Aerosol light absorption in a coastal city in Southeast China: Temporal variations and implications for brown carbon

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Abstract

Light-absorbing carbonaceous aerosols including black carbon (BC) and brown carbon (BrC) play significant roles in atmospheric radiative properties. One-year measurements of aerosol light absorption at multi-wavelength were continuously conducted in Xiamen, southeast of China in 2014 to determine the light absorption properties including absorption coefficients ($\sigma_{abs}$) and absorption Ångström exponent (AAE) in the coastal city. Light absorptions of BC and BrC with their contributions to total light absorption were further quantified. Mean $\sigma_{abs}$ at 370 nm and 880 nm were 56.6 ± 34.3 and 16.5 ± 11.2 Mm⁻¹, respectively. $\sigma_{abs}$ presented a double-peaks diurnal pattern with the maximum in the morning and the minimum in the afternoon. $\sigma_{abs}$ was low in warm seasons and high in cold seasons. AAE ranged from 0.26 to 2.58 with the annual mean of 1.46, implying that both fossil fuel combustion and biomass burning influenced aerosol optical properties. $\sigma_{abs}$ of BrC at 370 nm was 24.0 ± 5.7 Mm⁻¹, contributing 42% to the total absorption. The highest AAE (1.52 ± 0.02) and largest BrC contributions (47% ± 4%) in winter suggested the significant influence of biomass burning on aerosol light absorption. Long-distance air masses passing through North China Plain and the Yangtze River Delta led to high AAE and BrC contributions. High AAE value of 1.46 in July indicated that long-range transport of the air pollutants from intense biomass burning in Southeast Asia would affect aerosol light absorption in Southeast China. The study will improve the understanding of light absorption properties of aerosols and the optical impacts of BrC in China.

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Introduction

Atmospheric aerosols play significant roles in visibility impairment, air quality deterioration and climate change by absorbing solar radiation (Jacobson, 2001; Bellouin et al., 2005; Deng et al., 2011, 2013; Jo et al., 2016; Zuidema et al., 2016). Among the aerosols, light-absorbing carbonaceous components directly and indirectly influence global climate by changing earth radiation balance (Bond et al., 2013; Feng et al., 2013). Black carbon (BC) is the most efficient light-absorbing aerosol, absorbing solar radiation...
across ultraviolet (UV) to infrared (IR) spectrum (Bond and Bergstrom, 2006; Ramanathan and Carmichael, 2008; Moosmüller et al., 2009; Lack and Langridge, 2013). BC is regarded as the third most important anthropogenic climate-warming agent after carbon dioxide and methane (IPCC, 2013). Recent studies have revealed that some organic carbon aerosols called “brown carbon (BrC)” show strong absorption in UV regions (Andreae and Gelencsér, 2006; Bahadur et al., 2012; Liu et al., 2013; Utry et al., 2014; Olson et al., 2015; Saleh et al., 2015; Wang et al., 2016). Different from BC, light absorption of BrC is closely associated with wavelength (Andreae and Gelencsér, 2006; Cheng et al., 2011, 2016; Feng et al., 2013; Park and Son, 2017). Primary emissions from incomplete combustions of fossil fuel and biomass are considered as the sources of both BC and BrC (Bond et al., 2013; Bosch et al., 2014; Liu et al., 2015; Lu et al., 2015; Yan et al., 2015). In addition, BrC can also be formed through aqueous-phase or heterogeneous chemical reactions (Lukács et al., 2007; Zhang et al., 2011; Updyke et al., 2012; Powlision et al., 2014).

