

# Laser-induced fluorescence lidar detection of weak biomass burning aerosols at Nanping, aerosol transport from Indo-China Peninsula to South China: fluorescence lidar observation and analysis

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**Abstract.** South China, a densely populated region frequently affected by transported biomass burning aerosols (BBA), ~~is in need of~~ requires sensitive remote sensing observations to characterize these plumes. Laser-induced fluorescence (LIF) lidar is a powerful tool for detecting ~~fluorescence aerosols~~ fluorescent aerosol and has recently been demonstrated ~~to identify~~ effective in identifying transported BBA over Europe, while its applications in South China remain scarce. Here, we present LIF lidar observations of fluorescent aerosols conducted at Nanping, South China. The detected ~~fluorescence layer exhibited relatively weak intensity~~ (maximum fluorescence backscatter coefficient  $\approx 0.16 \times 10^{-5} \text{ Mm}^{-1} \text{ Sr}^{-1} \text{ nm}^{-1}$ ), fluorescent layer was relatively weak, with a fluorescence signal intensity more than two orders of magnitude lower than the  $\text{N}_2$  Raman backscatter signal (maximum spectral fluorescence backscatter coefficient  $\approx 0.16 \times 10^{-5} \text{ Mm}^{-1} \text{ sr}^{-1} \text{ nm}^{-1}$ ). Nevertheless, it showed a distinct spectral signature compared with typical urban aerosols. ~~By integrating~~ aerosol. Integration of multi-source datasets, ~~the fluorescence layer was attributed to~~ suggests that the long-range transported BBA ~~originating from~~ emitted by weak fire activity in the Indo-China Peninsula (ICP) was a major contributor to the fluorescent layer. Furthermore, the concurrent presence of BBA and enhanced water vapor indicated a humid environment favorable for aerosol processing. ~~This study demonstrates that multi-channel LIF lidar provides a sensitive and promising approach for detecting and characterizing BBA layers~~ Consistent with the high sensitivity of LIF lidar reported in previous studies, our observations show that weak, long-range transported BBA from the ICP can be observed over South China during periods of relatively weak fire activity, thereby offering new insights into their transport mechanisms and potential environmental impacts.

## 1 Introduction

Biomass burning aerosols (BBA), predominantly emitted from wildfires, ~~have~~ ~~has~~ significant impacts on atmospheric processes and public health. BBA can warm the atmospheric layer in which they reside and play an important role in aerosol–cloud–precipitation interactions (Lin et al., 2014). Once emitted, they undergo complex chemical transformations during transport, which affect downwind air quality and atmospheric composition (Zhou et al., 2017). Among BBA components, biomass burning organic aerosols are of particular concern due to their persistence in the atmosphere and potential health risks (Majdi et al., 2019; Vasilakopoulou et al., 2023). Interactions between wildfires, smoke, and meteorological conditions can also form positive feedback loops that aggravate regional air pollution and associated health outcomes (Huang et al., 2023).

Indo-China Peninsula (ICP), a sub-region of Southeast Asia, is ~~a major source of BBA~~ ~~one of the major source regions of BBA in Asia~~ during the pre-monsoon dry season and has substantial impacts on regional air quality and global climate (Yadav et al., 2017). Several international campaigns have investigated BBA in this region, including BASE-ASIA (Biomass-burning Aerosols in South-East Asia: Smoke Impact Assessment) and 7-SEAS (~~Seven South-East~~ ~~7-South-East~~ Asian Studies) (Lin et al., 2013). Multiple studies have reported ~~the that~~ meteorological conditions during the dry pre-monsoon months, particularly March and April, ~~promote~~ ~~are conducive to~~ vertical lifting of BBA over the ICP. These elevated plumes are subsequently transported eastward under the influence of prevailing monsoonal winds, reaching South China and even the Western Pacific, ~~and where they~~ can produce severe health effects. (Chi et al., 2010; Chang et al., 2013; Heese et al., 2017; Nguyen et al., 2020; Qin et al., 2024; Xue et al., 2025; Liu et al., 2025). Therefore, sensitive remote sensing observations are needed in these downwind regions.

As a well-established remote sensing technique, Raman lidar has been widely applied to atmospheric studies (Mattis et al., 2002; Reichardt et al., 2012; Baumgarten, 2010), and has also been adapted for aquatic environments (Shangguan et al., 2023b). Vibrational Raman channels detect molecular scattering and are commonly used as a molecular reference in lidar measurements (Fiedler and Baumgarten, 2024). In early 2005, Immler et al. reported an unexpected enhancement in the water vapor Raman channel signal, which they attributed to fluorescence interference from BBA (Immler et al., 2005). Since then, researchers ~~began to develop~~ ~~the have developed~~ single-channel (~~Rao et al., 2018; Veselovskii et al., 2021; Zhang et al., 2021~~) (Rao et al., 2018; Li et al., 2019; Veselovskii et al., 2020, 2021; Zhang et al., 2021; Hu et al., 2022; Veselovskii et al., 2022a, b; Jiang et al., 2024; Gast et al., 2025; Yufeng et al., 2025) and multi-channel (~~Sugimoto et al., 2012; Saito et al., 2018; Richardson et al., 2019; Reichardt et al., 2023; Wang et al., 2023; Huang et al., 2025; Tang et al., 2025a~~) (Sugimoto et al., 2012; Reichardt, 2014; Saito et al., 2018; Reichardt, Jens et al., 2018; Richardson et al., 2019; Reichardt et al., 2023; Wang et al., 2023; Veselovskii et al., 2023, 2024; Huang et al., 2025; Tang et al., 2025a; Veselovskii et al., 2025; Reichardt et al., 2025) laser-induced fluorescence (LIF) lidar systems, ~~which offer enhanced capabilities for environmental applications. Previous BBA observations using LIF lidar.~~ In addition to observations of the ambient atmosphere, LIF lidar has also been used in the remote sensing of released bioaerosols (Christesen et al., 1993; Simard et al., 2004; Farsund et al., 2012; Wojtanowski et al., 2015; ?; Shoshanim, 2023), aquatic oil spills (Leifer et al., 2012; Sun et al., 2023), and chlorophyll (Saito et al., 2016; Zhao et al., 2023; Shangguan et al., 2023a, 2024), highlighting its broad environmental applicability. Pre-

vious LIF lidar observations of BBA in the ambient atmosphere, generally built upon Mie-Raman lidar systems, have been conducted ~~primarily in Europe, where~~ mainly in Europe (Reichardt, 2014; Reichardt, Jens et al., 2018; Veselovskii et al., 2020, 2022a, b; Hu et al., 2022; Veselovskii et al., 2023; Reichardt et al., 2023; Veselovskii et al., 2024, 2025; Gast et al., 2025; Reichardt et al., 2025) and have shown that these systems provide high detection sensitivity (Gast et al., 2025; Reichardt et al., 2025). Within these European observations, distinct fluorescent layers and characteristic BBA spectra ~~were reported; those layers were often associated with~~ have been reported, and these layers often originated from long-range transport of BBA from strong fires in North America or Russia. ~~(Reichardt, Jens et al., 2018; Hu et al., 2022; Veselovskii et al., 2023; Gast et al., 2025; Veselovskii et al., 2025).~~ However, BBA fluorescence spectra can vary substantially across locations and cases (Reichardt et al., 2025). Consequently, further observations in ~~different locations and~~ weaker cases are needed diverse regions and under weak fire conditions are warranted, particularly in areas with high biomass burning emission potential and population density such as the ICP and South China, where LIF remote sensing observations remain limited.

Building on these advances, we conducted LIF lidar observations at Nanping, South China, during ~~April and May 2024, and detected a distinct fluorescence~~ April–May 2024. Section 2 describes the LIF lidar configuration and the multi-source datasets used in this study. Section 3 describes the calibration and retrieval of aerosol extinction as well as fluorescence backscatter coefficients from the LIF lidar data. Time-height profiles and fluorescence spectra are presented in Sect. 4.1 and 4.2 respectively, revealing a distinct fluorescent layer. Although the ~~fluorescence intensity was relatively low, the layer exhibited spectral signatures that different~~ overall fluorescence intensity is relatively weak, its spectral signatures differ from those of urban aerosols. ~~By integrating multi-source datasets, we attributed this fluorescence layer to BBA transported from weak aerosol.~~ To further investigate the origin of this layer, HYSPLIT backward trajectory analysis is presented in Sect. 4.3, demonstrating that the layer originates from fire sources in the ~~ICP. Radiosonde and LIF lidar data further suggested~~ Indo-China Peninsula (ICP). Section 5 compares the observed fluorescence characteristics with previous LIF lidar studies. Additional radiosonde data along the transport pathway are further incorporated in this section. By jointly analyzing radiosonde and LIF lidar data, we find that the BBA layer was transported ~~together with~~ alongside elevated water vapor, indicating a humid transport pathway. Conclusions and future implications are summarized in Sect. 6.

