

# Period-dependent decoupling of light absorption and absorption efficiency in methanol-soluble BrC in Southwest China

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## Research Article

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# Abstract

Atmospheric brown carbon (BrC) exhibits substantial variability in both atmospheric light absorption and mass-normalized absorption efficiency, yet their responses to changing aerosol conditions are not necessarily synchronous. Here, year-long  $\text{PM}_{2.5}$  samples collected in Southwest China were used to investigate the period-dependent optical properties of methanol-soluble BrC and the roles of organic carbon (OC) and measured chromophores.  $\text{Abs}_{365}$  was markedly enhanced during the late dry season (LDS), coinciding with elevated OC and chromophore concentrations due to long-range transport of biomass burning emission in South/Southeast Asian countries.  $\text{Abs}_{365}$  was strongly correlated with OC over the whole campaign ( $r = 0.88$ ) and particularly during the LDS period ( $r = 0.916$ ), demonstrating the dominant influence of organic aerosol loading on bulk absorption. However,  $\text{MAC}_{365}$  during the LDS period decreased to about two-thirds of its level in the early dry season and wet season, which probably caused by the simultaneous production of weak or non-absorbing organic materials in atmospheric aging processes during long-range transport. Overall, the results demonstrate a clear period-dependent decoupling between atmospheric BrC absorption and OC-normalized absorption efficiency, with enhanced LDS absorption driven primarily by increased organic aerosol loading rather than higher intrinsic absorptivity.

## 1. Introduction

Brown carbon (BrC) is a light-absorbing fraction of atmospheric organic aerosol (OA) that can efficiently absorb solar radiation in the near-ultraviolet (UV) and short-wavelength visible regions and is increasingly recognized as an important climate-forcing component (Andreae and Gelencsér, 2006; Laskin et al., 2015). By absorbing incoming solar radiation, BrC can reduce the amount of shortwave radiation reaching the Earth's surface and convert part of the absorbed energy into heat within the aerosol layer (Zhang et al., 2020). Such absorption alters the vertical distribution of radiative heating and may consequently affect atmospheric stability, boundary-layer development, and regional circulation (Feng et al., 2013). The light absorption of BrC is strongly wavelength dependent and typically decreases rapidly with increasing wavelength from the near-UV to the visible region (Sun et al., 2007). This spectral dependence is governed by the diverse in molecular composition and structures of BrC chromophores, including their functional groups, aromaticity, and degree of conjugation (Tang et al., 2020). Accordingly, the optical properties of BrC are commonly characterized using the light absorption coefficient (Abs), the mass absorption coefficient (MAC), and the absorption Ångström exponent (AAE) (Hennigan et al., 2023; Xie et al., 2019).

Although Abs, MAC, and AAE are commonly used together, they describe distinct aspects of BrC light absorption and are therefore not interchangeable. For methanol-soluble BrC,  $\text{Abs}_{365}$  represents the overall absorption intensity of methanol-extractable BrC in ambient air (Cheng et al., 2016),  $\text{MAC}_{365}$  reflects the OC-normalized absorption efficiency (Ting et al., 2022), and AAE characterizes the wavelength dependence of absorption (Srinivas et al., 2016). Because  $\text{Abs}_{365}$  is determined by both OC

loading and OC-normalized absorption efficiency, a high  $\text{Abs}_{365}$  does not necessarily indicate a high  $\text{MAC}_{365}$  (Cheng et al., 2016; Ting et al., 2022).  $\text{Abs}_{365}$  may increase with rising OC concentrations even when  $\text{MAC}_{365}$  decreases, producing an apparent period-dependent decoupling between total absorption intensity and mass-normalized absorptivity (Kim et al., 2016). Here, decoupling refers to contrasting period-dependent variations in  $\text{Abs}_{365}$  and  $\text{MAC}_{365}$  rather than a complete independence between the two parameters. Concurrent variations in AAE provide complementary information on changes in the wavelength dependence of BrC absorption, which may reflect differences in chromophore sources and composition (Yuan et al., 2020).

However, measured chromophore abundance cannot be directly translated into  $\text{MAC}_{365}$  because the quantified compounds represent only a limited fraction of the methanol-soluble organic aerosol and differ substantially in their intrinsic absorption efficiencies. Individual chromophores may contribute disproportionately to light absorption relative to their OC-normalized mass abundance, while the quantified compounds generally explain only a limited fraction of the total BrC absorption (Jiang et al., 2022; Wang et al., 2024). A simultaneous evaluation of OC loading, chromophore abundance, and  $\text{MAC}_{365}$  is therefore needed to determine whether changes in BrC absorption arise primarily from increased aerosol abundance or enhanced mass-normalized absorptivity.

Xishuangbanna, located along the southwestern border of China and adjacent to mainland Southeast Asia, lies in a tropical rainforest region. Atmospheric conditions in Xishuangbanna vary substantially throughout the year owing to seasonal changes in precipitation, regional fire activity, and air-mass transport, providing a suitable setting for examining the influence of different atmospheric regimes on BrC light absorption. Our previous year-long investigation at this site showed that organic aerosol concentrations were strongly enhanced during the late dry-season burning period, when transboundary biomass burning emissions from mainland Southeast Asia exerted a dominant influence. In contrast, biomass burning influence weakened markedly during the wet season, when biogenic emissions and secondary processing became relatively more important (Dong et al., 2026). These contrasting periods provide a useful framework for investigating how OC loading and chemical composition jointly regulate the optical properties of methanol-soluble BrC. Building on this established temporal framework, the present study investigates the year-round optical properties of methanol-soluble BrC and their relationships with OC loading and quantified chromophores. The primary objectives were to: (1) characterize the year-round and period-specific optical properties of methanol-soluble BrC; (2) quantify the concentrations, OC-normalized mass abundances, and solar-spectrum-weighted absorption contributions of measured chromophores; (3) determine whether changes of  $\text{Abs}_{365}$  during the different periods were driven primarily by increased OC loading or enhanced mass-normalized absorption efficiency.

## 2. Materials and Methods

### 2.1 Sample collection and chemical analysis

PM<sub>2.5</sub> samples analyzed in this study were collected during the same year-long field campaign previously described by Dong et al. (2026). Briefly, ambient PM<sub>2.5</sub> samples were collected in Mengla County, Xishuangbanna Dai Autonomous Prefecture, Southwest China (21°50'N, 101°05'E; 640 m a.m.s.l.) using a medium-volume sampler (16.7 L min<sup>-1</sup>, Genstar®, Qingdao, China). Sampling was conducted every six days from December 8, 2018 to October 29, 2019, with each sample collected for 24 h on quartz fiber filters pre-baked at 450°C for 6–8 h. A total of 51 PM<sub>2.5</sub> samples were obtained, sealed after collection, and stored at – 20°C until analysis. Following the period classification established by Dong et al. (2026), the samples were grouped into the early dry season (EDS; December 2018–January 2019), late dry season (LDS; February–April 2019), and wet season (WS; June–October 2019). May 2019 was treated as a transition interval because sustained wet-season precipitation had not yet developed and regional fire activity remained evident. Samples collected in May were included in the annual time-series and whole-period statistics but excluded from comparisons among the EDS, LDS, and WS periods. Meteorological data, including temperature (T), relative humidity (RH), wind speed, and precipitation, were used to characterize the meteorological conditions during the three periods.

As described in Dong et al. (2026), organic carbon (OC) and elemental carbon (EC) were quantified using a DRI Model 2001 Carbon Analyzer following the IMPROVE thermal-optical reflectance (TOR) protocol. Organic compounds were analyzed by gas chromatography–mass spectrometry (GC–MS; Agilent 7890A GC coupled with an Agilent 5975C mass selective detector) after solvent extraction and derivatization. The quantified organic compounds used in the present study included PAHs, oxygenated PAHs (OPAHs), and nitrophenols. Detailed analytical procedures, quality assurance/quality control, and compound-specific detection limits have been reported previously (Dong et al., 2026; Li et al., 2019).

## 2.2 Light absorption measurements

For light absorption analysis, a 2.284 cm<sup>2</sup> punch from each PM<sub>2.5</sub>-loaded quartz fiber filter was extracted three times with 5 mL of HPLC-grade methanol per extraction in an ice-cooled ultrasonic water bath for 15 min. The combined extracts were filtered through a 0.22 µm Teflon membrane filter to remove insoluble residues, gently evaporated under a stream of nitrogen, and then reconstituted to a final volume of 10 mL with methanol prior to instrumental analysis. The methanol extracts were used for the optical characterization of methanol-soluble BrC.

The light absorption spectra of the methanol extracts were measured using a UV–visible spectrophotometer (UV-6100S, MAPADA Instruments, China) over the wavelength range of 200–1000 nm. Methanol and field-filter blanks were analyzed using the same procedure, and the measured spectra were blank corrected. The wavelength-dependent absorption coefficient of the methanol-soluble extracts,  $Abs_{\lambda}$  (Mm<sup>-1</sup>), was calculated following Hecobian et al. (2010):

$$Abs_{\lambda} = (A_{\lambda} - A_{700}) \frac{V_l}{V_a \times L} \times \ln(10) \text{ (Eq. 1)}$$

where  $A_\lambda$  is the measured absorbance at wavelength  $\lambda$ , and  $A_{700}$  is the absorbance at 700 nm, which was used for baseline correction.  $V_l$  represents the final volume of the methanol extract,  $V_a$  is the sampled air volume corresponding to the filter punch, and  $L$  is the optical path length of the quartz cuvette, which was 1 cm in this study. The factor  $\ln(10)$  was used to convert decadic absorbance measured by the spectrophotometer to a Napierian absorption coefficient. Following previous studies, the absorption coefficient at 365 nm was selected to represent brown carbon light absorption, as this wavelength can reduce potential interference from inorganic species (Zeng et al., 2021).

