSO-driven variability caused a substantial drop in OBB emissions in Southeast Asia during the 2017–2018 La Niña event (Hu et al., 2025; Huang et al., 2024), leading to lower BC and BrC. Our simulations well captured this feature (Fig. S5c), showing good agreement with satellite-retrieved burned area (Chen et al., 2023). The SHAP analysis also confirms OBB as the dominant factor in modulating BC and BrC concentrations in Southeast Asia (Figs.

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S6e–S6f). Given the lower combustion efficiency of OBB, a larger decline occurred in BrC (–0.008 μg m^{-3} yr^{-1}; Fig. S4f) than BC (–0.005 μg m^{-3} yr^{-1}; Fig. S4e), thus driving the BrC/BC ratio downward.

In addition, changes in anthropogenic emissions further enhance the declining BrC/BC ratio. Industrialization and urbanization have driven substantial growth in power plant emissions (Liu et al., 2023), while improved access to electricity has simultaneously reduced household combustion (Aleluia et al., 2022; Hoesly et al., 2018; Shyu, 2022). These changes result in a net increase in BC (+0.007 μg m^{-3} yr^{-1}; Fig. S4e) and a decline in BrC (–0.008 μg m^{-3} yr^{-1}; Fig. S4f).

Notably, the SHAP analysis identifies OBB as the dominant factor in modulating the BrC/BC mass ratio in Southeast Asia (Fig. 3f), though anthropogenically- and OBB-driven trends in BC and BrC have comparable magnitudes (Fig. 3c). It is because the substantially higher interannual variability of OBB, which is sensitive to climate events, makes it exert greater influence on the evolving BrC/BC ratio. More importantly, unlike wildfires at high northern latitudes, which exhibit a persistent increasing trend (Zheng et al., 2023; Zhong et al., 2024), OBB in Southeast Asia has experienced notable fluctuations associated with ENSO (Yin, 2020). These variations, in turn, can affect climate through interactions of LACs with radiation and clouds. This underscores the need for greater attention to regional fire-aerosol-climate interactions.

3.3 Radiative effects of BrC/BC trend

We evaluated the shortwave DRF of BC and BrC, as well as their ratio (DRF_{BrC}/DRF_{BC}), over Asia from 2012 to 2019. Our estimates of DRF_{BrC} and DRF_{BC} over East, South and Southeast Asia are comparable to previous studies (Table S7). As shown in Fig. 4a, driven by changes in the BrC/BC mass ratio, the trend of DRF_{BrC}/DRF_{BC} also demonstrated significant spatial heterogeneity. East Asia exhibited a widespread and statistically significant positive trend, indicating the growing relative importance of BrC warming effect with respect to BC. In contrast, South and Southeast Asia showed a generally modest decline.

In East Asia, the DRF_{BrC}/DRF_{BC} increased from 34.1% in 2012 to 41.3% in 2019, driven by a decreasing DRF_{BC} (–0.20 W m^{-2}, from 1.09 W m^{-2}) alongside a relatively stable DRF_{BrC} (–0.005 W m^{-2}, from 0.37 W m^{-2}) (Fig. 4b). The modest change in DRF_{BrC} can be explained not only by the smaller decline in BrC concentrations (Fig. S4b), but also by the weaker absorption capacity of BrC compared to BC (Liu et al., 2015; Saleh, 2020). Anthropogenic emissions alone were responsible for larger declines in DRF_{BC} (–0.23 W m^{-2}) and DRF_{BrC} (–0.007 W m^{-2}). These results are comparable with recent estimates over China from 2014 to 2017 (–0.28 and –0.018 W m^{-2} in DRF_{BC} and DRF_{BrC}, respectively; Yang et al., 2024). However, despite being seasonal (You et al., 2026), increasing OBB emissions offset these anthropogenically driven reductions by 10.6% (DRF_{BC}) and 28.6% (DRF_{BrC}). These findings underscore the critical role of OBB in modulating the relative climate impacts of BrC and BC in this region.

Conversely, the DRF_{BrC}/DRF_{BC} in South Asia decreased from 53.5% to 50.4%, caused by the larger decline in DRF_{BrC} compared to DRF_{BC} (Fig. 4c). This decline is driven by variations in anthropogenic emissions, particularly reductions in residential emissions (Gould and Urpelainen, 2018; Roy, 2024), in line with changes in its BrC/BC mass ratio (see Sect. 3.2.2 for details).