Aerosol light absorption has been widely concerned in many studies due to its important impacts on atmospheric radiative forcing and visibility degradation. Many efforts have been made to investigate light absorption coefficient of aerosols (Horvath, 1995; Weingartner et al., 2003; Petzold and Schönlinner, 2004; Arnott et al., 2005; Fialho et al., 2005; Zhuang et al., 2015; Ran et al., 2016; Park and Son 2017). Several studies also focused on absorption Ångström exponent (AAE) which was used to describe the wavelength dependence of light absorption (Russell et al., 2010; Chung et al., 2012; Lack and Langridge, 2013; Utry et al., 2014; Zotter et al., 2017). However, previous studies mostly directed toward light absorption of BC aerosol, since it is difficult to directly identify optical properties of BrC due to its complex constituents (Cheng et al., 2011; Feng et al., 2013; Kirillova et al., 2014a, 2014b). In recent years, there are a few but limited studies aiming at continuous measurement of light absorption of BrC, although BrC has been proved to exist in the atmosphere and enhance the absorption of solar radiation. Lack and Langridge (2013) determined BrC light absorption at short-wavelength by using the AAE method. Higher BrC absorption contribution at 405 nm was observed in winter in the rural area because of biomass burning events nearby (Yuan et al., 2016). AAE of BrC at Lulang and Lhasa were investigated according to the measurements with an Aethalometer (Zhu et al., 2017). In a word, optical properties of BrC have attracted substantial attentions due to their impacts on atmospheric radiation especially shortwave radiation.

The Western Taiwan Strait (WTS) region is an urbanized area with fast economic development located in Southeast China, covering the area of Fujian Province and parts of Zhejiang Province, Guangdong Province and Jiangxi Province. Although the WTS does not belong to the area with high emission and high pollution, air quality in this region is affected by the pollutants transported from the high-polluted regions such as the Yangtze River Delta (YRD) in the north and the Pearl River Delta (PRD) in the southwest under certain meteorological conditions, since the WTS is adjacent to both the YRD and the PRD. Optical properties including light absorption and light scattering of wintertime aerosols at the single wavelength of 870 nm in the central city Xiamen in the WTS with the impacts of aerosol chemical components have been investigated (Deng et al., 2016). However, continuous study on light absorption at multi-wavelength has never been reported in the WTS. Neither the optical properties of BrC including light absorption and its wavelength dependence have been continuously measured.

In this study, aerosol light absorption properties including absorption coefficient (σ_{abs}) and AAE were studied based on one-year continuous online measurements by Aethalometer in the coastal city Xiamen in the WTS from January to December in 2014. Temporal variations of aerosol light absorption were analyzed. The AAE method was adopted to further investigate absorption properties of BrC. The impacts of long-range transport and biomass burning on aerosol light absorption were also studied. This is the first year-round continuous research on aerosol light absorption in the WTS. Furthermore, an attempt was made to discuss the indicating function of BrC and similar studies are not much at present.

1. Methodology

1.1. Observation station and instruments

The observation station is located at the Institute of Urban Environment, Chinese Academy of Sciences (IUECAS, 118°03'E, 24°36'N) in Xiamen. The IUECAS site is 15 km away from the city center of Xiamen. There are no big industrial pollution sources and only several roads and construction sites within 5 km radius around the observation site. The measuring instruments were set on the roof of a building with two floors at the IUECAS site.

One-year continuous measurements of aerosol light absorption from January 1 to December 31 in 2014 were conducted at the IUECAS site. A 7-wavelength Aethalometer (AE-31, Magee Scientific, USA) with a PM_{2.5} (particulate matters with aerodynamic diameter less than 2.5 μm) inlet was used to measure the aerosol light absorption coefficients at 370, 470, 520, 590, 660, 880 and 950 nm with a temporal resolution of 5 min. The method of determining aerosol light absorption by Aethalometer is measuring the attenuation (ATN) of light beam transmitted through the sample accumulated on quartz fiber filter (Hansen et al., 1984). The sample flow rate of Aethalometer was set to be 4.7 L/min.

1.2. Calculation of aerosol absorption coefficient

Light absorption coefficient of aerosols can be calculated based on the measured light attenuation at seven wavelengths as shown in Eq. (1):

\[
\sigma_{\text{ATN},\lambda} = \frac{(\text{ATN}(\lambda) - \text{ATN}_{-1}(\lambda))}{\Delta t} \times \frac{A}{V}
\]

(1)

where, Δt (min) is the time interval between t and t−1, λ is the wavelength of light, A (m²) is the area of the filter spot, and V (L/min) is the volumetric sampling flow rate.

