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Title: Biomass burning aerosol transport from Indo-China Peninsula to South China: fluorescence lidar observation and analysis

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Dear editor Gerd Baumgarten and Referee #3:

On behalf of the co-authors, thank you for giving us an opportunity to address the Referee #3's concerns. We appreciate all the great efforts and constructive comments from Referee #3. We have revised the manuscript carefully according to the Referee #3's comments and suggestions. Our point-by-point responses are appended below. All changes made in the revised manuscript are marked in blue. Attached please find the revised version of the manuscript, which we would like to submit for your kind consideration. We are looking forward to hearing from you!

Best regards!

Sincerely yours,

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Anonymous Referee #3:

General comment:

This study analyzes four cases of laser-induced fluorescence (LIF) lidar observations in South China. In Case 1, a pronounced fluorescence layer is detected and attributed to biomass burning aerosols (BBA) transported from the Indo-China Peninsula, based on HYSPLIT backward trajectories and other supporting datasets.

LIF lidar has been demonstrated as an effective tool for detecting BBA in Europe, but applications in South China remain limited. Deploying this technique in a region frequently impacted by Southeast Asian biomass burning smoke is therefore timely and valuable. The manuscript helps fill an observational gap and provides useful insights into BBA characteristics and transport pathways.

Thank you for your comment. South China is densely populated region frequently affected by transported biomass burning aerosol (BBA). Thus, this area requires sensitive laser-induced fluorescence (LIF) lidar observations to characterize these plumes.

Overall, the manuscript provides considerable evidence to support its conclusions, but the structure of Section 4 should be revised to align with the logical flow of evidence. Additionally, future perspectives should be added to the Conclusion section to provide useful references for the follow-up studies. Please refer to the specific comments below for details.

Thank you for your valuable suggestions. Section 4 has been revised, please see our response to your comments on **Lines 149-150** below for details. The Conclusion section has been enriched, please refer to our reply to Conclusion below for details.

We sincerely thank Referee #3 for constructive comments and suggestions, which have significantly improved the quality of our manuscript. Below, we provide our point-by-point responses to the comments:

Specific comments:

1. Line 31: 'the' should be deleted as no specific system is referred to.

Thank you for pointing this out. 'the' in **Line 31** has been deleted.

2. Lines 30-35: Besides atmospheric observations, LIF lidar has been applied in a range of other remote sensing applications, including aquatic oil spill detection and chlorophyll fluorescence monitoring. Adding a short discussion of these applications in the Introduction may help highlight the broader applicability of LIF lidar.

We appreciate your valuable suggestion. Brief discussions and relevant references on these applications have been added to the Introduction to highlight the broader applicability of LIF lidar. In addition, a concise background on Raman lidar has been included to clarify the observational context in which atmospheric fluorescence was first reported in water vapor Raman measurements. This also provides context that many LIF lidar systems use vibrational Raman channels as a molecular reference. We have also refined and supplemented the content pertaining to ambient atmosphere detection using LIF lidar, with additional relevant references incorporated, to provide a more comprehensive overview of LIF lidar applications:

"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 have developed single-channel (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; 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. 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; Duschek et al., 2017; 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. Previous LIF lidar observations of BBA in the ambient atmosphere, generally built upon Mie-Raman lidar systems, have been conducted 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 have been reported, and these layers often originated from long-range transport of BBA from strong fires in North America or Russia. However, BBA fluorescence spectra can vary substantially across locations and cases (Reichardt et al., 2025). Consequently, further observations in 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."

3. Line 39: To be clear, 'weaker cases' should be revised to 'weaker fire cases'.

Thank you for pointing this out. The wording has been revised to improve clarity and precision.

"Consequently, further observations in diverse regions and under weak fire conditions are warranted…"

4. Line 45: Please provide a brief overview of the section contents at the end of the Introduction.

Thank you for your suggestion. The overview has been added at the end of the Introduction:

"Building on these advances, we conducted LIF lidar observations at Nanping, South China, during 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 overall fluorescence intensity is relatively weak, its spectral signatures differ from those of urban 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 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 alongside elevated water vapor, indicating a humid transport pathway. Conclusions and future implications are summarized in Sect. 6."

5. Line 59: 'BBA layer' should be revised to 'fluorescent layer', as the fluorescence attribution is presented in Section 4.

We are grateful to you for pointing this out. 'BBA layer' has been revised to 'fluorescent layer'.

6. Lines 143-144: Please consider moving the sentence pertaining to spectral characteristics to Section 4.2, as it focuses on spectral analysis.

Thank you for your suggestion. The structure of Section 4 has been reorganized, please refer to our response to the comments on **Lines. 149-150** for details.

7. Line 145: Similarly, as the spectra are a key piece of evidence for characterizing urban aerosols, the corresponding conclusion should also be moved to Section 4.2.

We agree with your valuable suggestion, please refer to our response to the comments on **Lines 149-150** for details.

8. Lines 149-150: As already mentioned in the general comment, the conclusion of BBA characterization is premature to present here. It should be presented in Section 4.3.