## 2 Observations and data

### 2.1 Multi-channel LIF lidar

The LIF lidar was installed on the top floor of the National Center of Carbon Metrology Building in Nanping City, Fujian Province, China (26.59° N, 118.27° E). The system emitted a 355 nm ~~lasers~~ laser beam from an Nd:YAG laser (Innolas Spotlight EVOIII) with ~~energy greater than~~ pulse energy exceeding 200 mJ; ~~the laser~~. The laser beam was then expanded by a 10× beam expander, ~~and finally redirected to~~ and subsequently directed into the atmosphere at an elevation angle of 30° via a reflector. The ~~echo~~ backscattered signal was gathered by a 12-inch telescope (Meade LX 200) and detected by the lidar detector equipped with a 32-channel photomultiplier tube (Licel SP32HR). A 355 nm optical notch filter was placed between the telescope and

lidar-the detector to suppress elastic signal leakage. Many types of atmospheric aerosols can produce fluorescence under UV laser excitation, particularly organic carbon (OC), a major component of BBA. The dominant fluorescence emission wavelength occurs-is observed within 400–650 nm when excited by a 351 nm laser (Pan, 2015). To include-simultaneously capture both Raman and fluorescence signals simultaneously-(Table 1), in-this-study, the-spectrometer-the spectrometer central wavelength was set to 475 nm in this study, with a spectral resolution of 6.2 nm nm<sup>-1</sup>. Accordingly, the effective detection ranges of the 32 channels (labeled-Channels 0–31)-span-Channels 31–0) cover central wavelengths from 378.9 nm to 571.1 nm. Four observation cases (Cases 1–4) in April and May 2024 were discussed. Among them, a distinct BBA-A distinct fluorescent layer was identified in Case 1, while the remaining cases served-as-comparisons were analyzed for comparison. Further technical details of the LIF lidar system are-available-in-our-previous-publication-can be found in (Tang et al., 2025a).

**Table 1.** Channel settings-Spectral channel configuration of different-detection signals-the LIF lidar. Channel indices decrease with increasing wavelength.

Content-Detection signal	Central wavelength (nm)	Channel index
N <sub>2</sub> Raman	385.1	30
H <sub>2</sub> O Raman	403.7	27
N <sub>2</sub> Overtone	422.3	24
Fluorescence	434.7–571.1	22–0

## 2.2 Satellite, radiosonde and weather-ground-based observations

The Moderate-Resolution Imaging Spectroradiometer (MODIS) is a spaceborne multispectral sensor widely used in BBA studies (Shi et al., 2019; Yin, 2020). In this study, we utilized the MODIS Corrected Reflectance (True Color) imagery acquired on April 16, April 2024, to visually overview fire activities in the ICP. We selected two sub-regions with-dense-fires from the imagery to illustrate the spatial distribution of fire sources (Fig. 5a–b). To further quantify and identify fire events, we obtained the MODIS Collection 6.1 (C6.1) standard active fire product from NASA Fire Information for Resource Management System (FIRMS) (Giglio et al., 2016). This dataset includes fire locations, fire radiative power (FRP), detection confidence, and fire types. For quality control, we used fire points with-that had confidence > 80%, FRP > 100 MW, and were classified as type 0 (presumed vegetation fires).

To get the water vapor mixing ratio (WVMR) profiles, we used radiosonde data of five cities in South China downloaded from the University of Wyoming website (<https://weather.uwyo.edu/>); the location distributions are shown in Fig. 7a. To avoid cloud contamination in the radiosonde profiles, we discarded any level with relative humidity (RH) exceeding 95% , following the approach of Zhou et al. (2025).

The Aerosol RObotic NETwork (AERONET) (Holben et al., 1998) is a global ground-based aerosol monitoring program jointly established by NASA and PHOTONS (a European initiative coordinated by the University of Lille, the French Na-

tional Centre for Space Studies, and the National Institute for Earth Sciences and Astronomy of CNRS). To support the identification of BBA transport events, we selected three AERONET sites near burning areas in the ICP (Chiang\_Mai\_Met\_Sta, Doi\_Ang\_Khang, and Luang\_Namtha); their geographic locations are marked as red ~~rectangles~~ ~~triangles~~ in Fig. 5e. Temporal variations in the aerosol optical depth at 500 nm (~~AOD<sub>500</sub>~~ ~~AOD@500 nm~~) provided auxiliary evidence for biomass burning plumes. We obtained air pollution data (including PM<sub>2.5</sub> and PM<sub>10</sub> concentrations) from the China National Environmental Monitoring Centre (CNEMC). To reduce localized variability and measurement noise, we averaged data from three monitoring stations near the LIF lidar site. ~~For the water vapor mixing ratio (WVMR) profiles, we used sounding data of five cities in South China downloaded from the University of Wyoming website; the location distributions are shown in Fig. 7a. To avoid cloud contamination in the sounding profiles, we discarded any level with relative humidity (RH) exceeding 95%, following the approach of Zhou et al. (Zhou et al., 2025).~~

### 2.3 Reanalysis data and ~~trajectory~~ model

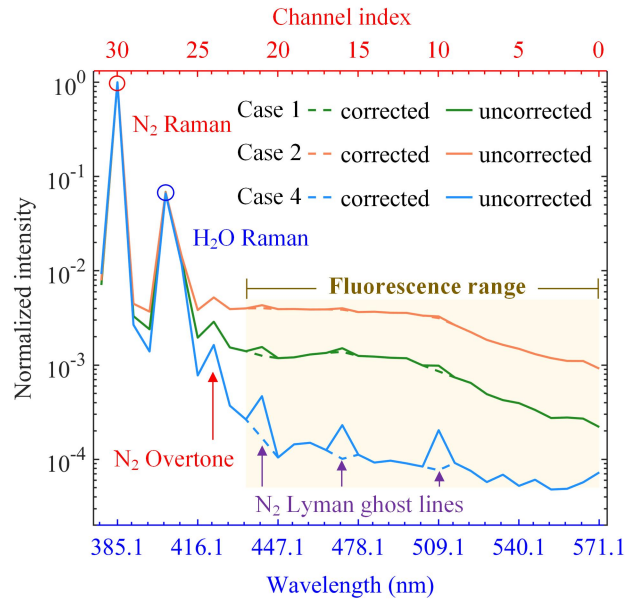
ERA5 (Hersbach et al., 2020) is the fifth-generation global climate reanalysis dataset from the European Centre for Medium-Range Weather Forecasts (ECMWF). In this study, we used ERA5 data to characterize ~~boundary layer height,~~ ~~temperature,~~ ~~geopotential,~~ wind fields, and RH at different altitudes, providing essential meteorological context for our analysis. The Modern-Era Retrospective analysis for Research and Applications, Version 2 (MERRA-2) is a long-term global reanalysis developed by NASA Global Modeling and Assimilation Office (GMAO). It assimilates satellite-based aerosol observations to represent interactions between aerosols and other physical processes in the climate system (Gelaro et al., 2017). In this study, we used hourly biomass burning OC emissions from the MERRA-2 tagv1\_2d\_adg\_Nx hourly dataset with a spatial resolution of  $0.625^\circ \times 0.5^\circ$  ~~degrees~~.

The Hybrid Single-Particle Lagrangian Integrated Trajectory (HYSPLIT) model, developed by NOAA Air Resources Laboratory, is widely used to analyze atmospheric transport, dispersion, air parcel trajectories, and pollutant transport pathways (Stein et al., 2015). In this study, we employed ~~HYSPLIT to compute 78-hour backward trajectories from the 78-hour backward trajectory analysis using the HYSPLIT model, initialized at the~~ LIF lidar site, aiming to identify the transport history and potential source regions of the observed fluorescent aerosol layer. The meteorological inputs were from the Global Data Assimilation System (GDAS).

## 3 ~~Calibration and retrieval of~~ LIF lidar data processing

### 3.1 Ghost line calibration

The calibration procedure was initially performed on the original fluorescence spectrum. Additionally, unavoidable imperfections in the diffraction grating can cause periodic spectral artifacts in fluorescence spectra, especially under weak fluorescence conditions. In our study, minor spurious peaks were found at ~~channels~~ ~~Channels~~ 21, 16, and 10 (Fig. 1). These peaks, known as Lyman ghosts (Tang et al., 2025a), were corrected based on their dependence on the primary wavelength (N<sub>2</sub> Raman signal;



**Figure 1.** Mean fluorescence spectra for **Case** Cases 1 (1.0–1.8 km), **Case**-2 (1.0–1.8 km altitude), and **Case**-4 (2.0–2.8 km altitude) measured at the **Nanping-LIF** lidar **station** site. Line colors indicate the different cases; **solid**. Solid lines show spectra before ghost-line correction and dashed lines show spectra after ghost-line correction (see legend). All the spectra are normalized by the  $N_2$  Raman signal.