Actually, light attenuation σ_{ATN} is larger than light absorption coefficient σ_{abs}. Therefore, it is necessary to introduce calibration factors C and R to correct the value as shown in Eq. (2) (Weingartner et al., 2003; Schmid et al., 2006):

\[
\sigma_{\text{abs},\lambda} = \frac{\sigma_{\text{ATN},\lambda}}{C \times R}
\]

(2)
Dependence of calibration factor $R$ on wavelengths is expressed in Eq. (3):

$$ R(\lambda) = \left( \frac{1}{f} - 1 \right) \times \frac{\ln(\text{ATH}(\lambda)) - \ln 10}{\ln 50 - \ln 10} + 1 \quad (3) $$

An empirical value $f = 1.2$ was suggested by Schmid et al. (2006). In urban sites, the values of C were 2.95, 3.37, 3.56, 3.79, 3.99, 4.51 and 4.64 at 370, 470, 520, 590, 660, 880 and 950 nm, respectively (Schmid et al., 2006; Zhuang et al., 2015).

### 1.3. Determination of absorption Ångström exponent

Spectral dependence analysis of aerosol light absorption is important for research on direct effects of aerosol climate forcing or source apportionment. Therefore, the wavelength dependence of aerosol light absorption in Xiamen was further investigated. AAE is a widely used parameter to describe the wavelength dependence of the light absorption. AAE can be obtained via fitting analysis based on the assumption that $\sigma_{abs}$ has the power-law relationship with the wavelength: $\sigma_{abs}(\lambda) \propto \lambda^{-\text{AAE}}$ (Moosmüller et al., 2011).

Besides, a simplified calculation of AAE can be expressed in Eq. (4):

$$ \text{AAE} = -\ln \left( \frac{\sigma_{abs,\lambda_1}}{\sigma_{abs,\lambda_2}} \right) / \ln \frac{\lambda_1}{\lambda_2} \quad (4) $$

In this study, $\lambda_1$ and $\lambda_2$ were set at 370 and 880 nm, respectively, following the study of Zotter et al. (2017).

### 1.4. Attribution of BrC and BC

A two-component model was adopted to apportion the light absorption coefficient into BrC and BC contributions. The calculated absorption coefficient was assumed to be the sum of the absorption coefficients of BC ($\sigma_{abs,BC}$) and BrC ($\sigma_{abs,BrC}$) (Massabò et al., 2015):

$$ \sigma_{abs}(\lambda) = \sigma_{abs,BC}(\lambda) + \sigma_{abs,BrC}(\lambda) \quad (5) $$

Both $\sigma_{abs,BC}$ and $\sigma_{abs,BrC}$ dependence on wavelength followed the relationship $\sigma_{abs}(\lambda) \propto \lambda^{-\text{AAE}}$. Thus, the related equations can be written as:

$$ \frac{\sigma_{abs,BC}(\lambda)}{\sigma_{abs,BC}(\lambda_{ref})} = \left( \frac{\lambda}{\lambda_{ref}} \right)^{-\text{AAE}_{BC}} \quad (6) $$

$$ \frac{\sigma_{abs,BrC}(\lambda)}{\sigma_{abs,BrC}(\lambda_{ref})} = \left( \frac{\lambda}{\lambda_{ref}} \right)^{-\text{AAE}_{BrC}} \quad (7) $$

where $\lambda_{ref}$ is the reference wavelength. AAE$_{BC}$ and AAE$_{BrC}$ are the absorption exponent of BC and BrC, respectively.

Eqs. (5), (6) and (7) can be joined and shown as Eq. (8):

$$ \sigma_{abs}(\lambda) = (BC \times MAC_{\lambda_{ref}BC}) \times \left( \frac{\lambda}{\lambda_{ref}} \right)^{-\text{AAE}_{BC}} + (BrC \times MAC_{\lambda_{ref}BrC}) \times \left( \frac{\lambda}{\lambda_{ref}} \right)^{-\text{AAE}_{BrC}} \quad (8) $$

where MAC$_{\lambda_{ref}BC}$ and MAC$_{\lambda_{ref}BrC}$ are the mass absorption coefficient (m$^2$/g) at the reference wavelength for BC and BrC.