The OC-normalized mass absorption coefficient ( $MAC_\lambda$ ,  $m^2 g^{-1}$ ) of methanol-soluble BrC at the wavelength of  $\lambda$  was calculated following Wu et al. (2020):

$$MAC_\lambda = \frac{Abs_\lambda}{C_{OC}} \text{ (Eq. 2)}$$

where  $Abs_\lambda$  is the absorption coefficient at wavelength  $\lambda$ , and  $C_{OC}$  is the bulk OC mass concentration corresponding to the sampled air volume. Methanol-soluble organic carbon (MSOC) was not directly measured in this study. Therefore, bulk OC was used as a surrogate for MSOC in the MAC calculation, based on the assumption that OC was completely extractable in methanol (Paraskevopoulou et al., 2023; Xu et al., 2022). This assumption may lead to an underestimation of the MAC of the methanol extracts, although previous studies have reported high extraction efficiencies for methanol extraction of organic aerosols (Chen and Bond, 2010; Liu et al., 2013).

The wavelength dependence of light absorption was described using an empirical power-law relationship following Laskin et al. (2015):

$$Abs_\lambda = K\lambda^{-AAE} \text{ (Eq. 3)}$$

where  $K$  is a wavelength-independent fitting constant, and  $AAE$  is the absorption Ångström exponent. In this study,  $AAE$  was calculated as the negative slope of the linear regression of  $\log(Abs_\lambda)$  versus  $\log(\lambda)$  over a wavelength range of 300–450 nm.

## 2.3 Chromophore-related calculations

In this study, the term “measured chromophores” was operationally used to refer to the targeted PAHs, OPAHs, and nitrophenols included in this study. These compounds represent a selected subset of the broader and chemically complex methanol-soluble BrC chromophore pool (Laskin et al., 2015; Yuan et al., 2020). The OC-normalized abundance of each chromophore was calculated by dividing its atmospheric mass concentration by the corresponding bulk OC concentration after appropriate unit conversion. The contributions of each measured chromophore to methanol-soluble BrC absorption at 365 nm was estimated using their atmospheric concentrations and compound-specific mass absorption coefficients at 365 nm ( $MAC_{i,365}$ ), which were obtained from published measurements of authentic standards (Samburova et al., 2016). Where compound-specific optical parameters were unavailable, values for structurally similar compounds were used as surrogates. The absorption attributable to each

compound was normalized by the measured  $\text{Abs}_{365}$  of the corresponding sample, and the resulting contributions were subsequently summed by compound class. The measured chromophore concentrations are summarized in Table S1, whereas the adopted  $\text{MAC}_{i,365}$  values and estimated absorption contributions are provided in Table 1. Detailed calculation procedures are given in Eqs. S1–S3.

Table 1

Mass absorption coefficients of individual chromophores at 365 nm and their contributions to methanol-soluble BrC light absorption during different atmospheric periods.

|                          | MAC <sub>i,365</sub><br>(m <sup>2</sup> g <sup>-1</sup> ) | Contribution to MS-BrC light absorption at 365 nm (%) |               |               |
|--------------------------|-----------------------------------------------------------|-------------------------------------------------------|---------------|---------------|
|                          |                                                           | EDS                                                   | LDS           | WS            |
| (a) parent-PAHs          |                                                           |                                                       |               |               |
| phenanthrene             | 4.038                                                     | 0.076 ± 0.072                                         | 0.048 ± 0.043 | 0.085 ± 0.135 |
| anthracene               | 4.038                                                     | 0.003 ± 0.002                                         | 0.005 ± 0.002 | 0.01 ± 0.013  |
| fluoranthene             | 4.038                                                     | 0.011 ± 0.005                                         | 0.009 ± 0.004 | 0.01 ± 0.009  |
| pyrene                   | 0.437                                                     | 0.002 ± 0.001                                         | 0.001 ± 0.001 | 0.001 ± 0.001 |
| benzo(a)anthracene       | 1.951                                                     | 0.008 ± 0.004                                         | 0.009 ± 0.005 | 0.005 ± 0.005 |
| chrysene                 | 1.951                                                     | 0.006 ± 0.002                                         | 0.008 ± 0.004 | 0.005 ± 0.004 |
| benzo(b)fluoranthene     | 3.904                                                     | 0.071 ± 0.029                                         | 0.067 ± 0.034 | 0.04 ± 0.038  |
| benzo(k)fluoranthene     | 3.304                                                     | 0.015 ± 0.006                                         | 0.015 ± 0.006 | 0.011 ± 0.011 |
| benzo(a)fluoranthene     | 3.304                                                     | 0.011 ± 0.005                                         | 0.011 ± 0.005 | 0.009 ± 0.009 |
| benzo(e)pyrene           | 8.864                                                     | 0.142 ± 0.059                                         | 0.111 ± 0.058 | 0.101 ± 0.099 |
| benzo(a)pyrene           | 8.864                                                     | 0.071 ± 0.038                                         | 0.079 ± 0.039 | 0.058 ± 0.063 |
| perylene                 | 4.038                                                     | 0.009 ± 0.004                                         | 0.01 ± 0.004  | 0.007 ± 0.006 |
| indeno(1,2,3-cd)pyrene   | 4.475                                                     | 0.063 ± 0.054                                         | 0.089 ± 0.055 | 0.06 ± 0.092  |
| benzo(ghi)perylene       | 8.558                                                     | 0.122 ± 0.094                                         | 0.129 ± 0.071 | 0.105 ± 0.146 |
| dibenzo(a,h)anthracene   | 8.558                                                     | 0.016 ± 0.014                                         | 0.039 ± 0.023 | 0.015 ± 0.024 |
| subtotal                 |                                                           | 0.627 ± 0.358                                         | 0.63 ± 0.294  | 0.522 ± 0.472 |
| (b) OPAHs                |                                                           |                                                       |               |               |
| Benzanthrone             | 5.436                                                     | 0.03 ± 0.013                                          | 0.034 ± 0.015 | 0.018 ± 0.016 |
| 6H-Benzo(cd)pyrene-6-one | 5.436                                                     | 0.071 ± 0.05                                          | 0.109 ± 0.059 | 0.065 ± 0.093 |
| subtotal                 |                                                           | 0.101 ± 0.06                                          | 0.143 ± 0.073 | 0.083 ± 0.108 |
| (c) Nitrophenols         |                                                           |                                                       |               |               |
| 4NP                      | 1.124                                                     | 0.001 ± 0                                             | 0.001 ± 0.001 | 0.001 ± 0     |
| 4NC                      | 3.675                                                     | 0.011 ± 0.008                                         | 0.063 ± 0.037 | 0.004 ± 0.003 |
| 4M5NC                    | 3.624                                                     | 0.006 ± 0.003                                         | 0.044 ± 0.042 | 0.016 ± 0.032 |

|          | MAC <sub>i,365</sub><br>(m <sup>2</sup> g <sup>-1</sup> ) | Contribution to MS-BrC light absorption at 365 nm (%) |               |               |
|----------|-----------------------------------------------------------|-------------------------------------------------------|---------------|---------------|
|          |                                                           | EDS                                                   | LDS           | WS            |
| subtotal |                                                           | 0.018 ± 0.01                                          | 0.108 ± 0.049 | 0.021 ± 0.033 |

### 3. Results and discussion

## 3.1 Temporal and optical characteristics of methanol-soluble BrC

Based on the same year-long PM2.5 sampling campaign, our previous study identified three characteristic periods: the early dry season (EDS; December 2018–January 2019), late dry season (LDS; February–April 2019), and wet season (WS; June–October 2019) (Dong et al., 2026). Backward-trajectory and fire-spot analyses showed that the LDS was characterized by intensive biomass-burning activity over upwind regions of mainland Southeast Asia and prevailing southwesterly air-mass transport toward the sampling site, indicating a strong influence of transboundary long-range transport of biomass-burning emissions. In contrast, the influence of regional biomass burning was substantially weaker during the EDS and WS periods. May 2019 was treated as a transition interval because sustained wet-season precipitation had not yet developed and regional fire activity remained evident. Representative air-mass trajectories and regional fire-spot distributions for the three periods are provided in Fig. S1.

Against this regional background, the temporal evolution of meteorological conditions, particulate matter and carbonaceous components, and the optical properties of methanol-soluble BrC were examined throughout the sampling period. The wavelength-dependent absorption spectra and period-specific distributions were further compared to distinguish changes in atmospheric absorption loading from those in mass-normalized absorption efficiency (Dong et al., 2024; Huang et al., 2018). These results establish the observational basis for the subsequent discussion of the contrasting variations in Abs and MAC.

### 3.1.1 Temporal variations in methanol-soluble BrC and meteorological conditions

Meteorological conditions varied markedly during the sampling period (Fig. 1a and b). Ambient temperature increased from the EDS period to the LDS period, remained relatively high during the WS period, and gradually decreased after September. Precipitation was scarce during the EDS and LDS periods but became frequent after May, with the maximum rainfall occurring in late August. Relative humidity ranged from approximately 38% to 92%, with relatively high values during the EDS and WS periods and lower, more variable values during the LDS period. Wind speed varied between approximately 0.3 and 1.6 m s<sup>-1</sup>, showing greater fluctuations during the LDS period and generally lower values during the WS period. The limited precipitation during the LDS period likely weakened the wet

scavenging of atmospheric particles, whereas the more frequent rainfall during the WS period may have enhanced aerosol removal and contributed to the lower particulate matter concentrations observed during this period (Li et al., 2023).

PM<sub>2.5</sub> and carbonaceous components also showed pronounced temporal variations (Fig. 1c). The PM<sub>2.5</sub> concentration ranged from 4.9 to 144.3  $\mu\text{g m}^{-3}$ , with an annual average of  $37.9 \pm 32.0 \mu\text{g m}^{-3}$ . Continuous elevations in PM<sub>2.5</sub> were observed from late February to late April, and its average concentration during the LDS period reached  $71.0 \pm 32.1 \mu\text{g m}^{-3}$ . OC exhibited a similar temporal pattern, increasing from  $4.0 \pm 1.2 \mu\text{g m}^{-3}$  during the EDS period to  $16.7 \pm 7.9 \mu\text{g m}^{-3}$  during the LDS period, before decreasing to  $2.2 \pm 1.2 \mu\text{g m}^{-3}$  during the WS period. EC and WSOC displayed broadly similar period-dependent variations, with their major increases also concentrated in the LDS period. The average WSOC concentration during the LDS period was  $7.1 \pm 4.9 \mu\text{g m}^{-3}$ . The maximum PM<sub>2.5</sub>, OC and WSOC concentrations occurred in late March, when OC and WSOC reached approximately 27 and 14  $\mu\text{g m}^{-3}$ , respectively. During the WS period, PM<sub>2.5</sub> and carbonaceous components remained at relatively low levels, apart from several short-term increases in August and September. The simultaneous increases in PM<sub>2.5</sub>, OC, and WSOC during the LDS period indicate that carbonaceous aerosols constituted an important component of the enhanced particulate loading. In contrast, their marked decreases during the WS period were consistent with the stronger removal effect associated with frequent precipitation.