**channel**-Channel 30, with a central wavelength of 385.1 nm (Meggers and Kiess, 1922). In Fig. 1, the spectra are normalized  
 140 by the  $N_2$  Raman signal. For each case, both uncorrected and corrected curves are shown for direct comparison. To quantify  
 ghost contributions and standardize correction across all **spectra** spectral data, we selected **the spectrum** three spectra with the  
 lowest fluorescence intensity **during the campaign** (the from three cases (where the  $N_2$  Raman signal maintains sufficient in-  
 tensity to ensure calibration reliability). One of them is the spectrum from Case 4 **uncorrected curve**, **bottom blue solid line**  
 (2.0–2.8 km), which is shown in Fig. 1). For this spectrum, the three ghost-affected intervals (**channels**-Channels 21, 16, and  
 145 10) were removed and reconstructed using linear interpolation, yielding a ghost-free reference spectrum (bottom blue dashed  
 line in Fig. 1). The differences between the two blue curves at the three affected channels represent the characteristic ghost  
 contribution for each channel. **Ghost correction**-Ghost correction coefficients were then defined as these channel-specific dif-  
 ferences divided by the corresponding  $N_2$  Raman signal intensity from the same spectrum. **The final channel-specific ghost**  
**correction coefficients were obtained by averaging the corresponding coefficients from the three reference spectra.** All analyzed  
 150 spectra **used** were corrected using the same three coefficients (one per ghost-affected channel). During the correction, ghost  
 contributions were estimated **by multiplying the** as the product of the  $N_2$  Raman signal intensity **of each affected channel by**  
**its corresponding coefficient, and these were** and channel-specific coefficients, and subsequently subtracted from the original  
 values to **yield** obtain the corrected spectra. Representative results for Cases 1 and **Case**-2 are shown in Fig. 1, where the dashed  
 lines denote ghost-free spectra.

The aerosol extinction coefficient is given by (Ansmann et al., 1990):

$$D = d/dz \{ \ln [N_R(z) / P_R(z) z^2] \} \quad (1)$$

$$\alpha_L^{\text{aero}}(z) = \frac{D - \alpha_L^{\text{mole}}(z) - \alpha_R^{\text{mole}}(z)}{1 + (\lambda_L / \lambda_R)^k} \quad (2)$$

where the superscripts "aero" and "mole" are indicate quantities related to aerosols and molecules, respectively. The subscripts "L" and "R" correspond to elastic and N<sub>2</sub> Raman channels. N<sub>R</sub> is the nitrogen concentration profile, which is calculated using the standard atmosphere model (Shang et al., 2018). λ<sub>L</sub> and λ<sub>R</sub> denote the elastic wavelength (355 nm) and the N<sub>2</sub> Raman channel central wavelength (385.1 nm), respectively. The ngstrm exponent *k* is assumed to be 1 (Ansmann et al., 1992a).

The fluorescence backscatter coefficient is given by (Veselovskii et al., 2020):

$$\beta_F = \frac{C_R P_F T_R}{C_F P_R T_F} N_R \sigma_R \quad (3)$$

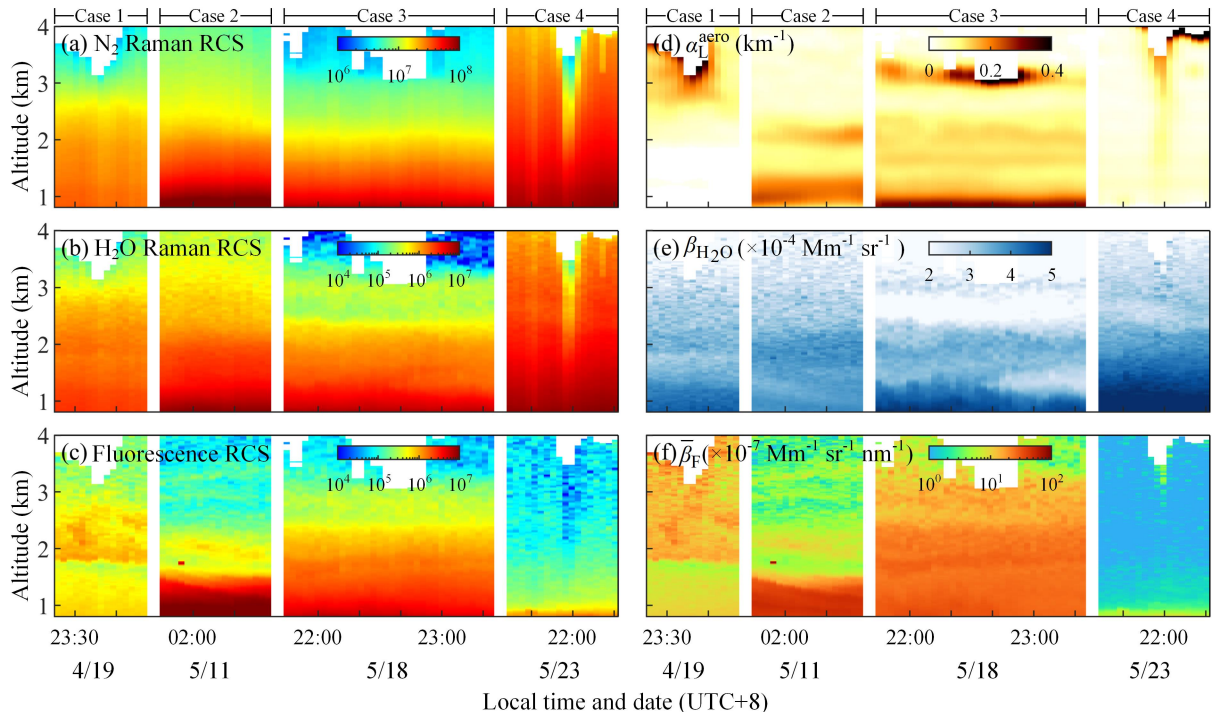
where P<sub>F</sub> and P<sub>R</sub> are the lidar signals from the fluorescence and N<sub>2</sub> Raman channels, respectively. σ<sub>R</sub> is the N<sub>2</sub> Raman differential backscatter cross section at 355 nm (Venable et al., 2011). T<sub>R</sub> and T<sub>F</sub> are the atmospheric transmittance for the N<sub>2</sub> Raman and fluorescence (channel 0–22, with Channels 22–0, with central wavelengths of 434.7–571.1 nm), respectively. Similarly, the water vapor Raman backscatter coefficient β<sub>H<sub>2</sub>O</sub> is derived by replacing the fluorescence channels with the water vapor Raman channel (channel 27, with a central wavelength of 403.7 nm). Unlike the single-channel fluorescence systems, our LIF lidar uses employs 23 fluorescence channels. So the total fluorescence backscattering coefficient. Accordingly, the fluorescence backscatter coefficient β<sub>F</sub> is obtained by summing contributions from all individual channels. For comparison, the resulting β<sub>F</sub> is then normalized by the fluorescence spectrum wavelength range spectral wavelength range to yield the spectral fluorescence backscatter coefficient:

$$\bar{\beta}_F = \frac{\beta_F}{\Delta\lambda} \quad (4)$$

## 175 4 Results

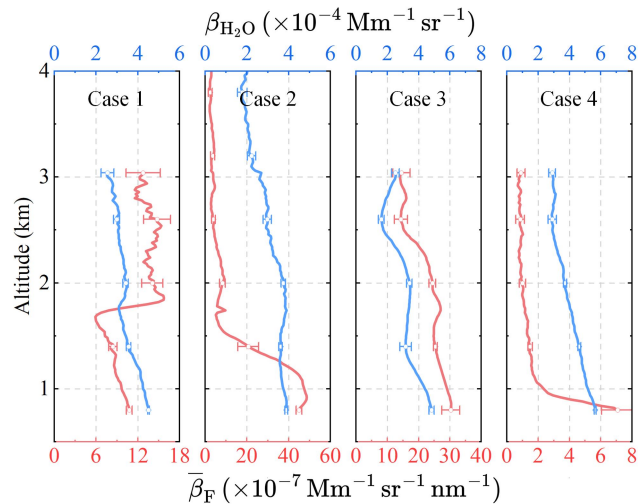
### 4.1 Vertical profiles observed by LIF lidar

Time-height profiles of four representative nighttime cases observed in 2024 are shown in Fig. 2. All observations were conducted at night to avoid strong solar background interference during the daytime. Four cases are included: Case 1 (19 April, 23:19–20 April, 00:05), when a distinct fluorescence layer was observed (Fig. 2c); Case 2 (11 May, 01:41–02:37); Case 3 (18 May, 21:43–23:29); and Case 4 (23 May, 21:27–23:08). All times are in local time (UTC+8), with the time axis labeled at



**Figure 2.** Time-height profiles for the four cases at the Nanjing-LIF lidar station site during 19 April–23 May 2024 (UTC+8). (a–c) The range-corrected range-corrected signal (RCS) from the respective detection channels (see as defined in Table 1 for channel definitions). (d–f) The retrieved Retrieved quantities for (derived using the a–c), respectively; retrieval methods are described in Sect. 3) corresponding to (a–c), respectively 3.2.