The parameter $\alpha_0$ is introduced to simplify the Eq. (8) as follows:

$$ \sigma_{0,BC} = \frac{MAC_{\lambda_{ref}BC}}{\lambda_{ref}^{-\text{AAE}_{BC}}} \quad (9) $$

$$ \sigma_{0,BrC} = \frac{MAC_{\lambda_{ref}BrC}}{\lambda_{ref}^{-\text{AAE}_{BrC}}} \quad (10) $$

Thus, Eq. (8) can be rewritten as:

$$ \sigma_{abs}(\lambda) = (BC \times \sigma_{0,BC}) \times \lambda^{-\text{AAE}_{BC}} + (BrC \times \sigma_{0,BrC}) \times \lambda^{-\text{AAE}_{BrC}} \quad (11) $$

The factors $A = BC \times \sigma_{0,BC}$ and $B = BrC \times \sigma_{0,BrC}$ are cited to change Eq. (11) to Eq. (12). According to Eq. (12), $\sigma_{abs}$ measured by the Aethalometer at seven wavelengths can be used to obtain $A$, $B$ and $\text{AAE}_{BrC}$:

$$ \sigma_{abs}(\lambda) = A \lambda^{-\text{AAE}_{BC}} + B \lambda^{-\text{AAE}_{BrC}} \quad (12) $$

Synthesizing Eqs. (11) and (12), $\sigma_{abs,BC}$ and $\sigma_{abs,BrC}$ can be calculated by Eqs. (13) and (14):

$$ \sigma_{abs,BC}(\lambda) = (BC \times \sigma_{0,BC}) \times \lambda^{-\text{AAE}_{BC}} = A \lambda^{-\text{AAE}_{BC}} \quad (13) $$

$$ \sigma_{abs,BrC}(\lambda) = (BrC \times \sigma_{0,BrC}) \times \lambda^{-\text{AAE}_{BrC}} = B \lambda^{-\text{AAE}_{BrC}} \quad (14) $$

The existing absorption of BC internally mixed with non-absorbing material was neglected in the two-component model (Lack and Langridge, 2013), which resulted in light absorption of BrC in IR.

### 1.5. Backward trajectory analysis

Five-day (120-hr) backward trajectories from the Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) model (Stein et al., 2015) from NOAA/ARL were used to investigate regional sources and transport pathways of air masses arriving at Xiamen. The meteorological data from the Global Data Assimilation System (GDAS) dataset with a horizontal resolution of 1° longitude × 1° latitude and a temporal resolution of 6 hr were adopted in trajectory model. Back-trajectories started 500 m above ground level at the observation site were modeled at an hourly frequency. Cluster analysis were then implemented to obtain trajectory clusters and average values of the light absorption properties with each cluster were calculated.

### 2. Results and discussion

#### 2.1. Statistics of aerosol light absorption coefficient and AAE

Statistics of aerosol light absorption coefficients $\sigma_{abs}$ at seven wavelengths and AAE with a temporal resolution of 5 min as well as their annual mean values in Xiamen in 2014 are
summarized in Table 1. \( \sigma_{\text{abs}} \) at 370, 470, 520, 590, 660, 880 and 950 nm were 56.6 ± 34.3, 38.8 ± 25.0, 32.8 ± 21.4, 28.1 ± 18.5, 24.6 ± 16.3, 16.5 ± 11.2 and 14.6 ± 9.9 Mm\(^{-1} \), respectively. Aerosol absorption of visible light (\( \sigma_{\text{abs},520} \)) in this coastal city was much lower than that in the urban area of Nanjing where \( \sigma_{\text{abs},532} \) was 43.2 ± 28.1 Mm\(^{-1} \) (Zhuang et al., 2015). Light absorption in the ultraviolet spectrum (\( \sigma_{\text{abs},370} \)) in Xiamen was higher than that in remote site in Lulang (15 ± 19 Mm\(^{-1} \)), while lower than that in urban site in Lhasa (53 ± 46 Mm\(^{-1} \)) (Zhu et al., 2017). Light absorption in Xiamen in both ultraviolet (\( \sigma_{\text{abs},370} \)) and infrared (\( \sigma_{\text{abs},880} \)) wavelength were about 10% lower than that in Gwangju, Korea (Park and Son, 2017). Since BrC showed strongest absorption at 370 nm and BC showed at 880 nm (Sandradewi et al., 2008a; Park and Son, 2017; Singh et al., 2018), \( \sigma_{\text{abs}} \) at these two wavelengths will be focused on in this study.