The optical properties of methanol-soluble BrC varied substantially throughout the sampling period (Fig. 1d–f). Abs<sub>365</sub> ranged from approximately 1 to 68  $\text{Mm}^{-1}$  over the entire sampling period, with the annual maximum occurring during the May transition interval. Abs<sub>365</sub> was generally below 20  $\text{Mm}^{-1}$  during the EDS period but increased markedly from late February to April. During the LDS period, several values exceeded 30  $\text{Mm}^{-1}$ , with a maximum of approximately 52  $\text{Mm}^{-1}$ . Abs<sub>365</sub> subsequently decreased rapidly and remained mostly below 10  $\text{Mm}^{-1}$  during the WS period. Its temporal variation broadly followed those of PM<sub>2.5</sub>, OC, and WSOC, particularly during the LDS period, suggesting that the enhancement in atmospheric BrC absorption was closely associated with the loading of carbonaceous aerosols. In contrast, MAC<sub>365</sub> fluctuated between approximately 0.3 and 4.0  $\text{m}^2 \text{g}^{-1}$  and did not exhibit a continuous increase during the LDS period. Relatively high MAC<sub>365</sub> values occurred intermittently during the EDS and WS periods, whereas the elevated Abs<sub>365</sub> values observed during the LDS period were not accompanied by corresponding increases in MAC<sub>365</sub>. AAE values ranged from approximately 5.3 to 7.5 and were mostly concentrated between 5.8 and 6.5. The highest AAE value was observed in late August, whereas several relatively low values occurred in late December and early June. Compared with the pronounced temporal variation in Abs<sub>365</sub>, the relatively limited variation in AAE suggests that changes in absorption magnitude were more evident than changes in the overall wavelength dependence of methanol-soluble BrC.

### 3.1.2 Wavelength dependence and period-dependent optical properties

Methanol-soluble BrC exhibited a pronounced wavelength dependence over the measured range of 300–700 nm, with both the absorption coefficient and mass absorption coefficient decreasing rapidly as wavelength increased. The steepest decline occurred between approximately 300 and 400 nm, whereas the decrease became progressively weaker at longer wavelengths. Differences among the three sampling periods were also most evident within the near-UV region (Fig. 2a and b). The Abs spectra were consistently highest during the LDS period, followed by the EDS and WS periods, indicating the greatest atmospheric absorption loading during the LDS period. In contrast, the MAC spectra exhibited a contrasting period-dependent pattern. From 300 nm onward, MAC values were generally highest during the WS period, intermediate during the EDS period, and lowest during the LDS period. The separation among the three curves was most pronounced between approximately 300 and 400 nm, but gradually decreased above 400 nm as the curves converged. Therefore, although the LDS period showed the strongest overall light absorption, its mass-normalized absorption efficiency was lower than that during the EDS and WS periods, providing initial evidence that atmospheric absorption loading and mass-normalized absorption efficiency varied independently among the sampling periods (Lei et al., 2019).

The period-dependent distributions at 365 nm further demonstrated the contrasting behavior of Abs<sub>365</sub> and MAC<sub>365</sub> (Fig. 2c and d). The median Abs<sub>365</sub> values were approximately 8, 20, and 4 Mm<sup>-1</sup> during the EDS, LDS, and WS periods, respectively. Abs<sub>365</sub> during the LDS period varied from approximately 8 to 52 Mm<sup>-1</sup>, which was considerably broader than the ranges observed during the EDS period (approximately 3–14 Mm<sup>-1</sup>) and WS period (approximately 1–8 Mm<sup>-1</sup>). In comparison, the median MAC<sub>365</sub> values were approximately 1.8, 1.5, and 2.0 m<sup>2</sup> g<sup>-1</sup> during the EDS, LDS, and WS periods, respectively. MAC<sub>365</sub> exhibited a relatively narrow range during the LDS period, approximately 1.1–2.1 m<sup>2</sup> g<sup>-1</sup>, whereas broader ranges extending to approximately 2.9 and 3.3 m<sup>2</sup> g<sup>-1</sup> were observed during the EDS and WS periods, respectively. These results indicate that the pronounced increase in Abs<sub>365</sub> during the LDS was not accompanied by a corresponding enhancement in MAC<sub>365</sub>, further supporting the different responses of atmospheric absorption loading and mass-normalized absorption efficiency among the sampling periods.

## **3.2 Concentrations and temporal characteristics of measured chromophores**

### **3.2.1 Concentrations and period-dependent variations of chromophores**

The abundance of the measured chromophores varied substantially among the different atmospheric periods. Their concentrations were generally moderate during the EDS period, increased markedly after the onset of the LDS period, and remained relatively high throughout most of February–April (Fig. 3). Several pronounced peaks occurred during March and April, followed by the highest concentrations during the transitional period in May. After the onset of the WS period, chromophore concentrations

decreased rapidly and remained at relatively low levels during most of June–October, although several isolated increases were observed in late September and October. The elevated chromophore concentrations during the LDS period broadly coincided with the increases in OC and Abs<sub>365</sub>, whereas some exceptionally high values in May occurred outside the three defined sampling periods. Among the measured chromophore classes, PAHs were the most abundant and largely determined the temporal variation in the total measured chromophore concentration. PAH concentrations were generally below approximately 20 ng m<sup>-3</sup> during the EDS period but frequently exceeded 20 ng m<sup>-3</sup> during the LDS period, with several values above 40 ng m<sup>-3</sup>. OPAHs displayed a similar temporal pattern but occurred at lower concentrations. Their concentrations increased progressively during the LDS period, reached a maximum of approximately 17 ng m<sup>-3</sup> in May, and subsequently declined to near-zero levels during most of the WS period. Nitrophenols exhibited more episodic temporal variations than PAHs and OPAHs. Their concentrations were generally low during the EDS period but increased sharply and repeatedly during the LDS period, with several peaks of approximately 10–16 ng m<sup>-3</sup>. The highest nitrophenol concentration was approximately 20 ng m<sup>-3</sup> and occurred during the May transition period. During the WS period, nitrophenol concentrations were close to zero in most samples, except for several isolated peaks. At the molecular level, most individual chromophores also exhibited higher mean concentrations during the LDS period than during the EDS and WS periods (Table S1). Indeno[1,2,3-cd]pyrene and benzo[b]fluoranthene were among the relatively abundant PAHs, whereas 6H-benzo[cd]pyren-6-one was the dominant measured OPAH. Among the nitrophenols, 4-nitrocatechol exhibited the highest mean concentration and showed a pronounced enhancement during the LDS period. These compound-specific variations were generally consistent with the period-dependent patterns observed for the corresponding chromophore classes. These results indicate that the accumulation of measured chromophores during the LDS period involved concurrent increases in PAHs, OPAHs, and nitrophenols, although their temporal variability differed among compound classes.

The period-dependent distributions further confirmed that the measured chromophores were most abundant during the LDS period (Fig. 4). The mean PAH concentration during the LDS period was approximately 24 ng m<sup>-3</sup>, which was about 2.6 and 6.0 times the corresponding mean values during the EDS and WS periods, respectively. More pronounced relative enhancements were observed for OPAHs and nitrophenols. The mean OPAH concentration increased from approximately 1.5 ng m<sup>-3</sup> during the EDS period to 5.6 ng m<sup>-3</sup> during the LDS period, corresponding to an increase by a factor of approximately 3.7, and was more than nine times the WS period value. Nitrophenols exhibited the strongest period-dependent contrast, with a mean concentration of approximately 7.7 ng m<sup>-3</sup> during the LDS period, compared with only approximately 0.4 and 0.2 ng m<sup>-3</sup> during the EDS and WS periods, respectively. Thus, although PAHs represented the largest fraction of the measured chromophore mass, nitrophenols showed the greatest relative enhancement during the LDS period. Correspondingly, the mean concentration of total measured chromophores increased from approximately 11 ng m<sup>-3</sup> during the EDS period to approximately 38 ng m<sup>-3</sup> during the LDS period, before decreasing to approximately 5 ng m<sup>-3</sup> during the WS period. The LDS period value was therefore approximately 3.5 times that during

the EDS period and more than seven times that during the WS period. PAHs accounted for roughly two-thirds of the total measured chromophore concentration during the LDS period, whereas OPAHs and nitrophenols together contributed approximately one-third. In contrast, PAHs contributed a larger proportion of the measured chromophore concentration during the EDS and WS periods. This difference indicates that the LDS period was characterized not only by an increase in the overall chromophore abundance but also by a compositional shift toward larger relative contributions from oxygenated and nitrated aromatic compounds.

The pronounced accumulation of measured chromophores during the LDS was likely related to enhanced combustion-related inputs and limited precipitation, the latter of which may have prolonged their atmospheric persistence by suppressing wet scavenging (Drotikova et al., 2020; Zhu et al., 2016). Enhanced combustion emissions can directly increase particle-bound PAHs, whereas subsequent atmospheric oxidation of parent PAHs and other aromatic precursors may further promote the secondary formation of OPAHs and nitrophenols (Atkinson et al., 1992; Shen et al., 2011). In particular, the much stronger relative increase in nitrophenols than in PAHs suggests that chemical processing of aromatic precursors, in addition to direct emissions, may have contributed to the LDS period enhancement (Finewax et al., 2018; Hartikainen et al., 2018; Salvador et al., 2021). By contrast, the low concentrations observed during the WS period were consistent with reduced regional combustion influence and frequent precipitation, which could lower particle-phase chromophore concentrations through wet scavenging and reduced atmospheric residence times.

The elevated chromophore concentrations during the LDS broadly coincided with the period of enhanced  $\text{Abs}_{365}$ , suggesting that the increased abundance of light-absorbing organic compounds contributed to the high volume-normalized BrC absorption. However, the contribution of each compound class to  $\text{Abs}_{365}$  is not necessarily proportional to its mass concentration because individual chromophores differ substantially in their absorption efficiencies. Therefore, the predominance of PAHs in terms of concentration does not necessarily imply that PAHs dominated the measured light absorption. This distinction provides the basis for further comparing the OC and  $\text{Abs}_{365}$  contributions of the measured chromophores (Xie et al., 2017; Xie et al., 2016).