20 minute intervals. The vertical white lines separate individual cases. Fig. 2a–c show the range-corrected Figure 2a–c show the range-corrected signal (RCS) of different detection channels, while Fig. 2d–f present retrieved parameters derived via the methods described in Sect. 3–3.2. Due to the LIF lidar’s 30° elevation angle, the effective detection height equals half of the line-of-sight range. The detection lower limit is within 800 m, which defines the starting altitude of all subplots. The N<sub>2</sub> Raman signal (Fig. 2a) decays more slowly in Case 4 than in the other three cases, likely due to the lower aerosol loading (Fig. 2d and Fig. A1a). The fluorescence signal intensity is also relatively weak in Case 4 (Fig. 2c, f, and Fig. 3), making it this case ideal for calibrating the Lyman ghost lines. Multiple cloud layers are identifiable via high In Cases 1, 3, and 4 (3–4 km), we observed abrupt enhancements in  $\alpha_L^{\text{aero}}(z)$  values in Fig. 2d, consistent with observations reported by Sugimoto et al. In several cases, low-level clouds exist around 3.5 km, significantly attenuating the lidar signal. During the observation period, both  $\bar{\beta}_F$  and  $\alpha_L^{\text{aero}}$  (0.8–1.4 km layer, (Fig. 2d and f) closely match the local PM concentration trends (Fig. A1a). Their corresponding average fluorescence spectra also exhibit similar shapes (Fig. 4a), consistent with previous observations of urban aerosols (Veselovskii et al., 2025). These lines of evidence support that low-altitude fluorescence is largely attributable to urban aerosols. ), indicating the presence of clouds (Sugimoto et al., 2012). In Case 3, an elevated boundary layer height (Fig. A1b) indicates



**Figure 3.** Mean vertical profiles of  $\beta_{\text{H}_2\text{O}}$  (blue lines) and  $\bar{\beta}_{\text{F}}$  (red lines) for the four cases at the Nanping-LIF lidar station site. Error bars indicate  $\pm 1$  standard deviation across the profile samples. Shaded boxes mark the 600 m thick atmospheric layers; box colors denote aerosol types (yellow for BBA; gray for urban aerosols).

enhanced vertical mixing. The low-altitude fluorescence layer ascends to  $\sim 3$  km due to the vertical mixing (Fig. 2f). This upward shift is further evident in Fig. 3, where the averaged  $\bar{\beta}_{\text{F}}$  in the low-altitude layers (0.8–1.4 km) decays rapidly in all cases except Case 3. In

Figure A1 presents the relationships among averaged  $\bar{\beta}_{\text{F}}$ ,  $\alpha_{\text{L}}^{\text{aero}}$  (0.8–1.4 km), surface RH, and surface PM concentrations. In Cases 1 and 4, RH remains close to saturation following preceding precipitation, favoring efficient wet deposition and resulting in reduced aerosol loading. Consequently, lower  $\alpha_{\text{L}}^{\text{aero}}$  ( $< 0.05 \text{ km}^{-1}$ ) are observed compared to Cases 2 and 3 ( $> 0.15 \text{ km}^{-1}$ ), which qualitatively agrees with the observed PM concentration differences. The slightly negative layer-averaged  $\alpha_{\text{L}}^{\text{aero}}$  in Case 1 can be attributed to retrieval uncertainties under very clean conditions, a behavior also reported in previous studies (Ansmann et al., 1992b; Hu et al., 2025). In particular, hygroscopic growth under elevated RH can enhance aerosol optical extinction by modifying particle size and refractive index (Ansmann et al., 1992a; Haerig et al., 2025). This effect likely contributes to the slightly higher  $\alpha_{\text{L}}^{\text{aero}}$  in Case 2 compared to Case 3 (RH  $\approx 89.2\%$  versus  $\approx 83.6\%$ ). In contrast to aerosol extinction, fluorescence signals are expected to be much less affected by ambient humidity and hygroscopic growth. Under the assumption of minimal water-induced fluorescence quenching (Veselovskii et al., 2025a), negligible hygroscopic effects on aerosol fluorescence, and unchanged aerosol mixing state,  $\bar{\beta}_{\text{F}}$  can be regarded as a reliable proxy for dry aerosol material concentrations (Miri et al., 2024), which is consistent with the dry-state nature of the measured PM mass concentrations. However, the relative magnitudes of  $\bar{\beta}_{\text{F}}$  in Cases 2 and 3 still exhibit an opposite ordering compared to PM concentrations, indicating that aerosol fluorescence does not scale linearly with bulk particulate mass. This discrepancy reflects the combined influence of fluorescent particle types and concentrations, rather than particle mass alone (Reichardt, 2014).

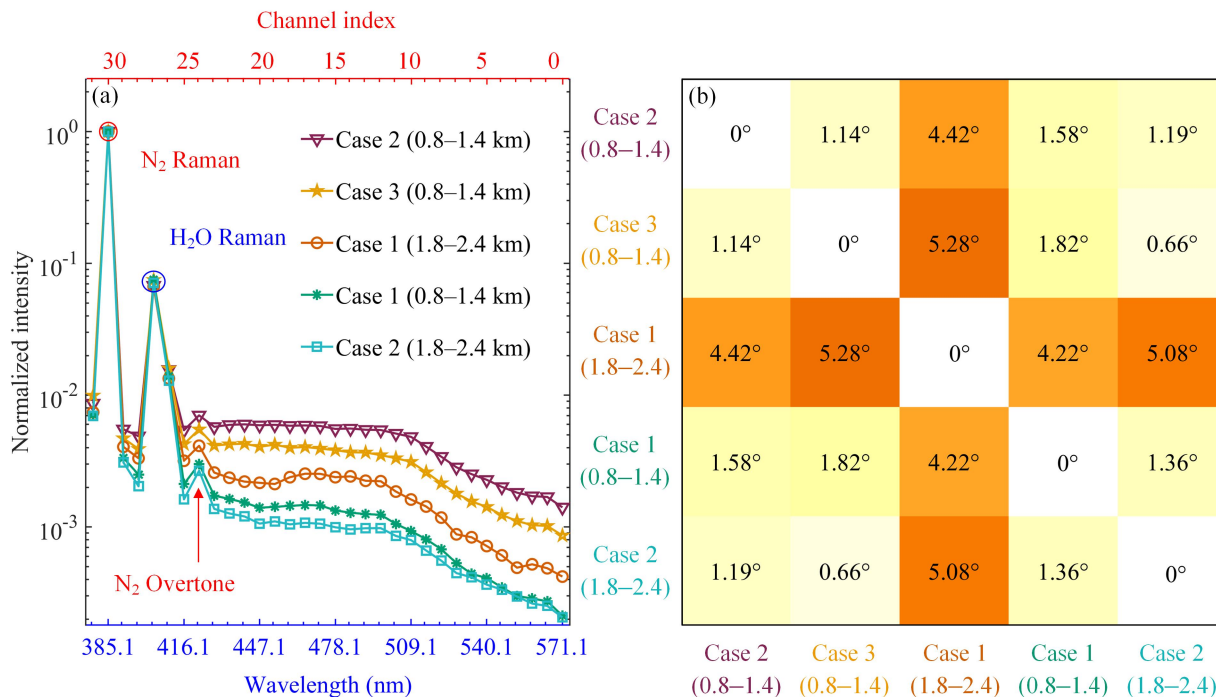
In Case 1, a distinct fluorescence layer (enhanced  $\bar{\beta}_F$ ) accompanied by enhanced water vapor was observed at  $\sim 1.8$  km despite relatively low  $\alpha_L^{\text{aero}}$  (Fig. 2c, e, and ff, and Fig. 3). ~~Such fluorescence enhancement is absent~~ This enhancement is not observed in the other three cases (Fig. 3). ~~We attributed the~~ To further analyze the fluorescence characterization, we use quantitative analyses of the spectral fluorescence capacity  $G_F = \frac{\bar{\beta}_F}{\beta_L}$ , where  $\bar{\beta}_F$  is the spectral fluorescence backscatter coefficient and  $\beta_L$  is the elastic backscatter coefficient (Reichardt, 2014; Veselovskii et al., 2022b). As  $\beta_L$  was not directly available in this study, we estimated  $\hat{G}_F = \frac{\bar{\beta}_F}{\alpha_L^{\text{aero}}} \cdot S$  using a typical lidar ratio  $S \approx 55$  sr for aged smoke (Ansmann et al., 2021). To enable direct comparability with the fluorescence wavelength range (444–488 nm) from (Gast et al., 2025), we selected Channels 20–14 (444–487.4 nm) for  $\hat{G}_F$  estimation.  $\hat{G}_F$  values are provided in Table 2, excluding Case 1 (0.8–1.4 km): negative  $\alpha_L^{\text{aero}}$  results in negative  $\hat{G}_F$ , which is thus omitted. Table 2 presents the highest  $\hat{G}_F$  for Case 1 (1.8–2.4 km layer in km)  $\approx 3.1 \times 10^{-6} \text{ nm}^{-1}$ , which falls within the typical smoke range of  $2 \times 10^{-6}$ – $9 \times 10^{-6} \text{ nm}^{-1}$  (Gast et al., 2025) and is at least twice as high as  $\hat{G}_F$  values from other layers. ~~to BBA transported from the ICP. Detailed source-attribution results are presented in Sect. 4.3.~~

**Table 2.** Estimates of layer-averaged spectral fluorescence capacity ( $\hat{G}_F = \frac{\bar{\beta}_F}{\alpha_L^{\text{aero}}} \cdot S$ ), computed over the fluorescence spectral range 444–487.4 nm (Channels 20–14). A lidar ratio  $S$  of 55 sr (typical for aged smoke) is assumed (Ansmann et al., 2021).