AAE of aerosols in Xiamen was calculated according to the power–law relationship. As depicted in Fig. 1, annual mean value of AAE in Xiamen in 2014 was 1.46 and seasonal AAE values in spring, summer, autumn and winter were 1.42, 1.44, 1.45 and 1.51, respectively. The annual mean AAE obtained by the simplified method in Section 1.3 was also 1.46, equivalent to the fitting result in accordance with \( \sigma_{\text{abs}} \) at seven wavelengths. It indicated that the simplified method could capture the AAE in Xiamen well. AAE in Xiamen was higher than AAE in southern Sweden (1.26) (Martinsson et al., 2017) and Lhasa (1.04) and Lulang (1.18) in China (Zhu et al., 2017); while it was lower than that in Nanjing (1.54) in China (Zhuang et al., 2015).

Light absorption of BC has a weak relationship with wavelength and thus AAE for pure BC was assumed to be 1 (Sandradewi et al., 2008b; Moosmüller et al., 2011). BrC absorbing strongly in ultraviolet can increase the value of AAE (Kirchstetter et al., 2004; Andreae and Gelencsér, 2006). The AAE value of 1.46 obtained in this study reflected the important impact of BrC on light absorption in Xiamen. Furthermore, the AAE value can be used to indicate the sources of aerosols from fossil fuel and biomass burning (Zotter et al., 2017). Emissions from fossil fuels burning mainly contain BC and consequently the AAE for fossil fuels burning emissions is 1 (Kirchstetter et al., 2004; Bond et al., 2013). Whereas biomass burning emissions contain an abundance of BrC, so that the AAE for biomass burning emissions is larger than fossil fuels burning emissions (Zotter et al., 2017). Biomass burning emissions are assumed to have an AAE larger than 2.0 (Sandradewi et al., 2008b). The AAE value in Xiamen implied that the aerosol light absorption was both influenced by the emissions from fossil fuel and biomass burning.

### 2.2. Temporal variations of aerosol light absorption

Diurnal variations of absorption coefficients \( \sigma_{\text{abs}} \) at the wavelengths of 370 and 880 nm are shown in Fig. 2. Both \( \sigma_{\text{abs},370} \) and \( \sigma_{\text{abs},880} \) exhibited double-peak patterns. The amplitude of fluctuation at 370 nm was larger than that at 880 nm, because BrC can strongly absorb solar radiation at 370 nm and has little absorption at 880 nm (Bahadur et al., 2012; Lack and Langridge, 2013; Zhu et al., 2017). The first sharp peak of \( \sigma_{\text{abs},370} \) with the value of 80.3 Mm\(^{-1} \) appeared at 6:00 in the early morning and the more gentle peak with value of 63.0 Mm\(^{-1} \) appeared around 22:00 in the evening. The valleys appeared at 2:00 and 13:00 with the value of 58.1 and