### **3.2.2 OC-normalized abundances and light absorption contributions of measured chromophores**

Normalization to OC distinguished changes in chromophore composition from variations caused by the overall organic aerosol loading. Among the three measured chromophore classes, PAHs accounted for the largest fraction of OC, with mean PAH-to-OC mass ratios of approximately 0.22%, 0.17%, and 0.19% during the EDS, LDS, and WS periods, respectively (Fig. 5a). Although the absolute PAH concentration was substantially higher during the LDS period, its OC-normalized abundance was lower than that during the EDS period. This indicates that the increase in PAH concentration during the LDS period largely accompanied the overall accumulation of OC rather than representing a preferential enrichment of PAHs relative to bulk organic carbon. The OC-normalized abundance of OPAHs varied less markedly among

the atmospheric periods. The mean OPAH-to-OC mass ratios were approximately 0.035%, 0.038%, and 0.028% during the EDS, LDS, and WS periods, respectively (Fig. 5b). The comparable ratios during the EDS and LDS periods suggest that the enhancement of OPAHs during the LDS period generally occurred in parallel with the increase in OC loading. By contrast, nitrophenols showed a distinct period-dependent pattern. Their mean contribution to OC increased from approximately 0.011% during the EDS period to 0.044% during the LDS period and subsequently decreased to approximately 0.012% during the WS period (Fig. 5c). The nitrophenol-to-OC mass ratio during the LDS period was therefore approximately four times those during the EDS and WS periods, indicating a selective enrichment of nitrated aromatic compounds relative to bulk OC.

The estimated light absorption contributions showed a different pattern from the OC-normalized mass abundances. Parent PAHs were the largest contributors among the measured chromophore classes, accounting for  $0.627 \pm 0.358\%$ ,  $0.630 \pm 0.294\%$  and  $0.522 \pm 0.472\%$  of bulk  $\text{Abs}_{365}$  during the EDS, LDS, and WS periods, respectively (Fig. 5d and Table 1). Despite their substantially higher absolute concentration during the LDS period, the relative contribution of PAHs to  $\text{Abs}_{365}$  remained nearly unchanged compared with the EDS period. This result demonstrates that an increase in PAH mass concentration did not necessarily produce a proportional increase in their relative optical contribution, because the absorption of the entire methanol-soluble organic mixture also increased during the LDS period. OPAHs contributed  $0.101 \pm 0.060\%$ ,  $0.143 \pm 0.073\%$  and  $0.083 \pm 0.108\%$  to  $\text{Abs}_{365}$  during the EDS, LDS, and WS periods, respectively (Fig. 5e). Their estimated absorption contribution was highest during the LDS period, despite the relatively small difference in their OC-normalized abundance between the EDS and LDS periods. This mismatch suggests that changes in the molecular composition of OPAHs, in addition to their total abundance, may have influenced their optical importance. Nitrophenols exhibited the strongest variation in their estimated light absorption contribution. Their mean contribution to  $\text{Abs}_{365}$  increased from  $0.018 \pm 0.010\%$  during the EDS period to  $0.108 \pm 0.049\%$  during the LDS period, before decreasing to  $0.021 \pm 0.033\%$  during the WS period (Fig. 5f). The contribution during the LDS period was approximately six times that during the EDS period and five times that during the WS period. The concurrent increases in nitrophenol concentration, OC-normalized abundance, and  $\text{Abs}_{365}$  contribution indicate that nitrophenols became both more abundant and more optically relevant during the LDS period. This pattern differs from that of PAHs, whose increased absolute concentrations were not accompanied by comparable increases in their OC-normalized abundance or relative absorption contribution.

At the molecular level, the absorption contribution of an individual compound depended jointly on its atmospheric concentration and intrinsic  $\text{MAC}_{365}$  (Table 1). Benzo(e)pyrene and benzo(ghi)perylene consistently were among the largest contributors within the measured PAH group, corresponding to their high  $\text{MAC}_{365}$  values of  $8.864$  and  $8.558 \text{ m}^2 \text{ g}^{-1}$ , respectively. During the LDS period, their contributions to  $\text{Abs}_{365}$  were approximately 0.111% and 0.129%, respectively. Indeno[1,2,3-cd]pyrene also made a relatively large contribution during the LDS period, reaching approximately 0.089%. In contrast, pyrene contributed only approximately 0.001% during the LDS period because of its low  $\text{MAC}_{365}$  of  $0.437 \text{ m}^2 \text{ g}^{-1}$ .

<sup>1</sup>. These differences demonstrate that compounds with relatively high concentrations did not necessarily make the largest absorption contributions when their intrinsic absorption efficiencies were low.

Comparison of the upper and lower panels of Fig. 5 further shows that the mass contributions of the measured chromophores to OC were not directly proportional to their contributions to light absorption. PAHs represented approximately 0.17–0.22% of OC but accounted for approximately 0.52–0.63% of  $\text{Abs}_{365}$ . Similarly, OPAHs contributed approximately 0.03–0.04% of OC but approximately 0.08–0.14% of  $\text{Abs}_{365}$ . During the LDS, nitrophenols represented only approximately 0.044% of OC but contributed approximately 0.108% of  $\text{Abs}_{365}$ . Thus, these aromatic chromophores exerted a disproportionately strong optical influence relative to their minor contributions to total OC, demonstrating that their importance to BrC absorption cannot be inferred from mass abundance alone.

Collectively, PAHs, OPAHs, and nitrophenols explained approximately 0.746%, 0.881%, and 0.626% of bulk  $\text{Abs}_{365}$  during the EDS, LDS, and WS, respectively. This low absorption closure does not imply that the measured compounds were optically irrelevant; rather, it indicates that they represented only a small targeted fraction of the highly complex BrC chromophore mixture. Accordingly, the measured PAHs, OPAHs, and nitrophenols are more appropriately regarded as molecular indicators of changes in BrC composition and atmospheric processing than as a complete representation of the light-absorbing organic fraction. Overall, the comparison between OC-normalized abundance and estimated light absorption contribution reveals a clear mismatch between chromophore mass loading and optical importance. PAHs showed pronounced increases in absolute concentration during the LDS but no corresponding enhancement in their OC-normalized abundance or relative contribution to  $\text{Abs}_{365}$ . In contrast, nitrophenols became enriched relative to OC and made a substantially larger contribution to  $\text{Abs}_{365}$  during the LDS.

### 3.2.3 Relationships of $\text{Abs}_{365}$ and $\text{MAC}_{365}$ with OC and measured chromophores

The contrasting relationships of  $\text{Abs}_{365}$  and  $\text{MAC}_{365}$  with OC and the measured chromophores suggest that bulk methanol-soluble brown carbon (MS-BrC) absorption was primarily associated with organic aerosol loading, whereas its mass-normalized absorption efficiency was more sensitive to variations in chemical composition and intrinsic chromophore absorptivity (Ting et al., 2022; Zhang et al., 2013). Across the entire campaign,  $\text{Abs}_{365}$  was strongly correlated with OC concentration ( $r = 0.88$ ,  $p < 0.001$ ; Fig. 6a). The relationship was particularly strong during the LDS period ( $r = 0.916$ ,  $p < 0.001$ ; Fig. 6c) and remained significant during the WS period ( $r = 0.641$ ,  $p < 0.001$ ; Fig. 6d), whereas no significant relationship was observed during the EDS period (Fig. 6b). These results demonstrate that variations in the volume-normalized absorption of MS-BrC were closely associated with changes in organic aerosol loading, especially during the LDS period. The lack of a significant relationship during the EDS period may partly reflect the relatively small sample size and the limited ranges of both OC and  $\text{Abs}_{365}$ .

Abs<sub>365</sub> also exhibited strong positive correlations with the measured chromophore concentrations over the entire campaign. The correlation coefficients were 0.901 for total measured chromophores, 0.914 for nitrophenols, and 0.858 for PAHs, with all relationships significant at  $p < 0.001$  (Fig. 6e, i, and m). During the LDS period, Abs<sub>365</sub> remained significantly correlated with total measured chromophores ( $r = 0.645$ ,  $p < 0.01$ ), nitrophenols ( $r = 0.763$ ,  $p < 0.001$ ), and PAHs ( $r = 0.498$ ,  $p < 0.05$ , Fig. 6g, k, and o). Among these compound classes, nitrophenols showed the strongest relationship with Abs<sub>365</sub> during the LDS period, consistent with their pronounced increases in absolute concentration, OC-normalized abundance, and estimated absorption contribution during this period. The period-specific relationships, however, were not identical to those obtained for the entire campaign. During the WS period, Abs<sub>365</sub> was significantly correlated with nitrophenols ( $r = 0.588$ ,  $p < 0.01$ , Fig. 6l), whereas its relationships with total measured chromophores and PAHs were not significant (Fig. 6h and p). No significant relationships between Abs<sub>365</sub> and the measured chromophore classes were observed during the EDS period. The stronger correlations observed for the whole-campaign dataset therefore partly reflected the common period-dependent variations in OC, chromophore concentrations, and Abs<sub>365</sub>, including the elevated values observed in several transitional samples. The measured chromophores should consequently be interpreted as sensitive molecular indicators of conditions associated with enhanced MS-BrC absorption rather than as the dominant compounds directly responsible for the bulk Abs<sub>365</sub>.