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Southeast Asia, a wildfire hotspot, had the largest DRF_{BrC}/DRF_{BC} (> 70%) among the three regions, but this ratio decreased from 75.4% to 70.5% during 2012–2019 (Fig. 4d). This resulted from opposing changes in DRF_{BC} and DRF_{BrC}. DRF_{BC} increased due to growing anthropogenic emissions outweighing declining OBB emissions (Huang et al., 2024; Liu et al., 2023), whereas DRF_{BrC} decreased from reductions in both sources (Aleluia et al., 2022; Hoesly et al., 2018; Huang et al., 2024), as discussed in Sect. 3.2.3. Notably, OBB once again considerably modulated anthropogenically induced changes, with its decreasing emissions offsetting 50% of the DRF_{BC} increase and contributing 27.2% to the DRF_{BrC} reduction. Together with the findings in East Asia, these results highlight the substantial influence of OBB on regional climate forcing, despite its seasonal nature.

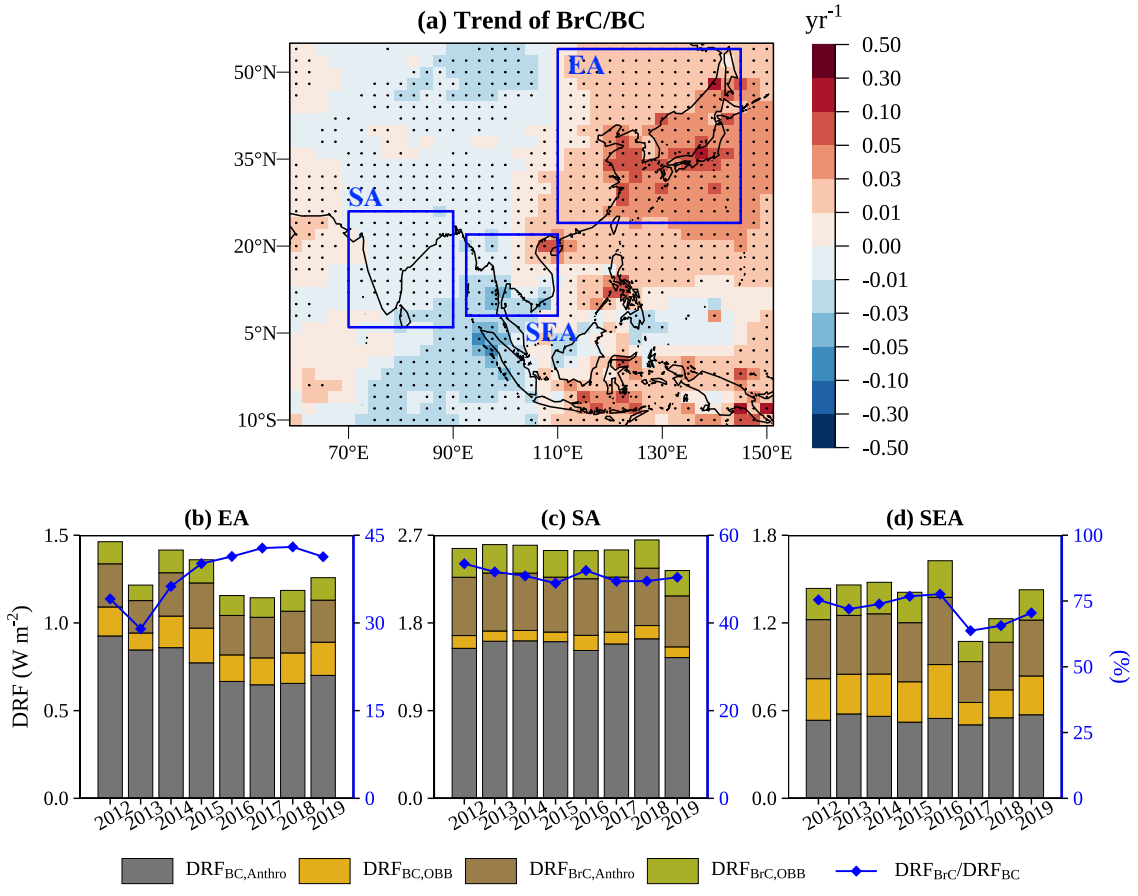

Figure 4. (a) Trends in DRF_{BrC}/DRF_{BC} across Asia for 2012–2019, with dots indicating statistical significance ($p < 0.05$). East Asia (EA), South Asia (SA) and Southeast Asia (SEA) are outlined by blue rectangles. (b-d) Regional DRF of BC and BrC from anthropogenic ($DRF_{BC,Anthro}$, $DRF_{BrC,Anthro}$) and OBB sources ($DRF_{BC,OBB}$, $DRF_{BrC,OBB}$), and the corresponding DRF_{BrC}/DRF_{BC}.