We appreciate your suggestion. Combined with the suggestion of Referee #2, We have reorganized the structure of Section 4 to follow the flow of our evidence. The revised Section 4 is as follows:

"4.1 Vertical profiles observed by LIF lidar

Table 2. Estimates of layer-averaged spectral fluorescence capacity ($\hat{G}_{\mathrm{F}} = \frac{\overline{\beta}_F}{\alpha_{\mathrm{L}}^{\mathrm{aero}}} \cdot S$), computed over the fluorescence 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	$\hat{G}_{\mathrm{F}}$ (× 10^{-6} nm^{-1}) (0.8–1.4 km)	$\hat{G}_{\mathrm{F}}$ (× 10^{-6} nm^{-1}) (1.8–2.4 km)
Case 1	–	3.1
Case 2	1.5	0.4
Case 3	1.2	1.4
Case 4	0.5	0.2

In Case 1, a distinct fluorescence layer (enhanced $\overline{\beta}_{\mathrm{F}}$) accompanied by enhanced water vapor was observed at ~ 1.8 km despite relatively low $\alpha_{\mathrm{L}}^{\mathrm{aero}}$ (Fig. 2c, e, and f and Fig. 3). This enhancement is not observed in the other three cases (Fig. 3). To further analyze the fluorescence characterization, we use quantitative analyses of the spectral fluorescence capacity $G_{\mathrm{F}} = \frac{\overline{\beta}_{\mathrm{F}}}{\beta_{\mathrm{L}}}$, where $\overline{\beta}_F$ is the spectral fluorescence backscatter coefficient and β_{L} is the elastic backscattering coefficient (Reichardt, 2014; Veselovskii et al., 2022b). As β_{L} was not directly available in this study, we estimated $\hat{G}_{\mathrm{F}} = \frac{\overline{\beta}_F}{\alpha_{\mathrm{L}}^{\mathrm{aero}}} \cdot S$ using a typical lidar ratio S ≈ 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 $\widehat{G}_{\mathrm{F}}$ estimation. $\widehat{G}_{\mathrm{F}}$ values are provided in Table 2, excluding Case 1 (0.8–1.4 nm): negative $\alpha_{\mathrm{L}}^{\mathrm{aero}}$ results in negative $\widehat{G}_{\mathrm{F}}$, which is thus omitted. Table 2 presents the highest $\widehat{G}_{\mathrm{F}}$ for Case 1 (1.8–2.4 km) ≈ 3.1 × 10^{-6} nm^{-1}, which falls within the typical smoke range of 2×10^{-6}–9×10^{-6} nm^{-1} (Gast et al., 2025) and is at least twice as high as $\widehat{G}_{\mathrm{F}}$ values from other layers.

4.2 Fluorescence spectra

The spectrum of Case 1 (1.8–2.4 km) is distinct from other aerosol spectra (Fig. 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, urban aerosol) is ~ 4.9°, notably larger than the SAM angle (≈ 1.14°) between 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), HYSPLIT backward trajectory analysis was performed in Sect. 4.3.

4.3 Source attribution of the fluorescence layer in Case 1

…Considering the distinct $\overline{\beta}_{\mathrm{F}}$ layer (Fig. 2f), the highest $\widehat{G}_{\mathrm{F}}$ (≈ 3.1 × 10^{-6} nm^{-1}; Table 2), the unique fluorescence spectral shape (Fig. 4a–b), and HYSPLIT backward trajectory analysis (Fig. 5d), these lines of evidence support that BBA transported from the ICP was a major contributor to the fluorescent layer observed in Case 1 (1.8–2.4 km).”

9. Lines 160-162: Please specify only the precise height ranges to avoid confusion.

Thank you for pointing this out. The height-related sentences are revised to only precise height ranges.

10. Lines 202-205: The consideration of the influence from high altitudes to low altitudes is noteworthy, but the discussion is insufficient based solely on two weak spectra. Therefore, the authors are advised to remove the relevant descriptions and focus instead on the implications for future research.

Thank you for your suggestion. We have deleted the relevant discussions. To strengthen the discussion on future research implications, we have supplemented relevant references and revised the corresponding content as follows:

“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).”

11. Line 213: "was originated" should be revised to "originated".

Thank you for pointing this out. ‘was’ has been deleted.

12. Lines 213-217: Please reorder the sentences for clearer logic. The description should specify that onshore flow introduces the potential for mixing between marine aerosols and BBA.

Thank you for your suggestion. The order of sentences has been reorganized:

“As shown in Fig. 5d, HYSPLIT backward trajectories indicate that the observed BBA layer originated from fire sources near coastal regions and was 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).”

13. Conclusion: As noted in the general comments, it is recommended to add a brief discussion of future research prospects at the end of the Conclusion to better outline potential directions for subsequent studies.

Thank you for your insightful suggestion. Combined with the suggestion of Referee #2, we have added future research implications at the end of the Conclusion section:

“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 advancing aerosol type differentiation (Veselovskii et al., 2022) and gaining deeper insights into regional BBA characteristics."

In addition, several relevant references have been incorporated into the revised manuscript in response to the constructive comments from both Referee #2 and Referee #3:

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