In contrast to Abs<sub>365</sub>, MAC<sub>365</sub> did not increase with OC loading. A weak but significant negative relationship between MAC<sub>365</sub> and OC was observed over the entire campaign ( $r = -0.314$ ,  $p < 0.05$ , Fig. 7a), while a stronger negative relationship occurred during the WS ( $r = -0.597$ ,  $p < 0.01$ , Fig. 7d). No significant relationships were found during the EDS or LDS periods (Fig. 7b and c). The negative relationship during the WS period indicates that increases in OC were not accompanied by proportional increases in Abs<sub>365</sub>. Instead, the additional organic carbon was likely characterized by relatively weak absorption at 365 nm, thereby reducing the absorption normalized to OC mass. Overall, MAC<sub>365</sub> exhibited a negative association with OC loading, particularly during the WS. No significant relationships were observed between MAC<sub>365</sub> and the total measured chromophore-to-OC mass ratio, either for the entire campaign or within the EDS, LDS, and WS periods (Fig. S2). Although nitrophenols were selectively enriched during the LDS period, variations in the relative abundance of the quantified chromophores alone were insufficient to explain the variability in bulk MAC<sub>365</sub>. This result is consistent with their limited absorption closure and suggests that the mass-normalized absorption efficiency was likely influenced by the broader molecular composition of MS-BrC, including numerous unquantified chromophores as well as weakly or non-light-absorbing organic compounds. These contrasting correlations indicate that Abs<sub>365</sub> and MAC<sub>365</sub> responded differently to changes in organic aerosol abundance, motivating a quantitative evaluation of their period-dependent decoupling in Section 3.4.

### 3.3 Enhanced BrC light absorption during the LDS period

The consistently elevated Abs spectra and Abs<sub>365</sub> values identified the LDS as the period with the highest atmospheric BrC light absorption. This enhancement was observed in multiple consecutive samples rather than being driven by a few isolated high values, indicating that the elevated BrC absorption was a characteristic feature of the LDS period. The enhanced BrC absorption during the LDS period was closely associated with increased OA loading. PM<sub>2.5</sub> and OC concentrations were both significantly higher during the LDS period than during the EDS and WS periods (Fig. 1 and Table 1). The limited precipitation during most of the LDS period likely weakened wet scavenging and favored the accumulation of particulate organic matter. In addition, the strong positive correlation between Abs<sub>365</sub> and OC indicates that the abundance of organic aerosol played an important role in controlling the overall absorption intensity. Therefore, increased organic aerosol loading was the principal mass-related driver of the elevated Abs<sub>365</sub> during the LDS period.

The increase in OA loading was accompanied by higher absolute concentrations of measured chromophores. Nitrophenols, PAHs, OPAHs, and total measured chromophores generally reached their highest concentrations during the LDS period (Figs. 3 and 4). The positive correlations between Abs<sub>365</sub> and several chromophore classes further indicate that the accumulation of light-absorbing organic compounds contributed to the enhanced BrC absorption. This pattern was also consistent with the strong biomass-burning influence previously identified at the same sampling site. Previous source-apportionment and transport analyses showed that biomass burning accounted for approximately 54% of OC during the LDS period, coinciding with extensive upwind fires in Southeast Asia and prevailing southwesterly air-mass transport (Dong et al., 2026). Transboundary biomass burning may therefore have enhanced Abs<sub>365</sub> by increasing the absolute loadings of OA and combustion-related or atmospherically processed chromophores. However, this interpretation is based on previous analyses conducted at the same site rather than an independent source apportionment of BrC absorption in the present study. In addition, the measured compounds represented only a fraction of the chemically diverse BrC chromophore pool, and the observed absorption likely reflected the combined contributions of both measured and uncharacterized light-absorbing species.

Despite the elevated OC and chromophore concentrations, MAC<sub>365</sub> remained relatively low during the LDS period. Although the absolute concentrations of PAHs, OPAHs, and nitrophenols increased, their OC-normalized variations were not uniform. In particular, nitrophenols showed relatively stronger enrichment, whereas PAHs/OC and OPAHs/OC were not correspondingly elevated compared with the other periods. This compositional pattern suggests that the enhanced chromophore burden during the LDS period was not simply proportional across all chromophore classes, but was accompanied by changes in the chemical composition of OA. Given the substantial influence of transported biomass-burning emissions during this period, such changes may partly reflect atmospheric processing of combustion-derived organic compounds during regional transport. Biomass-burning BrC has been reported to undergo substantial chemical and photochemical aging, during which initially absorbing chromophores can be transformed or fragmented into more oxygenated and weakly absorbing products, leading to progressive photobleaching (Forrister et al., 2015; Sumlin et al., 2017). Nitrophenol-related

chromophores may also undergo secondary formation during oxidation of biomass-burning-derived phenolic precursors, followed by further oxidation and fragmentation that reduce their light absorption (Hems and Abbatt, 2018; Zhao et al., 2015). Therefore, the LDS period may have involved both the accumulation of light-absorbing chromophores and the simultaneous production of aged, weakly absorbing organic material.

### 3.4 Decoupled variations in Abs<sub>365</sub> and MAC<sub>365</sub>

Because Abs<sub>365</sub> is the product of bulk OC concentration and OC-normalized MAC<sub>365</sub>, its period-dependent variation may reflect changes in aerosol loading, absorption efficiency, or both. The normalized period averages showed distinctly different variations among OC, Abs<sub>365</sub>, and MAC<sub>365</sub> (Fig. 8a). Relative to the EDS period, OC increased by more than fourfold during the LDS period, whereas Abs<sub>365</sub> increased by approximately threefold. In contrast, MAC<sub>365</sub> decreased to approximately two-thirds of its EDS value. During the WS period, both OC and Abs<sub>365</sub> declined to nearly half of their EDS levels, whereas MAC<sub>365</sub> recovered to a level comparable to that during the EDS period. These contrasting variations demonstrate that the period with the strongest total absorption was not the period with the highest mass absorption efficiency.

To quantitatively distinguish the effects of aerosol loading and mass-normalized absorption efficiency, the period-to-period changes in Abs<sub>365</sub> were separated into an OC-loading effect and a MAC<sub>365</sub> effect (Fig. 8b). The interaction associated with simultaneous changes in OC and MAC<sub>365</sub> was equally allocated to the two effects, ensuring that their sum equaled the total change in Abs<sub>365</sub>. From the EDS to the LDS period, the increase in OC made a strong positive contribution to Abs<sub>365</sub>, whereas the decrease in MAC<sub>365</sub> partially offset this enhancement. The resulting increase in Abs<sub>365</sub> was therefore dominated by the OC-loading effect. From the LDS to the WS period, the pronounced decrease in OC produced a large negative contribution, while the recovery of MAC<sub>365</sub> provided only a relatively small positive contribution. Consequently, Abs<sub>365</sub> decreased markedly despite the increase in mass-normalized absorption efficiency. The smaller decrease from the EDS to the WS period was also mainly attributable to reduced OC loading because their mean MAC<sub>365</sub> values were relatively similar.

The sample-level relationship between OC and MAC<sub>365</sub> further illustrates this decoupling (Fig. 8c). Most LDS period samples were distributed in the high-OC and low-to-moderate-MAC<sub>365</sub> region, whereas samples from the EDS and WS periods generally had lower OC concentrations but included several relatively high MAC<sub>365</sub> values. Thus, high organic aerosol loading did not necessarily correspond to high absorption efficiency. However, this apparent inverse relationship should not be interpreted as a direct suppressive effect of OC on MAC<sub>365</sub>. Instead, it more likely reflects period-dependent differences in organic aerosol composition. The accumulation of nonabsorbing or weakly absorbing organic compounds during high-loading periods may dilute the contribution of strongly absorbing chromophores within the bulk OC pool, thereby lowering the overall MAC<sub>365</sub>. Similar variations in BrC absorptivity have been attributed to changes in the relative abundance of absorbing and nonabsorbing organic

components and to atmospheric aging processes (Wong et al., 2019). Differences in chromophore abundance, molecular structure, degree of conjugation, and atmospheric processing may also alter  $\text{MAC}_{365}$  independently of total OC loading (Saleh et al., 2013).

The observed decoupling highlights the need to evaluate  $\text{Abs}_{365}$  and  $\text{MAC}_{365}$  together.  $\text{Abs}_{365}$  characterizes the total atmospheric absorption burden but can increase simply because of organic aerosol accumulation, even when the average absorption efficiency decreases. In contrast,  $\text{MAC}_{365}$  reflects composition-dependent absorption efficiency but does not represent the total amount of light absorbed in the atmosphere. Considering  $\text{Abs}_{365}$  alone may therefore lead to an increase in aerosol loading being misinterpreted as enhanced intrinsic absorptivity, whereas considering  $\text{MAC}_{365}$  alone may underestimate the importance of polluted periods with high total absorption. The combined analysis of OC,  $\text{Abs}_{365}$ , and  $\text{MAC}_{365}$  provides a more complete distinction between the effects of aerosol abundance and chemical composition on methanol-soluble BrC absorption.

## 4. Conclusion

Methanol-soluble BrC exhibited pronounced period-dependent differences in atmospheric absorption and mass-normalized absorption efficiency.  $\text{Abs}_{365}$  was highest during the LDS period and increased concurrently with  $\text{PM}_{2.5}$ , OC, and measured chromophore concentrations. However,  $\text{MAC}_{365}$  did not increase synchronously and remained relatively low to moderate, while AAE varied within a comparatively narrow range. These results show that the strongest BrC absorption was mainly expressed as an increase in absorption magnitude rather than a marked change in wavelength dependence or absorption efficiency per unit OC mass. PAHs dominated the measured chromophore mass, whereas nitrophenols showed the strongest enrichment relative to OC and the largest increase in their estimated contribution to  $\text{Abs}_{365}$  during the LDS period. The strong  $\text{Abs}_{365}$ –OC relationship and the decomposition analysis showed that the elevated absorption during the LDS period was dominated by increased organic aerosol loading, while the concurrent decrease in  $\text{MAC}_{365}$  partially offset this enhancement. This contrasting response provides observational evidence for a period-dependent decoupling between bulk BrC absorption and OC-normalized absorption efficiency. This contrast provides direct evidence for the period-dependent decoupling between BrC absorption loading and mass-normalized absorption efficiency.