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4. Conclusion

We investigated the responses of BC and BrC to profound variations in anthropogenic and open biomass burning emissions across Asia from 2012 to 2019, along with their key drivers, using the GEOS-Chem model combined with SHAP analysis. The corresponding changes in DRF of BC and BrC, alongside their relative contributions to the DRF of LACs, were also examined. East (policy-driven), South (near-baseline transition) and Southeast Asia (climate-sensitive) were analyzed in particular to inform mitigation strategies under different emission trajectories.

Our results reveal that emission mitigation does not uniformly reduce LACs loading across Asia, but instead drives a spatially heterogeneous redistribution of BC and BrC with distinct radiative consequences. In East Asia, rising OBB emissions from seasonal shifts in crop residue burning under open-fire restrictions slowed the anthropogenically driven declines in BC and BrC concentrations by 22.4% and 59.0%, respectively. Consequently, this elevated the BrC/BC mass ratio and enhanced the radiative importance of BrC, driving an increase in DRF_{BrC}/DRF_{BC} from 34.1% to 41.3%. In contrast, transitions to cleaner fuels and climate-driven wildfire variability drove opposing trends in South and Southeast Asia, respectively, where both the BrC/BC ratio and DRF_{BrC}/DRF_{BC} declined. Notably, in East and Southeast Asia, open burning accounted for up to half of the anthropogenically driven changes in radiative forcing of BC and BrC, underscoring its disproportionate influence on the regional energy budget despite its episodic and seasonal nature.

We note that these estimates are subject to uncertainties inherent in open burning emission inventories, which remain poorly constrained due to the high spatiotemporal variability of fire activity and fuel consumption (Pan et al., 2020; Xu et al., 2023b). Furthermore, the optical properties of BrC, particularly its wavelength-dependent absorption (Laskin et al., 2025; Saleh, 2020) and atmospheric aging-associated photobleaching (Laskin et al., 2025; Qiu et al., 2026), introduce additional uncertainty into radiative forcing estimates that warrants further observational and laboratory constraints. Nevertheless, these uncertainties do not weaken our findings. First, though open burning emissions remain uncertain, their trends are consistent across multiple inventories (Liu et al., 2026). Thus, the simulated trends of OBB-emitted BC and BrC, and their influence on the BrC/BC mass ratio, are robust. Second, photobleaching indeed reduces BrC absorption and may affect the instantaneous DRF_{BRC}/DRF_{BC} ratio, but its impact on the multi-year trend of this ratio is limited, because this effect is unlikely to vary substantially across years. Finally, concentrations of BC and OC, absorption coefficients of BrC, and trends in OBB-emitted BC and BrC are validated against observations. All show good agreement, further supporting the robustness of our results.

Therefore, our results suggest that the open burning, spanning both policy-regulated agricultural burning and climate-sensitive wildfires, plays an increasingly important role in Asia's aerosol-climate system, as clean air policies effectively suppress anthropogenic emissions. Achieving co-benefits for air quality and climate will therefore require integrated management strategies that address open burning in parallel with ongoing anthropogenic emission controls.

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Code and data availability

The GEOS-Chem model is publicly available at https://github.com/geoschem/, and the version we used (v.13.2.0) can be found at http://10.5281/zenodo.5500536. The RRTMG_SW model is publicly available at https://github.com/AER-RC/RRTMG_SW. Observation of BC mass concentration at Fukue is available at https://www.jamstec.go.jp/egcr/e/atmos/observation/topics1.html; other observations of BC and OC mass concentrations are obtained from previous studies, as indicated in the text. Observations of BrC absorption are obtained from previous studies and in-situ measurements, as indicated in the text. Satellite-retrieved burned area is obtained from t https://doi.org/10.5281/zenodo.7668423 (Chen et al., 2023).

Author contributions

YZ: data curation, formal analysis, writing (original draft preparation). AA: data curation, writing (original draft preparation). YLZ: conceptualization, writing (review and editing).

Competing interests

The contact author has declared that none of the authors has any competing interests.

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