Cases	$\hat{G}_F$ ( $\times 10^{-6} \text{ nm}^{-1}$ ) (0.8–1.4 km)	$\hat{G}_F$ ( $\times 10^{-6} \text{ nm}^{-1}$ ) (1.8–2.4 km)
Case 2	—	3.1
Case 2	1.5	0.4
Case 3	1.2	1.4
Case 4	0.5	0.2

## 4.2 Fluorescence spectra of BBA

As shown in Fig. 4a, mean fluorescence spectra from multiple 600 m thick layers are normalized to the  $\text{N}_2$  Raman signal. The ~~box colors are consistent with the layers marked in Fig. 3.~~ The maximum fluorescence intensity is more than two orders of magnitude lower than that of the  $\text{N}_2$  Raman signal. ~~Although the overall fluorescence intensity is weaker than reported in previous Asian LIF lidar studies (Sugimoto et al., 2012; Wang et al., 2023), clearly discernible spectral patterns can be classified into two distinct groups.~~ Spectra in To quantitatively analyze the spectral similarity, we adopted the spectral angle mapping (SAM) analysis (Farsund et al., 2010) using Channels 20–14 (444–487.4 nm) from the fluorescence spectra. This algorithm quantifies spectral similarity by treating spectra as vectors and calculating the vector angle, ranging from  $0^\circ$  (identical spectral shapes) to  $90^\circ$  (completely distinct spectral shapes). Fig. 4b ~~correspond to urban aerosols, showing a gradual intensity decrease~~ shows the SAM angle matrix for the selected spectra in Fig. 4a. The low SAM angle ( $\approx 1.14^\circ$ ) between Cases 2 and 3 (0.8–1.4 km) indicates high spectral similarity. Both spectra exhibit decreasing intensity with increasing wavelength. ~~This is consistent with~~



**Figure 4.** (a) Mean fluorescence spectra (normalized by N<sub>2</sub> Raman signal) for the derived from 600 m-thick m-thick layers indicated in Fig for Cases 1–3. Line colors and marker shapes indicate denote the different cases and layer altitudes (see legend). Box colors correspond to aerosol types defined in Fig. 3 (yellow for BBA; gray for urban aerosols). (b) SAM angle matrix for layers influenced by BBA. The five selected spectra (Channels 20–14, 444–487.4 nm). A SAM angle of 0° indicates identical spectral shapes, with larger angles corresponding to urban aerosols greater dissimilarity.

, consistent with reported urban aerosol spectra in the boundary layer reported in Russia (Veselovskii et al., 2025). One layer in Case 2 (1.8–2.4 km) (Veselovskii et al., 2025). Considering these spectral features with the low  $\hat{G}_F$  ( $\leq 1.5 \times 10^{-6} \text{ nm}^{-1}$ ; Table 2) and the higher averaged  $\alpha_L^{\text{aero}}$  (0.8–1.4 km, shown in Fig. 2e and f and) in Cases 2 and 3 compared to Cases 1 and 4 (linked with PM concentration trends; Fig. 3), although located above the local boundary layer, matches this urban spectral pattern and is therefore classified as such. By contrast, the BBA layer (1.8–2.4 km), our results suggest that the fluorescence of Cases 2 and 3 (0.8–1.4 km layer in Case 1) exhibits stronger fluorescence with distinct peaks. Notably, the low-altitude layer observed at our LIF lidar site was likely attributable to urban aerosol. Regarding potential biogenic interference, although local dominant tree species (e.g., pines) may release pollen in May, pollen is unlikely to be the dominant contributor to the fluorescence signal in Cases 2 and 3 (0.8–1.4 km). This is evidenced by the absence of distinct characteristic peaks in the fluorescence spectra (Saito et al., 2018) and the low  $\hat{G}_F$ .

The spectrum of Case 1 shows no distinct fluorescence maximum in the time-height profiles (1.8–2.4 km) is distinct from other spectra (Fig. 3)4a), with quantitative support from spectral angle mapping (SAM) analysis (Fig. 4b): the SAM angle

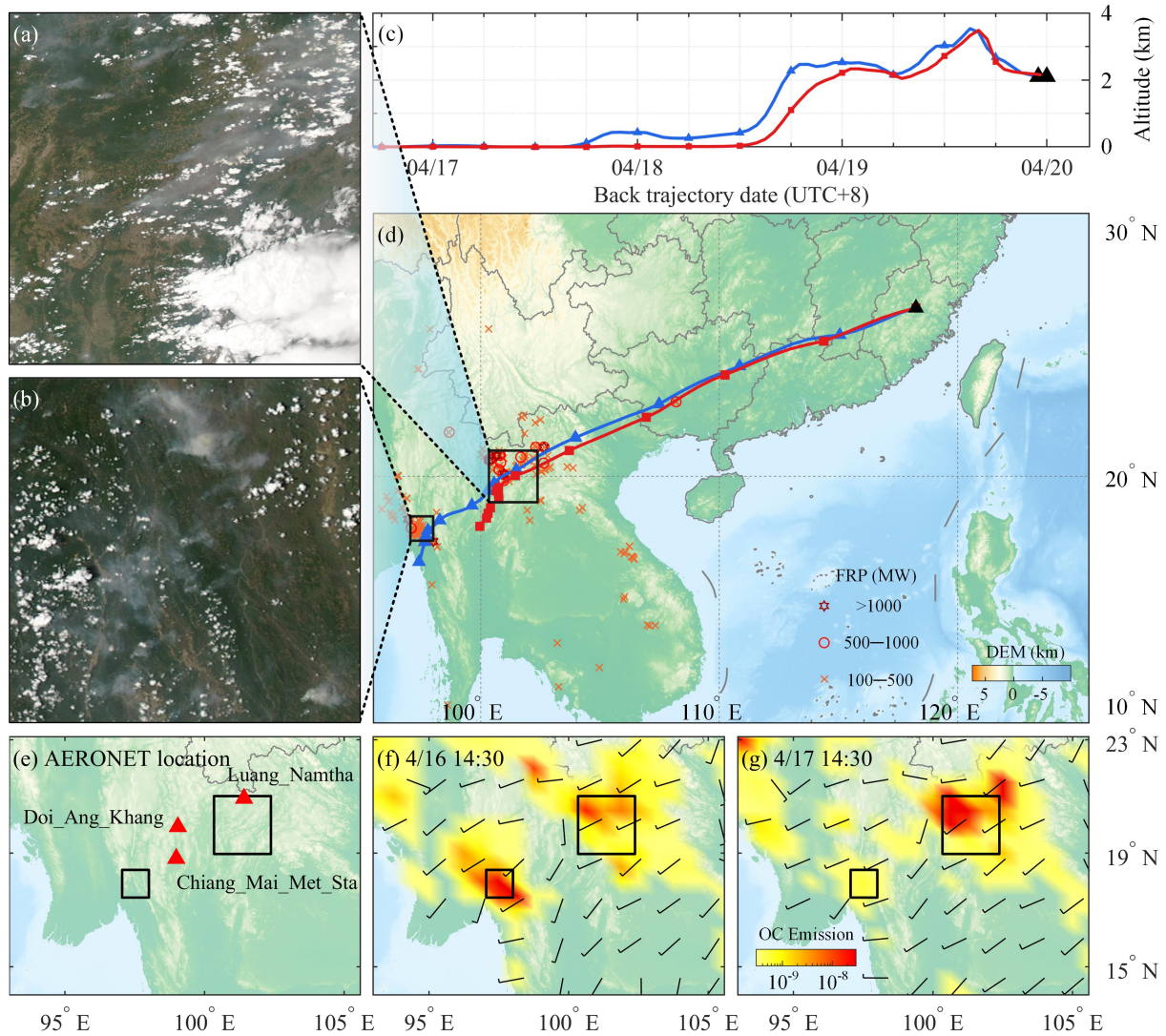
between Case 1 (1.8–2.4 km) and Cases 2 and 3 (0.8–1.4 km) themselves. Additionally, SAM angles between Case 1 (1.8–2.4 km) and Case 1 (0.8–1.4 km) as well as between Case 1 (1.8–2.4 km) and Case 2 (0.8–1.4 km) both exceed 4°, further confirming the spectral dissimilarity. To better constrain the aerosol source in Case 1 (1.8–2.4 km) BBA signature-, HYSPLIT backward trajectory analysis was performed in Sect. 4.3.