## Declarations

## Declaration of interests

☐ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

✉ The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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## Figures

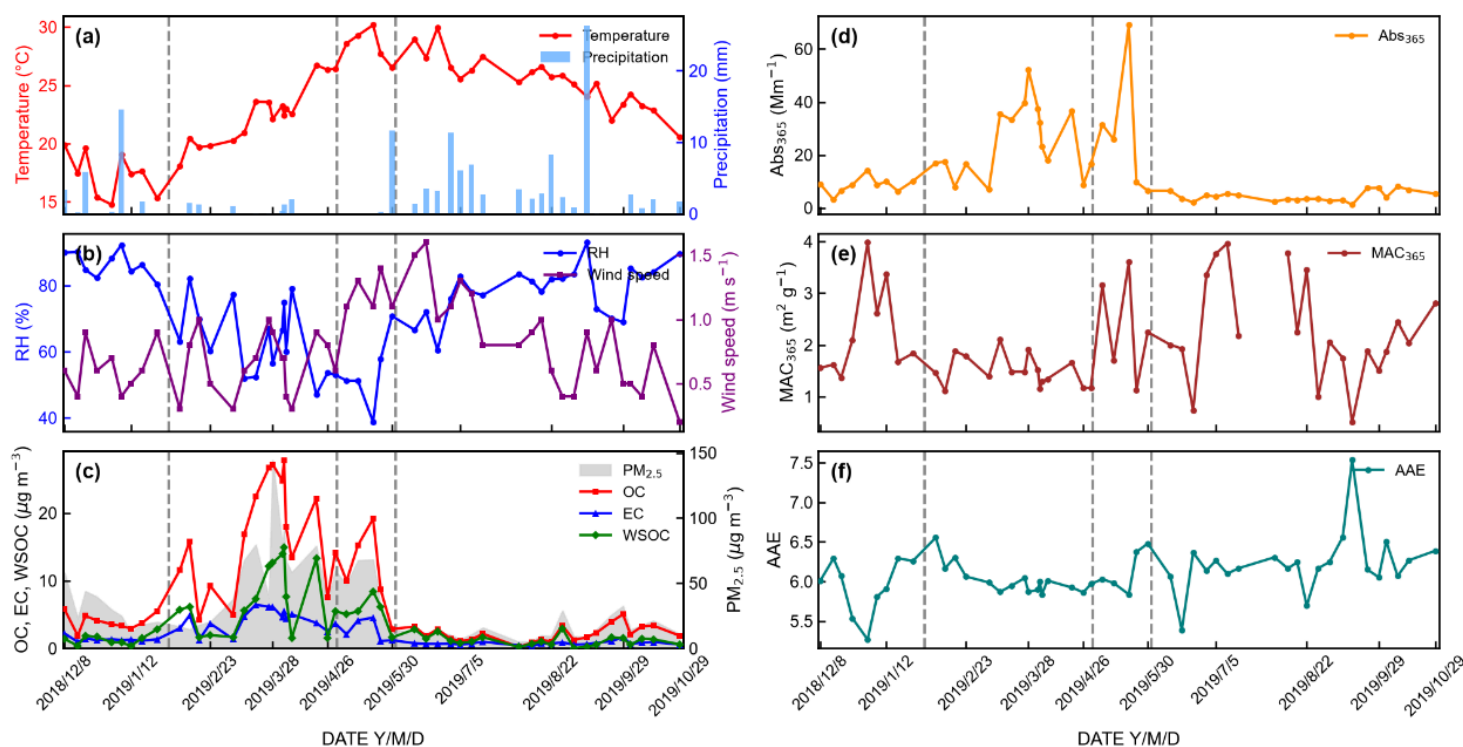


Figure 1

Temporal variations in meteorological conditions, PM2.5 and carbonaceous components, and optical properties of methanol-soluble brown carbon during the sampling period.

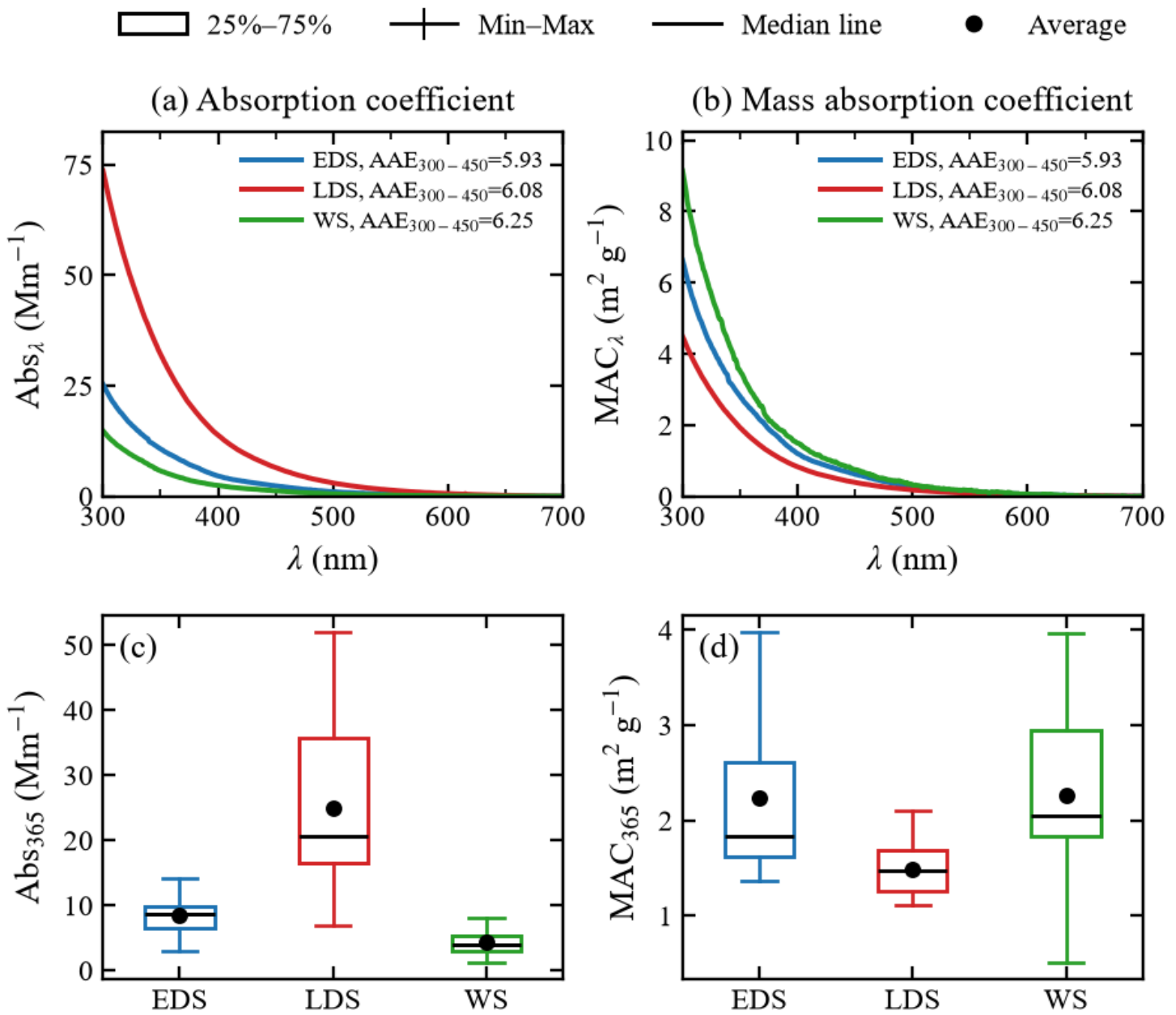


Figure 2

Wavelength-dependent optical properties and period-specific distributions of methanol-soluble BrC during the EDS, LSD, and WS periods.

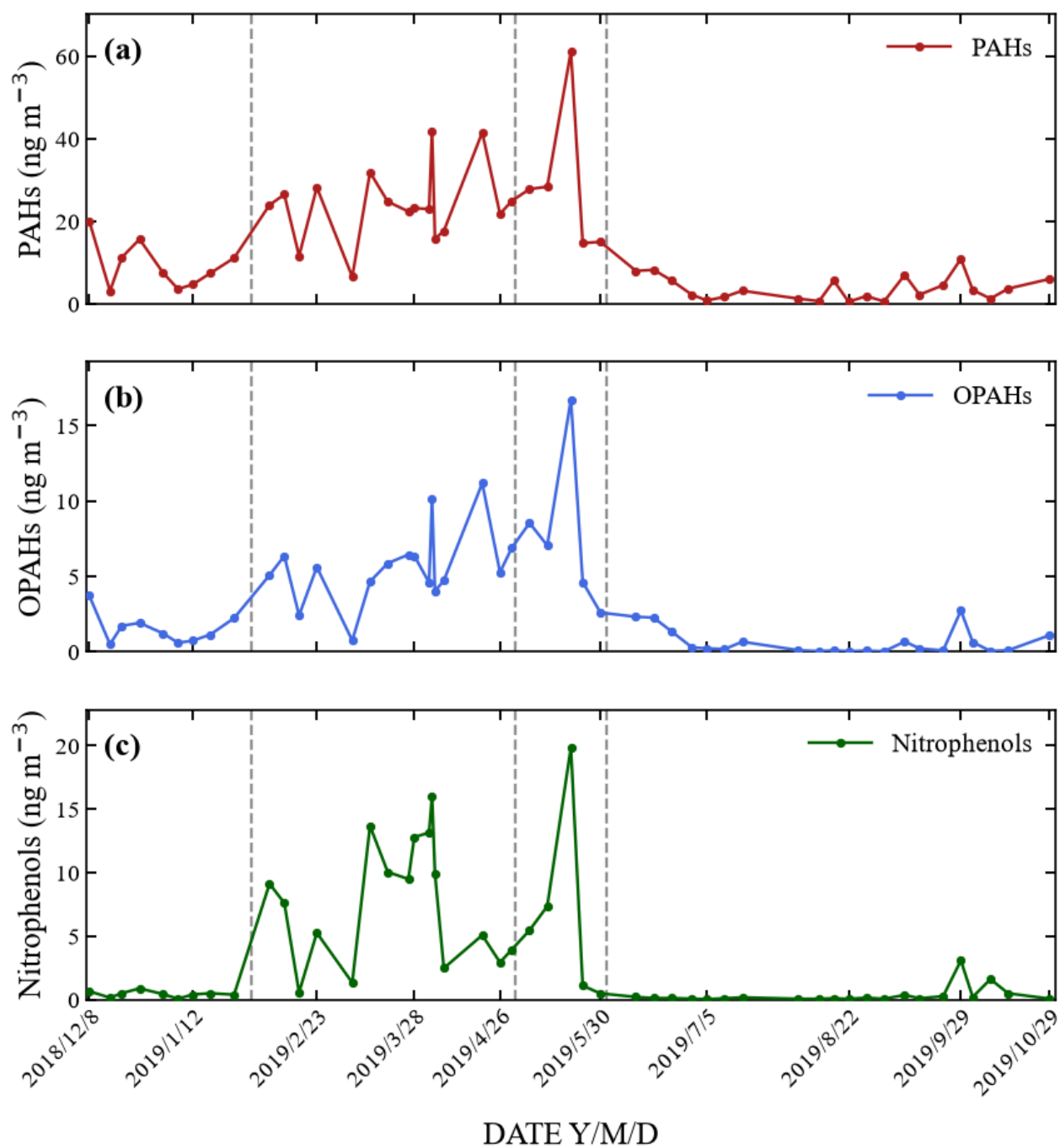


**Figure 3**

Temporal variations in the concentrations of measured chromophores during the sampling period.