<table>
<thead>
<tr>
<th>Wavelength (nm)</th>
<th>Mean</th>
<th>SD</th>
<th>Min.</th>
<th>Max.</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma_{\text{abs},370} )</td>
<td>56.6</td>
<td>34.3</td>
<td>3.8</td>
<td>297.5</td>
</tr>
<tr>
<td>( \sigma_{\text{abs},470} )</td>
<td>38.8</td>
<td>25.0</td>
<td>2.0</td>
<td>217.4</td>
</tr>
<tr>
<td>( \sigma_{\text{abs},520} )</td>
<td>32.8</td>
<td>21.4</td>
<td>1.6</td>
<td>188.5</td>
</tr>
<tr>
<td>( \sigma_{\text{abs},590} )</td>
<td>28.1</td>
<td>18.5</td>
<td>1.4</td>
<td>164.3</td>
</tr>
<tr>
<td>( \sigma_{\text{abs},660} )</td>
<td>24.6</td>
<td>16.3</td>
<td>1.2</td>
<td>145.9</td>
</tr>
<tr>
<td>( \sigma_{\text{abs},880} )</td>
<td>16.5</td>
<td>11.2</td>
<td>0.8</td>
<td>100.7</td>
</tr>
<tr>
<td>( \sigma_{\text{abs},950} )</td>
<td>14.6</td>
<td>9.9</td>
<td>0.7</td>
<td>89.1</td>
</tr>
<tr>
<td>AAE</td>
<td>1.46</td>
<td>0.16</td>
<td>0.26</td>
<td>2.58</td>
</tr>
</tbody>
</table>

SD: represents the standard deviation.

Fig. 2 – Diurnal variations of \( \sigma_{\text{abs}} \) at 370 and 880 nm and AAE.
39.3 Mm$^{-1}$, respectively. $\sigma_{\text{abs,}880}$ had similar diurnal trend with $\sigma_{\text{abs,}370}$. The first minimal value of $\sigma_{\text{abs,}880}$ (17.2 Mm$^{-1}$) appeared around 2:00 at midnight. Then $\sigma_{\text{abs,}880}$ increased to the first maximum 24.8 Mm$^{-1}$ around 6:00. The other minimum 11.1 Mm$^{-1}$ appeared around 13:00 and then another maximum 18.2 Mm$^{-1}$ appeared around 22:00. Diurnal cycles of $\sigma_{\text{abs}}$ were closely related with anthropogenic emissions and the evolution of the atmospheric boundary layer. From midnight to the early morning, $\sigma_{\text{abs}}$ increased due to the low boundary layer height. After traffic rush hour $\sigma_{\text{abs}}$ gradually decreased inducing by the developing boundary layer and weakened vehicle emissions. From the mid-afternoon, $\sigma_{\text{abs}}$ increased gradually with the decreasing temperature and boundary layer height. A mass of vehicle emissions (especially from the nighttime heavy trucks) and the continuous anthropogenic activities during the evening rush hour peak also contributed to the high $\sigma_{\text{abs}}$ in the evening. Monthly variation of AAE is presented in Fig. 3. The maximum value 1.54 appeared in December and the minimum value 1.40 appeared in June. AAE is closely related to the type of combustion. The larger AAE value (1.52 ± 0.02) in winter implied the more important impacts of aerosols emitted from biomass burning during the period. The minimum AAE value in July was 1.46, which was apparently higher than that in other months in the warm period. The high AAE in July possibly associated with the long-range transport of intense biomass burning, which will be discussed in Section 2.4.

### 2.3. Apportionment of light absorption to BC and BrC

The AAE method described in Section 1.4 was used to separate

![Fig. 3](image3.png) Monthly variations of $\sigma_{\text{abs}}$ at 370 and 880 nm and AAE.

![Fig. 4](image4.png) Absolute and relative contributions to total light absorption of BC and BrC.

![Fig. 5](image5.png) Monthly variations of $\sigma_{\text{abs,BC}}$, $\sigma_{\text{abs,BrC}}$ and BrC contributions to total light absorption at 370 nm.