### 4.3 Source attribution of the fluorescence fluorescent layer in Case 1

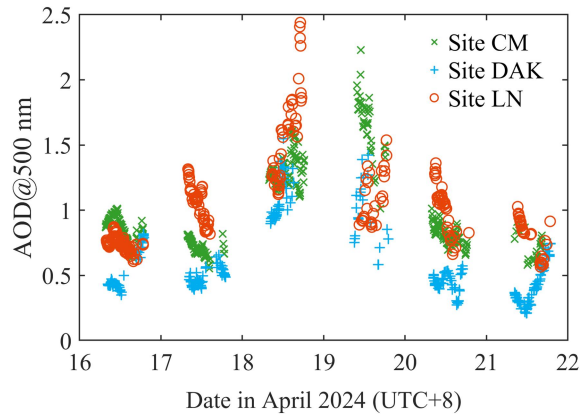
HYSPLIT backward trajectories for Case 1 indicate that the air mass linked to the fluorescent layer originated from the ICP during 16–18 April, 2024 (Fig. 5ed). This event can be divided into three stages: local biomass burning, vertical lifting, and long-range transport. MODIS true-color imagery for 16–17 April (Fig. 5a–b) reveals multiple fire points, with near-surface plume orientations consistent with winds blowing toward the northeast (Fig. 5f–g). Two source regions with the most intense fire activity are highlighted by black boxes in Fig. 5d–g (these boxes correspond to the areas as in Fig. 5a–b). MODIS C6.1 fire products also identify numerous low-intensity vegetation fire pixels within these regions (Fig. 5d), while the MERRA-2 emission fields indicate elevated OC emissions coincident with these suspected sources (Fig. 5f–g). Additionally, the 10-m wind barbs align with the plume directions visible in the satellite imagery. As shown in Fig. 6, AOD<sub>500–@500 nm</sub> at three AERONET stations (locations marked as red rectangles-triangles in Fig. 5e) increased over a period, indicating the passage of strongly absorbing aerosols during the period. The BBA then underwent vertical lifting to a higher altitude—the 2–3 km altitude range (Fig. 5c). During the pre-monsoon season, frequent small-scale cumulus convection can transport pollutants above 3 km—an optimal altitude for long-range transport (Shan et al., 2016). For our case, a similar phenomenon was visible in Fig. 5a–b. Additionally, the higher terrain (Fig. 5d) also provides favorable conditions for BBA uplift. Thereafter, the BBA were rapidly transported by the southwest summer monsoon (Fig. 5d) to altitudes above our LIF lidar site, where a fluorescent layer was observed. All of the above—Considering the distinct  $\bar{\beta}_F$  layer (Fig 2f), the highest  $\hat{G}_F$  ( $\approx 3.1 \times 10^{-6} \text{ nm}^{-1}$ ; Table 2), the unique fluorescence spectral shape (Fig 4a–b), and HYSPLIT backward trajectory analysis (Fig. 5d), these lines of evidence indicate that BBA generated by the fire points were lifted, transported to South China, and eventually detected by our LIF lidar in Case 1—support that BBA transported from the ICP was a major contributor to the fluorescent layer observed in Case 1 (1.8–2.4 km). On the contrary, HYSPLIT trajectories-results-backward trajectory analysis with a starting altitude of 1 km show that the low-altitude fluorescence was not affected by the transported BBA (Fig. B1).

## 5 Discussion

The Asian summer monsoon brings substantial rainfall to the region. However-, while the pre-monsoon season (February–April March–April) is typically dry across the ICP. During this period, frequent biomass burning events (predominantly forest fires) occur frequently over the ICP, driving seasonal maximum and agricultural burnings) lead to seasonal peaks in BBA loadings (Gautam et al., 2013; Shi and Yamaguchi, 2014). Fire activity peaks in March but declines sharply by late April (Huang et al.,



**Figure 5.** Imagery, trajectory analysis and modeled biomass burning emissions for Case 1. (a–b) MODIS (Aqua) true-color images acquired on ~~16 April, 2024~~ 16 April 2024 (UTC), sourced from NASA Worldview (<https://worldview.earthdata.nasa.gov/>), showing smoke plumes originating from multiple fire points (areas highlighted by black boxes in panels d–g). (c) Vertical variation of air mass altitude from HYSPLIT backward trajectories (starting altitude: 2.1 km; ~~black triangle marks the Nanping lidar station~~). (d) Horizontal (longitude-latitude) HYSPLIT backward trajectories overlaid on presumed vegetation fire locations; marker colors and shapes indicate FRP levels, and the underlying digital elevation model (DEM) highlights topography (the black triangle denotes ~~the lidar station~~ the LIF lidar site). (e) Locations of the AERONET stations (red triangles) used in Fig. 6. (f–g) MERRA-2 biomass burning organic carbon (OC) emissions ( $\text{Kg m}^{-2} \text{s}^{-1}$ ) for two temporal conditions, plotted with background 10-m wind fields.



**Figure 6.** Aerosol optical depth at 500 nm ( $AOD_{500}$ ) retrieved from three AERONET sites during 16–22 April 2024. Marker colors and shapes indicate the stations: CM represents Chiang\_Mai\_Met\_Sta, DAK represents Doi\_Ang\_Khang, and LN represents Luang\_Namtha (locations shown in Fig. 5e, red triangles).

2016). MODIS FRP data indicate that over 84% of ~~source fires~~ fire points had FRP < 500 MW (with only a few high-intensity ~~event~~ points), while MERRA-2 data show a maximum OC emission rate of  $1.5 \times 10^{-8} \text{ Kg m}^{-2} \text{ s}^{-1}$ . The ~~corresponding~~ maximum  $\bar{\beta}_F \approx 0.16 \times 10^{-5} \text{ Mm}^{-1} \text{ Sr}^{-1} \text{ nm}^{-1}$  is lower than most previously reported values detected fluorescent layer was relatively weak, with a fluorescence signal intensity more than two orders of magnitude lower than the  $\text{N}_2$  Raman signal intensity. The maximum  $\bar{\beta}_F \approx 0.16 \times 10^{-5} \text{ Mm}^{-1} \text{ sr}^{-1} \text{ nm}^{-1}$  observed in Case 1 (1.8–2.4 km) lies at the lower end of the range of  $\bar{\beta}_F$  values reported for BBA in France (Hu et al., 2022),  $\bar{\beta}_F \approx 1.8 \times 10^{-5} \text{ Mm}^{-1} \text{ Sr}^{-1} \text{ nm}^{-1}$ ; Germany (Gast et al., 2025),  $\bar{\beta}_F \approx 11 \times 10^{-5} \text{ Mm}^{-1} \text{ Sr}^{-1} \text{ nm}^{-1}$ ; Germany (Gast et al., 2025; Reichardt et al., 2025), and Russia (Veselovskii et al., 2025)  $\bar{\beta}_F \approx 4.5 \times 10^{-5} \text{ Mm}^{-1} \text{ Sr}^{-1} \text{ nm}^{-1}$ . This study highlights. Consistent with the high sensitivity of the LIF lidar: even in late April 2024 (weak ICP fire activity), it still detected a weak BBA layer over South China. Additionally, LIF lidar reported in previous studies (Gast et al., 2025; Reichardt et al., 2025), our results show that weak, long-range BBA transport transported BBA from the ICP to South China can occur even can be observed over South China during periods of relatively weak fire activity (e.g., late April).