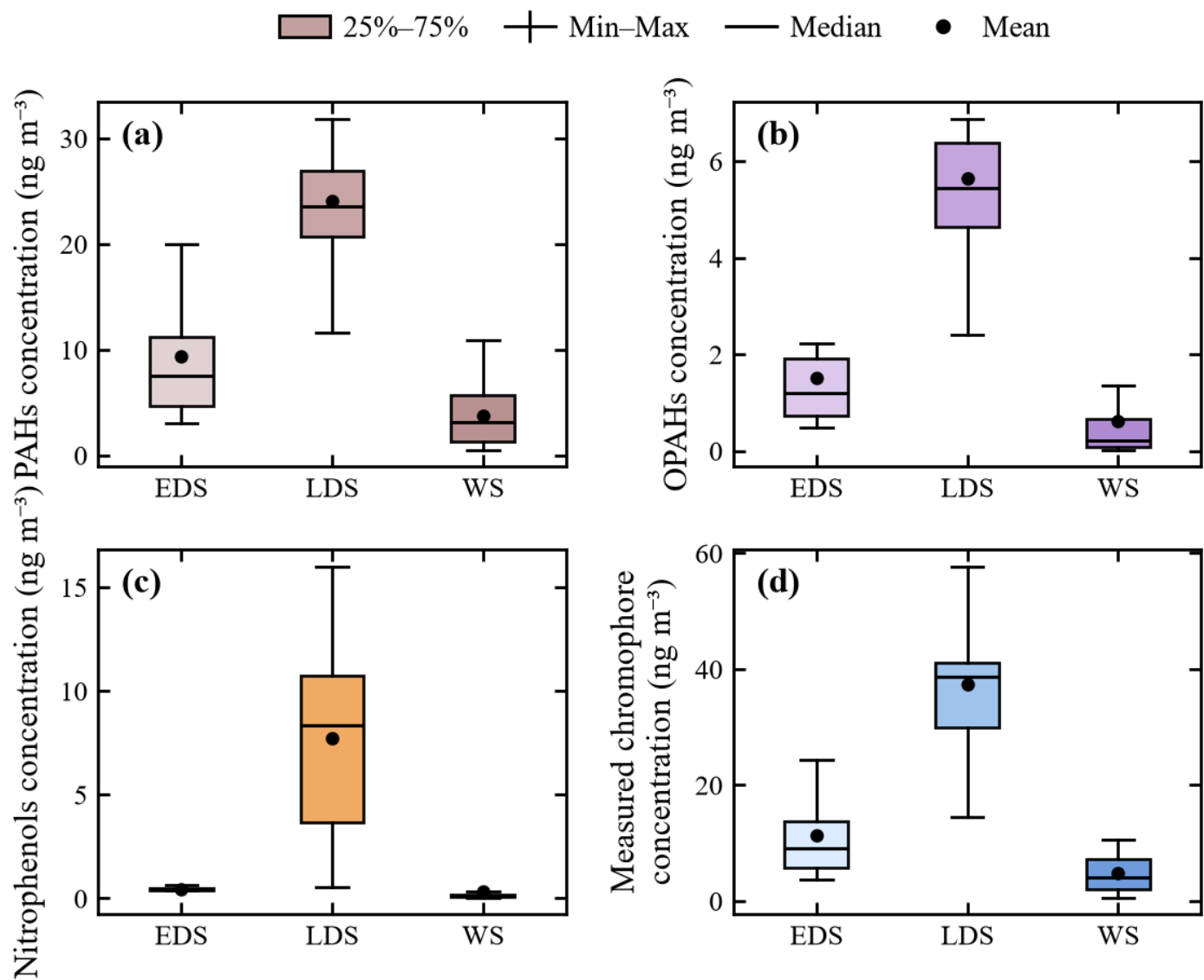


**Figure 4**

Period-dependent distributions of the concentrations of measured chromophores.

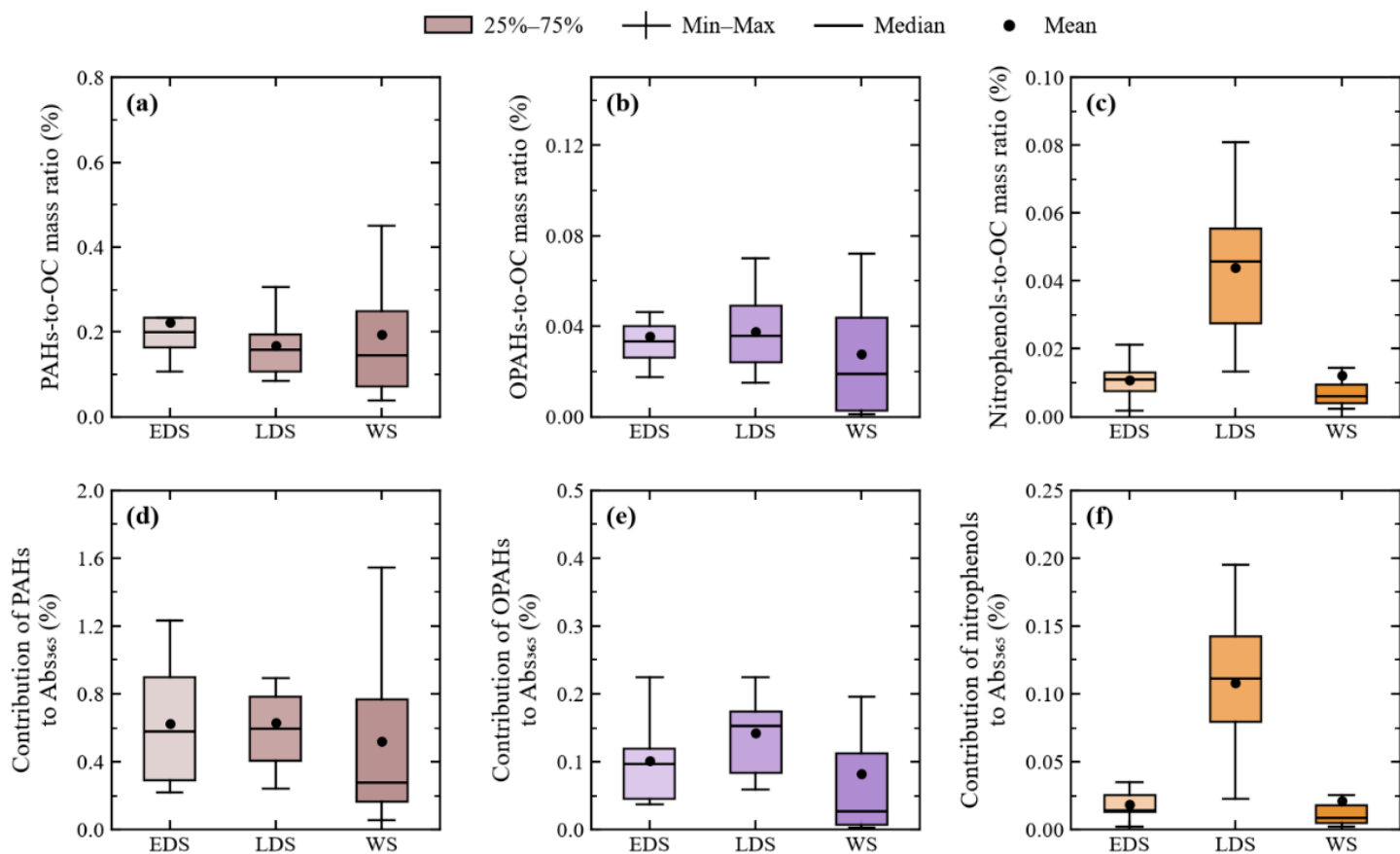


**Figure 5**

OC-normalized mass ratios and estimated contributions of measured chromophores to MS-BrC light absorption at 365 nm during different atmospheric periods.