maximum of $\sigma_{\text{abs,}370}$ and $\sigma_{\text{abs,}880}$ appeared in January with the value of 71.8 and 20.3 Mm$^{-1}$, respectively, while the minimum of $\sigma_{\text{abs,}370}$ and $\sigma_{\text{abs,}880}$ both appeared in February with the value of 38.2 and 11.0 Mm$^{-1}$, respectively. $\sigma_{\text{abs}}$ reached its minimum in February probably because the local and nearby emissions significantly decreased during the Chinese Spring Festival. Monthly variation of AAE is also presented in Fig. 3. The maximum value 1.54 appeared in December and the minimum value 1.40 appeared in June. AAE is closely related to the type of combustion. The larger AAE value (1.52 ± 0.02) in winter implied the more important impacts of aerosols emitted from biomass burning during the period. Note that the AAE value in July was 1.46, which was apparently higher than that in other months in the warm period. The high AAE in July possibly associated with the long-range transport of intense biomass burning, which will be discussed in Section 2.4.
light absorption of BC and BrC. According to $\sigma_{\text{abs}}$ at seven wavelengths, AAE$_{\text{BrC}}$ was calculated as 2.54 in Xiamen in 2014. Annual average absorption coefficients of BC ($\sigma_{\text{abs,BC}}$) and BrC ($\sigma_{\text{abs,BrC}}$) with their contributions to total light absorption at seven wavelengths were then obtained (Fig. 4). $\sigma_{\text{abs,BC}}$ and $\sigma_{\text{abs,BrC}}$ were 32.6 ± 5.8 and 24.0 ± 5.7 Mm$^{-1}$ at 370 nm, respectively. At 880 nm, $\sigma_{\text{abs,BC}}$ was 13.7 ± 2.5 Mm$^{-1}$, while $\sigma_{\text{abs,BrC}}$ was only calculated as 2.8 ± 1.3 Mm$^{-1}$. The contribution made by BrC was high in UV (42% and 33% for 370 and 470 nm, respectively) while falling in visible spectrum (30%, 26% and 22% for 520, 590 and 660 nm, respectively). It confirms that BrC occupied an important position on light absorption, especially in the UV wavelength. This finding is consistent with previous studies (Massabò et al., 2015; Devi et al., 2016; Zhu et al., 2017). The contributions to total light absorption of BC accounted for >70% in visible spectrum and >80% in the IR spectrum, respectively. Although BrC is supposed to have no absorption in the IR region, BrC contribution at 880 nm was still calculated as about 16% in this study. Similarly, Massabò et al. (2015) also found that BrC contribution at 850 nm was 11% in Liguria in Italy.

Monthly variations of $\sigma_{\text{abs,BC}}$ and $\sigma_{\text{abs,BrC}}$ at 370 nm with BrC contributions to total light absorption are illustrated in Fig. 5. The maximum of $\sigma_{\text{abs,BrC}}$ (35.9 Mm$^{-1}$) was in January while the minimum (15.2 Mm$^{-1}$) was in June. The largest contributions (47 ± 4%) made by BrC appeared in winter (49% in December, 50% in January and 43% in February), which was consistent with the highest wintertime AAE. This may be due to the high biomass burning emissions and complex secondary chemical formations of secondary light-absorbing organic aerosols in winter.

### 2.4. Impacts of transport pathway on light absorption

Five-day backward trajectories for air masses arriving at Xiamen computed with HYSPLIT were classified into five clusters (Fig. 6). The coastal cluster passing through Zhejiang Province and Fujian Province (C1), the marine cluster passing through the South China Sea (C2), two long-range inland clusters transporting through North China and East China (C3 and C4) and the marine cluster originating from the East Sea (C5) contributed to 35.3%, 23.4%, 22.2%, 7.9% and 11.2% of the total air masses reaching Xiamen, respectively. Fig. 7 illustrates aerosol light absorption properties of each trajectory cluster. C3 and C4 originating from Siberia and Mongolia and passing through North China Plain (NCP) and the YRD region had higher AAE values with the average of 1.49 and 1.55, respectively. Furthermore, BrC contributions of the two clusters reached 49% and 53%, respectively, which might be due to strong biomass burning emissions in agricultural provinces in North and East China such as Hebei, Henan, Shandong and Jiangsu (Huang et al., 2012). Light absorption coefficients $\sigma_{\text{abs}}$ of the marine clusters passing through the South China Sea (C2) and East Sea (C5) were comparable with those of the inland clusters C3 and C4. Vertical profile of each trajectory cluster is implemented in Fig. 6. It is implied from the vertical transport that the two marine clusters might be more affected by the air pollutants in the...
atmospheric boundary layer or near surface and therefore their light absorption coefficients were relative high. However, AAE values of C2 (1.40) and C5 (1.45) and BrC contributions of C2 (44%) and C5 (44%) were lower since the marine clusters were less influenced by biomass burning. The northern coastal cluster (C1) passing through the YRD region had the largest absorption coefficients (62.45 and 18.42 Mm$^{-1}$, at 370 and 880 nm, respectively) and relative high AAE (1.45) and BrC (48%) contribution, suggesting it was not only significantly affected by air pollution near the earth surface, but also influenced by aerosols emitted from biomass burning.