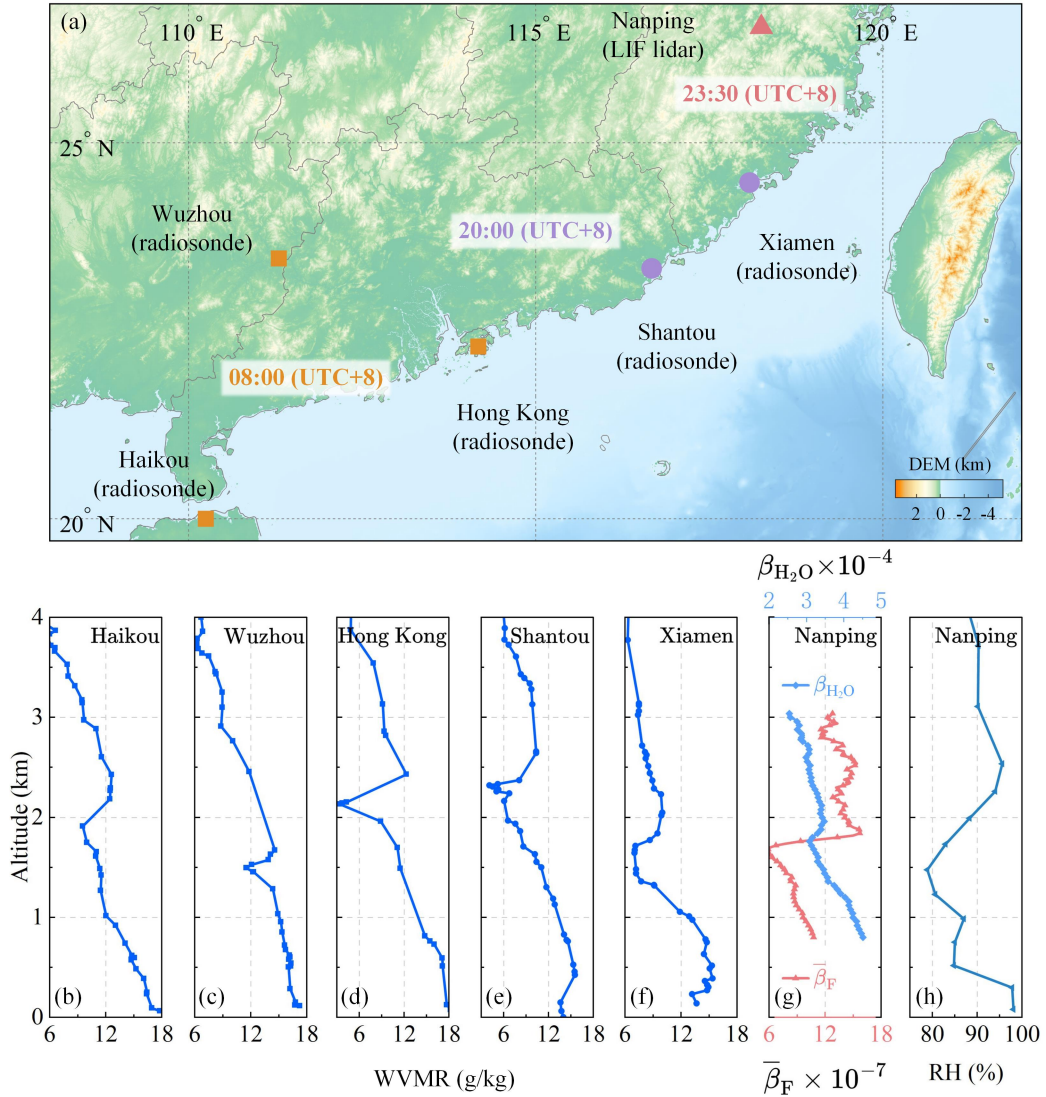
290 For the spectrum of Case 1 (1.8–2.4 km), the relatively weak peak intensity is likely attributable to the overall low fluorescence signal intensity (which is over two orders of magnitude lower than the  $\text{N}_2$  Raman signal) and mixing with urban aerosol due to the long-range transport, while the peak wavelength discrepancy relative to previous studies is likely due to distinct fire sources. Biomass burning emits complex carbonaceous aerosols, which undergo further chemical transformations during atmospheric transport and result in more diverse compositions (Hodshire et al., 2019; Wang et al., 2019). Many components in BBA, such as polycyclic aromatic hydrocarbons (PAHs) and humic-like substances (HULIS), can produce fluorescence under UV excitation (Pöhlker et al., 2012; Yue et al., 2022). In As shown in Fig. 4a, Case 1, the (1.8–2.4 km) layer (Fig. 4b) exhibited a spectral shoulder starting at channel which begins at Channel 18 (central wavelength is 459.5 nm), showing suggesting the presence of fluorophores. As summarized in Table C1, fluorescence peaks in the 440–480 nm range have been

reported for certain PAHs and HULIS under ~355 nm excitation, which are similar to our observed spectral feature. In contrast, previous LIF lidar observations in Europe ~~reported BBA fluorescence peaks at 482–560 nm~~ exhibited BBA fluorescence peak wavelengths approximately between 498 and 560 nm (Table C2), highlighting the influence of source characteristics and atmospheric processing on spectral signatures. ~~Notably, the low-altitude (0.8–1.4 km) layer in Case 1, despite lacking visually distinct fluorescence enhancement in Fig. 3, exhibited a weak spectral peak resembling that of the high-altitude (1.8–2.4 km) BBA layer. This suggests partial downward mixing of BBA and indicates that even low-intensity fires can introduce potentially hazardous fluorescent species into the lower troposphere. Future work combining LIF lidar with in-situ measurements could help further investigate the mechanisms of BBA downward transport (Dajuma et al., 2020)~~ Via vertical mixing, such transported BBA may influence the near-surface atmosphere (Dajuma et al., 2020). Future observations combining LIF lidar with in-situ instrumentation such as the Wideband Integrated Bioaerosol Sensor (WIBS), which also operates on LIF principles (Tang et al., 2022), would facilitate a more in-depth investigation of the near-surface impacts exerted by transported BBA. Combined LIF lidar and WIBS measurements have recently been reported (Gidarakou et al., 2025).

To further investigate BBA transport processes, we analyzed radiosonde observations from multiple sites in South China (Fig. 7a), with colors representing different observation times corresponding to the BBA transport period (Fig. 5d, the "long-range transport" stage). In Fig. 7g, the  $\bar{\beta}_F$  shows a marked increase at 1.8 km, coinciding with enhanced  $\beta_{\text{H}_2\text{O}}$  at Nanping. Although previous studies have noted fluorescence interference in water vapor Raman channels (Chouza et al., 2022; Liu et al., 2022), our measurements show the fluorescence signal was roughly an order of magnitude lower than the water vapor signal (shown in Fig. 4ba), indicating that fluorescence interference is unlikely to be the primary cause of the observed  $\beta_{\text{H}_2\text{O}}$  enhancement. The ERA5 RH profile (Fig. 7h) additionally verifies the presence of a high-humidity layer. As shown in Fig. 5d, HYSPLIT backward trajectories indicate that the observed BBA layer ~~was originated from coastal fire sources and originated from fire sources near coastal regions and were~~ transported inland by onshore flow, which suggests possible entrainment of marine aerosols (such as sea salt) (Dang et al., 2022). Furthermore, radiosonde data (Fig. 7b–f) reveal that the BBA was co-transported with water vapor, a feature consistent with previous lidar and ~~in-situ observations (Kim et al., 2009; Fadnavis et al., 2013; Pistone et al., 2021; Chavan et al., 2021; Hu et al., 2022; Rubin et al., 2023; Pistone et al., 2024) and suggests possible entrainment of marine aerosols (such as sea salt) (Dang et al., 2022)~~ in-situ observations (Kim et al., 2009; Fadnavis et al., 2013; Pistone et al., 2021; Chavan et al., 2021; Hu et al., 2022; Rubin et al., 2023; Pistone et al., 2024). Such humid, sea salt containing conditions could enhance sunlight driven reactions, accelerating secondary sulfate formation and thereby exerting important environmental impacts (Tang et al., 2023, 2025b).

## 6 Conclusion

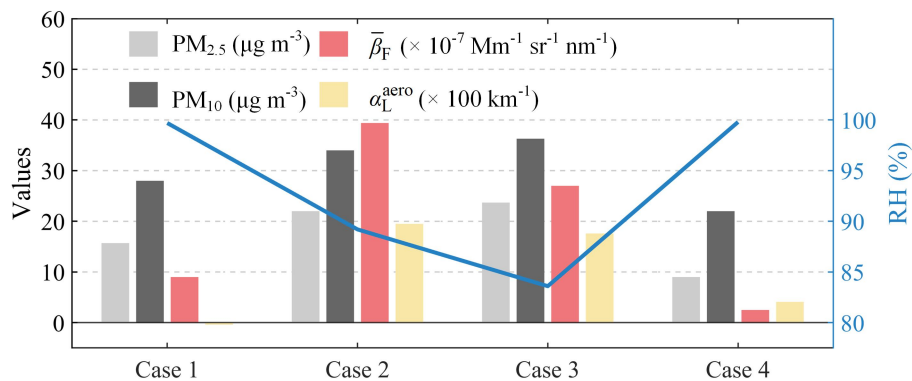
In this study, we reported LIF lidar observations at Nanping, South China during April–May, 2024. ~~The lidar captured a weak but a~~ distinct fluorescent layer ~~whose spectral characteristics differ from those of urban aerosols. Source attribution indicates~~ ~~the~~ was observed, exhibiting unique spectral characteristics and an estimated fluorescence capacity ( $\hat{G}_F \approx 3.1 \times 10^{-6} \text{ nm}^{-1}$ ). HYSPLIT backward trajectory analysis indicates that this layer originated from low-intensity fire ~~sources~~ points in the ICP, and



**Figure 7.** Radiosonde, LIF lidar, and reanalysis profiles for 19 April 2024 (UTC+8), Case 1. (a) Map overview of radiosonde launch **site** and the **Nanping-LIF lidar station**; marker colors and shapes indicate acquisition time; the LIF lidar measurement period is 19 April 2024, 23:19–20 April 00:05 (UTC+8). (b–f) Water vapor mixing ratio (WVMR) profiles from radiosonde measurements. (g) Water vapor Raman backscatter coefficient  $\beta_{\text{H}_2\text{O}}$  ( $\text{Mm}^{-1} \text{Sr}^{-1}$ ) and **spectral** fluorescence backscatter coefficient  $\bar{\beta}_{\text{F}}$  ( $\text{Mm}^{-1} \text{Sr}^{-1} \text{nm}^{-1}$ ) profiles. (h) ERA5 **relative humidity** (RH) profile for Nanping at 19 April 2024, 23:00 (UTC+8).