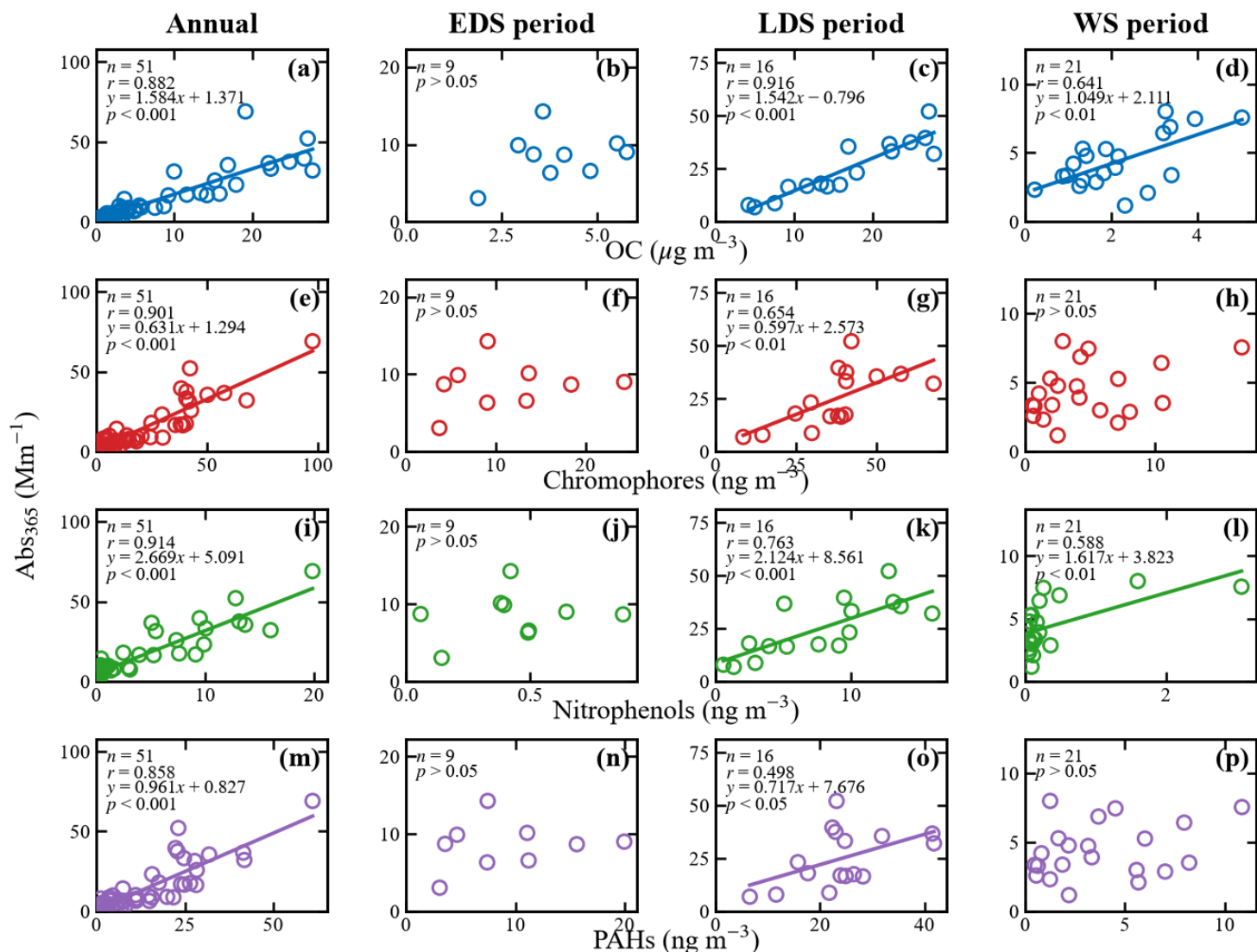


**Figure 6**

Relationships of  $Abs_{365}$  with OC and measured chromophore concentrations during the entire campaign and different atmospheric periods.

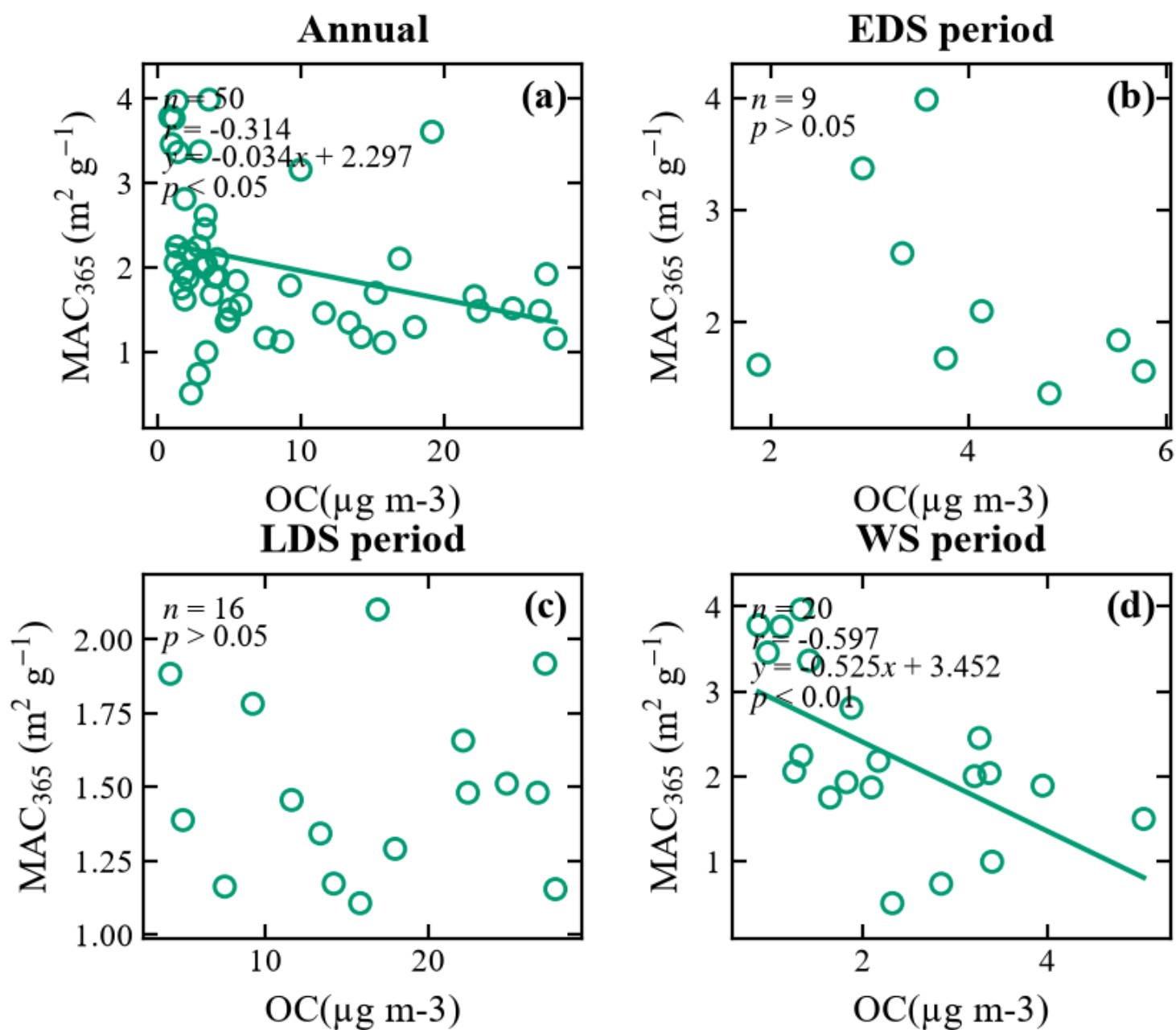


**Figure 7**

Relationships between MAC<sub>365</sub> and OC concentration during the entire campaign and different atmospheric periods.

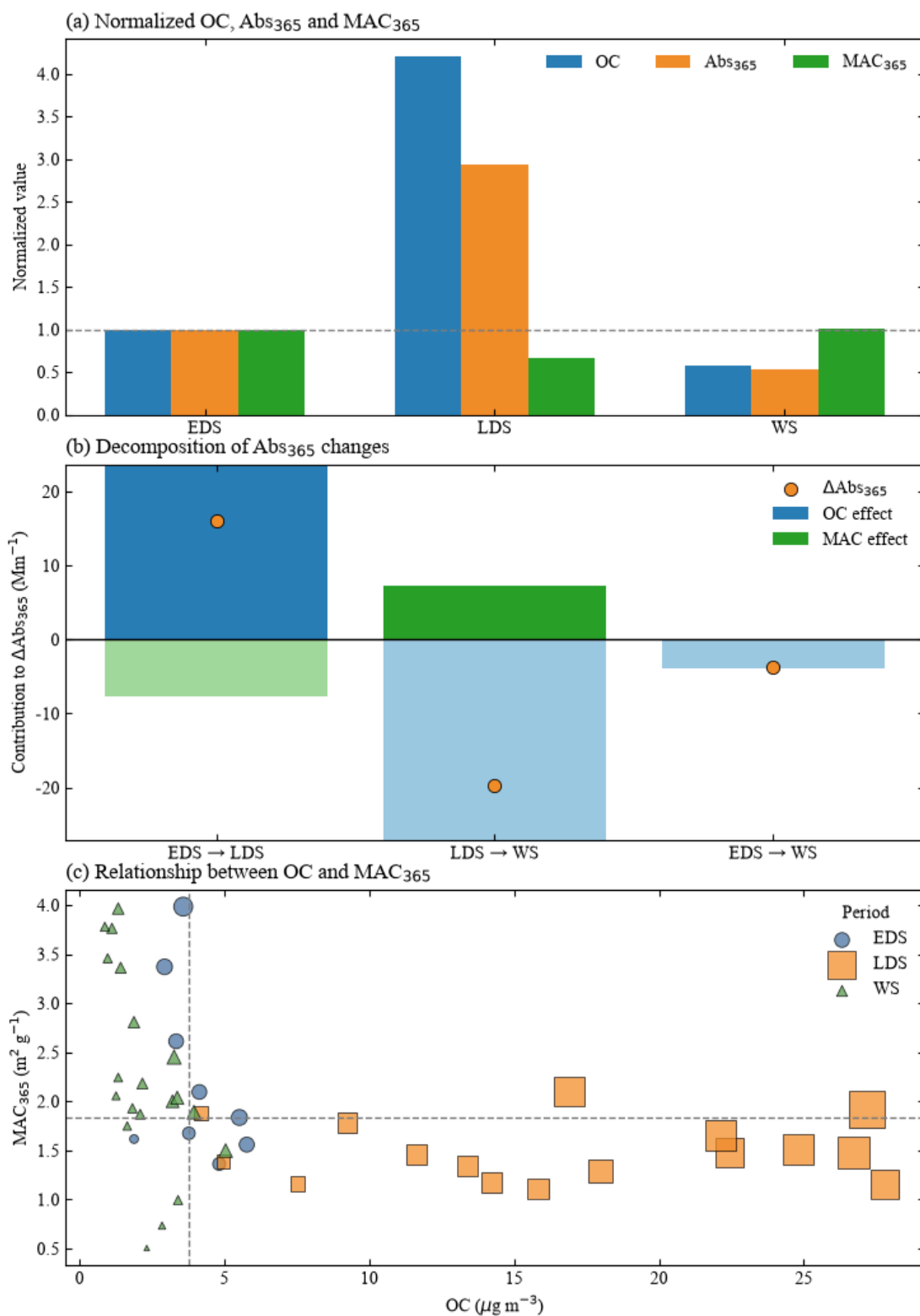


**Figure 8**

Decoupled variations in Abs<sub>365</sub> and MAC<sub>365</sub> among different atmospheric periods.

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