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Multiwavelength fluorescence lidar observations of fresh smoke plumes

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Abstract

A five-channel fluorescence lidar was developed for the study of atmospheric aerosol. The fluorescence spectrum induced by 355 nm laser emission is analyzed in five spectral intervals using interference filters. Central wavelengths and the widths of these five interference filters are respectively: 438/29, 472/32, 513/29, 560/40 and 614/54 nm. The relative calibration of these channels has been performed using a tungsten-halogen lamp with color temperature 2800K. This new lidar system was operated during Summer – Autumn 2022, when strong forest fires occurred in the Moscow region and generated a series of smoke plumes analyzed in this study. Our results demonstrate that, for urban aerosol, the maximal fluorescence backscattering is observed in 472 nm channel. For the smoke the maximum is shifted toward longer wavelengths, and the fluorescence backscattering coefficients in 472 nm, 513 nm and 560 nm channels have comparable value. Thus, from the analysis of the ratios of fluorescence backscattering in available channels, we show that it is possible to identify smoke layers. The particle classification based on single channel fluorescence capacity (ratio of the fluorescence backscattering to elastic one), has limitations at high relative humidity (RH). Fluorescence capacity is indeed decreasing when water uptake of particles enhances the elastic scattering. However, the spectral variation of fluorescence backscattering does not evidence any dependence on RH and can be therefore considered for aerosol identification.

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Atmospheric Measurement Techniques Discussions

1. Introduction

The knowledge of the chemical composition of atmospheric aerosol is important for characterization of its impact on the Earth radiation balance (Boucher et al., 2013; IPCC 2022). The composition of aerosol, however, is strongly variable, and in practice, several general aerosol types, usually, are considered, based of their origin (Dubovik et al., 2002). The Mie-Raman and high spectral resolution lidars provide the opportunity to derive vertical distribution of the particle extinction and backscattering coefficients together with multispectral depolarization ratio. Based on these observations the main aerosol types can be distinguished (Burton et al., 2012, 2013; Groß et al., 2013; Mamouri et al., 2017; Papagiannopoulos et al., 2018; Nicolae et al., 2018; Hara et al., 2018; Wang et al., 2021; Mylonaki et al., 2021). However, due to the variability of aerosol parameters, the particle intensive properties (properties that are independent on concentration), such as lidar ratios, depolarization ratios and Angstrom exponents can vary in a wide range, even for aerosols from the same origin, which complicates their identification.

The fluorescence measurements provide new independent information about aerosol composition, which can be used for classification. (Veselovskii et al., 2022b). Being induced by 355 nm laser radiation the atmospheric fluorescence emission spreads in a wide spectral range from approximately 380 nm to beyond 700 nm. The multianode photomultipliers combined with spectrometer, in principle, allow profiling the full fluorescence spectrum (Sugimoto et al., 2012; Saito et al., 2022; Reichardt et al., 2022). In a more simple approach a single fluorescence channel has been integrated into existing multiwavelength Mie-Raman lidar (Veselovskii et al., 2020), and a fraction of the fluorescence spectrum is selected by a wideband interference filter. High transmittance of modern interference filters (above 95%), allows efficient detection of fluorescence emission, and when combined with simultaneous depolarization measurements the main aerosol types, such as dust, smoke, pollen and urban can be identified (Veselovskii et al., 2022b). This classification scheme relies on the fluorescence capacity G_λ, which is the ratio of fluorescence backscattering to elastic backscattering at laser wavelength. The fluorescence capacity, however, depends on the relative humidity (RH), because enhanced elastic backscattering leads to decrease of G_λ (Veselovskii et al., 2021). Thus, at high RH, we cannot attribute unambiguously the decrease of G_λ to some water uptake to some changes in the aerosol composition.

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Atmospheric Measurement Techniques Discussions

The water uptake increases the elastic backscattering but normally does not alter the chemical components thus, total amount of fluorescent molecules within a particle does not change. The illumination intensity distribution within a particle, as well as the emission angular distribution can be altered by the change of particle size and refractive index during the hygroscopic growth. However, this effect occurs for relatively big microspheres with size parameter exceeding approximately 10 (Veselovskii et al., 2002). Thus, fluorescence of the fine mode particles should be less influenced by the hygroscopic growth. Our existing lidar data-base in well mixed boundary layer situations demonstrate that, at least, for urban and smoke particles, the fluorescence backscattering coefficient did not change during water uptake. Thus, we have good reason to expect, that fluorescence spectrum is not modified by the aerosol hygroscopic growth, and several fluorescence channels should provide more reliable information upon aerosol type.

Smoke is one of the most abundant aerosol types and it was intensively studied with Mie-Raman lidars for decades (Adam et al., 2021 and references therein). Smoke is characterized also by high fluorescence capacity, thus fluorescence lidar measurements proved to be very efficient for smoke identification and analysis (Hu et al., 2022, Veselovskii et al., 2022a,b). However, as mentioned, at high RH classification of smoke, based on a single channel fluorescence may fail. The solution could be the detection of fluorescence at several wavelengths. In July 2022 a new lidar system equipped with five fluorescence channels, was assembled in Prokhorov General Physics Institute, Troitsk, Moscow. The lidar was in operation during Summer and Autumn 2022, when strong forest fires occurred in the Moscow region. In this paper we analyze the spectral dependence of the fluorescence backscattering inside and outside the smoke plumes. The results demonstrate that the hygroscopic growth does not affect the spectral dependence of fluorescence backscattering.