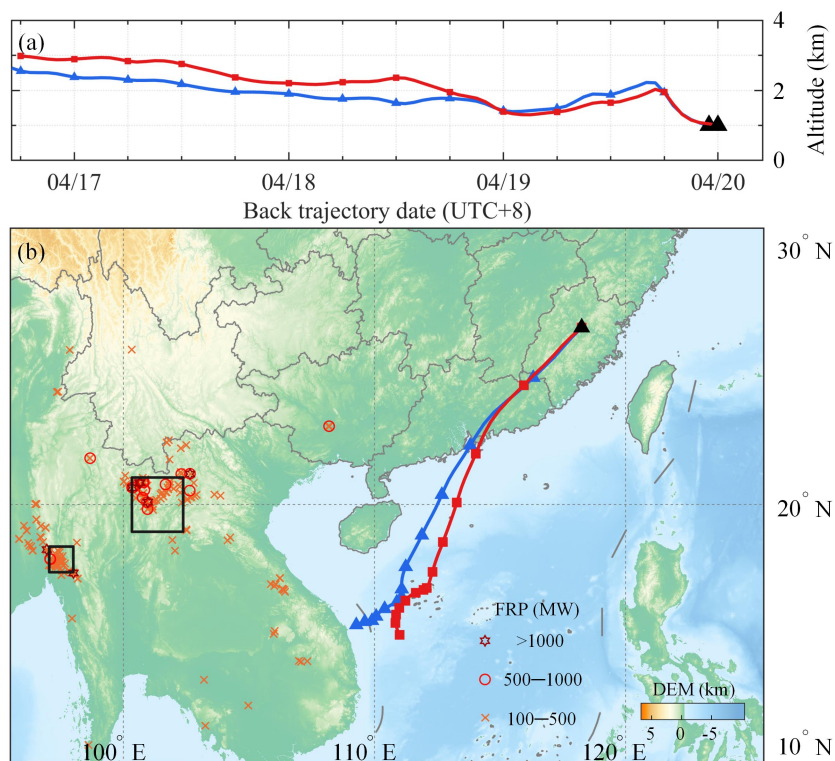
the aerosol underwent a three-stage transport process (local biomass burning, vertical lifting, and long-range transport). These observations demonstrate. These lines of evidence support that the BBA transported from the ICP was a major contributor to the fluorescent layer. Consistent with the high sensitivity of LIF lidar to relatively weak fires and faint fluorescence signals reported in Europe (Gast et al., 2025; Reichardt et al., 2025), these results show that LIF lidar can detect faint BBA fluorescence signals from relatively weak fires in Asia. Fluorescence spectral analysis reveals peaks similar to previous in-situ fluorescence—a peak similar to those reported in previous in-situ studies of certain hazardous organics, yet the overall. However, the peak wavelengths of fluorescence spectra differ from previous LIF lidar studies, implying suggesting compositional variability linked to source or aging types or aging processes. Notably, we also observed co-transport of water vapor with the BBA was also observed, which may enhance aerosol processing and increase impacts in downwind regions. Future studies should aim to couple LIF lidar with coordinated in-situ observations to better evaluate impacts on low-altitude air; upgrades to the lidar system, including elastic and polarization channels, are under consideration.

March marks the peak of seasonal biomass burning across the ICP, with widespread agricultural burning (for planting preparation) and forest fires (Gautam et al., 2013; Huang et al., 2016). As South China lies downwind of the ICP, it provides a favorable setting for long-term LIF lidar observations of transported BBA across different stages of the burning season. To improve quantitative aerosol classification, a LIF lidar system that integrates elastic scattering, depolarization, and fluorescence detection is under development. It will enable direct retrieval of spectral fluorescence capacity  $G_F$  (Reichardt, 2014) and depolarization ratio—key parameters for refining aerosol type differentiation (Veselovskii et al., 2022b) and gaining deeper insights into regional BBA characteristics.



**Figure A1.** Temporal variations Comparison of pollution and meteorological key parameters at the Nanping lidar station. Gray shaded bands indicate the time intervals of the four cases studied: averaged  $\bar{\beta}_F$ ,  $\alpha_L^{\text{aero}}$  (a) 0.8–1.4 km) PM<sub>10</sub>, surface RH, and surface PM<sub>2.5</sub> concentrations. (b) Boundary layer height (BLH) derived from ERA5 hourly reanalysis. The values of  $\alpha_L^{\text{aero}}$  have been multiplied by 100 for clarity. Note that the averaged  $\alpha_L^{\text{aero}}$  for Case 1 is negative, which can be attributed to overestimated molecular extinction or retrieval uncertainties associated with temperature and pressure profiles (Ansmann et al., 1992b).

## Appendix B: Source attribution of Case 1 with a starting altitude of 1 km



**Figure B1.** HYSPLIT backward trajectory analysis initialized at 1 km above ground level (Nanping the LIF lidar station site marked by black triangle). (a) Vertical variation of air mass altitude for the study period. (b) Horizontal (longitude-latitude) trajectories overlaid on presumed vegetation fire locations; marker colors and shapes indicate FRP levels.

## Appendix C: Fluorescence spectra of previous studies

**Table C1.** Previous ~~in-sttu-in-situ~~ studies showing fluorescence signatures similar to the BBA spectrum observed in Case 1.

Substances	Excitation/emission wavelength (nm)	References
Pyrene	355/450–470	
Fluoranthene	355/460–480	(Zhang et al., 2019)
BBA (volume correction)	355/450–470	
Cluster 5 (from ambient air)	351/440–470	(Pan et al., 2012)
HULIS	340/475 (max)	(Muller et al., 2008)
Fresh fulvic acids	332–358/410–456	(Klapper et al., 2002)
Fluoranthene	355/450–470	(Louzon et al., 2025)

**Table C2.** ~~Other-Previously~~ reported LIF lidar fluorescence ~~signatures-peaks~~ of ~~biomass-burning-aerosols~~BBA.

Origin or time	Excitation/ <del>emission-wavelength</del> -reported peak wavelengths (nm)	References
East and west Canada	355/505–518	
West Canada	355/ <del>500–545</del> -498–535	(Reichardt et al., 2025)
In gardening season	355/ <del>482–545</del> -499–540	
American, Siberian	355/513, 560	(Veselovskii et al., 2025)

*Data availability.* Lidar data used in this study can be provided for non-commercial research purposes upon request to the first author (zkl@nuist.edu.cn).

355 *Author contributions.* ZL: methodology, data curation, formal analysis, visualization, writing (original draft). DT: conceptualization, investigation, writing (review and editing). TW: methodology, writing (review and editing). SY: writing (review and editing). JC: writing (review and editing). KW: writing (review and editing). ZZ: writing (review and editing). JH: writing (review and editing). HH: writing (review and editing). YW: writing (review and editing). HX: resources, supervision, writing (review and editing).

*Competing interests.* The authors declare that they have no conflict of interests.

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model (<https://www.ready.noaa.gov/>), NASA FIRMS (<https://firms.modaps.eosdis.nasa.gov/>) and NASA worldview  
(<https://worldview.earthdata.nasa.gov/>) for providing satellite products, NASA and PHOTON for providing AERONET  
(<https://aeronet.gsfc.nasa.gov/>) sites data (Site managers: Sumaman Buntoung and Somjet Pattarapanitchai), the University of Wyoming  
weather website (<https://weather.uwyo.edu/>) for providing radiosonde data, ECMWF for providing ERA5 data  
365 (<https://cds.climate.copernicus.eu/>), NASA for providing MERRA-2 data (<https://disc.gsfc.nasa.gov/>), CNEMC for providing air quality data  
(available at <https://quotsoft.net/air/>), and NOAA (<https://www.ncei.noaa.gov/>) for providing DEM data, ~~and authors also thank FLATICON  
website for providing the icons used in the graphical abstract (<https://www.flaticon.com/>).~~

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