As depicted in Fig. 3 and Fig. 5, AAE value and BrC contribuion to light absorption in July in 2014 was the highest among those in warm seasons, which might be affected by biomass burning. Air masses reaching Xiamen in July were also investigated with the HYSPLIT model and four trajectory clusters were ultimately obtained (Fig. 8a). C1 and C4 represented long-range transporting air masses originating from Southeast Asia, while C2 and C3 were typical marine clusters originating from the marine areas in the south and east, respectively. Southwestern clusters C1 and C4 from Southeast Asia totally accounted for about half of the total air masses. As depicted in Fig. 8b, C1 and C4 had higher AAE values (1.46 and 1.46, respectively) and BrC contributions (49% and 50%, respectively). It might be related to long-distance transport of air pollutants which were emitted from intensive biomass burning in Southeast Asia. Active fire data with high and nominal confidence for July from the Visible Infrared Imaging Radiometer Suite (VIIRS) providing by NASA’s Earth Observing System (EOS) (https://firms.modaps.eosdis.nasa.gov/firemap/) suggested that intensive fires appeared in countries in Southeast Asia such as Vietnam, Thailand, Laos, Cambodia, Malaysia and Indonesia (Fig. 8a). According to the transport pathways of air masses, BrC from these high-biomass-burning-emission areas in Southeast Asia would exert significant impacts on light absorption in Xiamen.

3. Conclusions

In this study, light absorption of PM$_{2.5}$ including absorption coefficient $\sigma_{\text{abs,370}}$, absorption Ångström exponent AAE as well as contributions made by BC and BrC to total light absorption were analyzed in the coastal city Xiamen in Southeast China in 2014 based on one-year online measurements with a 7-wavelength Aethalometer. Impacts of transport pathways and biomass burning on aerosol light absorption were also investigated. Main findings from this study are as follows.

1) Annual average $\sigma_{\text{abs}}$ at 370, 470, 520, 590, 660, 880 and 950 nm were 56.6 ± 34.3, 38.8 ± 25.0, 32.8 ± 21.4, 28.1 ± 18.5, 24.6 ± 16.3, 16.5 ± 11.2 and 14.6 ± 9.9 Mm$^{-1}$, respectively. $\sigma_{\text{abs}}$ showed obvious seasonality since it was low in warm seasons and high in cold seasons.

2) Annual AAE was 1.46, indicating that aerosol light absorption in Xiamen was both influenced by the emissions from fossil fuel and biomass burning. Diurnal variation of AAE was different from that of $\sigma_{\text{abs}}$ with its minimum in the early morning. Seasonal average AAE was highest in winter and lowest in spring. $\sigma_{\text{abs}}$ of BrC was 24.0 ± 5.7 Mm$^{-1}$ and contributed 42% to total light absorption at 370 nm, indicating the important impact
of biomass burning on light absorption in Xiamen. The largest seasonal contribution of BrC (47 ± 4%) occurred in winter.

3) Transport pathways have significant impacts on aerosol light absorption. Marine air masses passing through the South China Sea and East Sea had comparable $\sigma_{\text{abs}}$ with the inland air masses originating from Siberia and Mongolia and passing through North China and the YRD region. However, inland air masses had higher AAE values and BrC contributions due to intensive biomass burning emissions in agricultural provinces in North and East China. The northern coastal air masses passing through the YRD region had the highest $\sigma_{\text{abs}}$ with large BrC contribution.

4) Transport pathway and the active fire map suggested that high AAE value and BrC contribution in July are related to long-distance transport of air pollutants which were emitted from intensive biomass burning in Southeast Asia.

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