2. Experimental setup

The fluorescence lidar is based on a tripled Nd:YAG laser with pulse energy of 80 mJ at 355 nm and repetition rate of 20 Hz. Backscattered light is collected by a 40 cm aperture Newtonian telescope and the lidar signals are digitized with Licel transient recorders with 7.5 m range resolution, allowing simultaneous detection in the analog and photon counting modes. The optical scheme of the receiving module is presented in Fig.1. The system is designed to detect

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elastic backscattering at 355 nm, nitrogen Raman backscattering at 387 nm and fluorescence backscattering in five spectral intervals. These intervals are separated with dichroic beamsplitters and isolated by the interference filters manufactured by Alluxa. The central wavelengths and the widths of transmission bands (FWHM) of these fluorescence channels are respectively: 438/29, 472/32, 513/29, 560/40 and 614/54 nm. The transmission of the filters exceeds 97%, while suppression of optical signal out of band is above OD6. To improve the suppression of elastic backscattering we installed two filters in tandem in every channel.

Laser radiation at 532 nm can induce additional aerosol fluorescence which will contaminate long-wave channels. To remove potential contamination, the emission at 532 nm and 1064 nm are separated with dichroic mirrors and redirected to an optical dump. Therefore, the laser beam sent into the atmosphere has only one wavelength - 355 nm. As follows from Fig.1, the 532 nm radiation is out of the transmission band of the filters, which prevents the leaking of residual 532 nm component to the fluorescence channels. We should mention, that the vibrational overtone of N_2 Raman scattering at 424.4 nm is within the transmission band of 438 nm channel. In accordance with results of Knippers et al. (1985), Raman intensity of this overtone is about three orders lower than intensity of N_2 fundamental vibration (for 488 nm laser wavelength). Based on our measurements, contribution of N_2 overtone to fluorescence signal from urban aerosol (with backscattering coefficient of 1.0 $Mm^{-1}sr^{-1}$ at 355 nm and G_{438}=0.3×10^{-4}) is estimated to be below 5% at 1000 m height. In all the channels the PMTs R9880U-01 were used, except in the 614 nm channel, where R9880-20 PMT was installed, due to its higher sensitivity in the red spectral region. The strong sunlight background at daytime restricts the fluorescence observations to only nighttime.

The aerosol extinction coefficients at 355 nm (α_{355}) were calculated from Raman observations as described in Ansmann et al., (1992). For calculation of backscattering coefficient β_{355} in the presence of clouds, this method was modified (Veselovskii et al, 2022b). Additional information about atmospheric properties was available from radiosonde measurements at Dolgoprudnyi station, located about 50 km away from the observation site. It should be mentioned that the current lidar configuration does not allow measurement of the depolarization ratio.

The fluorescence backscattering coefficient $\beta_{F\lambda}$ is calculated from the ratio of fluorescence signal to 387 nm nitrogen Raman signal, as described in Veselovskii et al. (2020).

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One reminds that $\beta_{F\lambda}$ is the integral of fluorescence backscattering over the filter transmission band D_λ. For calculation of $\beta_{F\lambda}$ one needs to know the differential cross section of nitrogen Raman scattering, σ_R, and the relative sensitivity of the nitrogen and fluorescence detection channels. The value σ_R=2.744*10^{-30} cm^{2}sr^{-1} at 355 nm was taken from Venable et al. (2011). Sensitivity of R9880U-01 photocathode in the 387 nm - 438 nm range varies for less than 10%, so we neglect this variation and calculate relative sensitivity of the PMTs as described in Veselovskii et al. (2020). The relative sensitivity of the rest of the fluorescence channels in respect to the 438 nm one, was calculated from laboratory measurements using a tungsten-halogen lamp Thorlabs QTH10/M with color temperature 2800K as a source, assuming this source follows the Planck blackbody emission. This procedure was performed once a week and variations of the calibration coefficients during August-September 2022 period were below 15%.

To compare $\beta_{F\lambda}$ at different fluorescence channels we compute the mean backscattering coefficients per elementary spectral interval, $B_\lambda = \frac{\beta_{F\lambda}}{D_\lambda}$, denoted as "fluorescence spectral backscattering coefficient". The fluorescence capacity G_λ, which is the ratio of the fluorescence backscattering to the elastic one, in principle, can be calculated for any laser wavelength. In our previous studies we calculated G_λ with respect to β_{532}, however, in this work, it was calculated with respect to 355 nm $G_\lambda = \frac{\beta_{F\lambda}}{\beta_{355}}$, since 532 nm wavelength was not available. All $\beta_{F\lambda}$, G_λ and B_λ profiles presented in this work were smoothed with the Savitzky – Golay method, using a second order polynomial with 21 points in the window.

3. Measurements and analysis

In August 2022 numerous smoke layers originating from the forest fires in Ryazan region (about 160 km South – East of Moscow) were detcted over the lidar station. The travel time of the layers was less than two days, thus smoke can be considered as fresh. The previous fluorescence studies of smoke plumes transported over Atlantic and including 466/44 nm fluorescence measurements revealed that fluorescence capacity (calculated for β_{532}), in the absence of hygroscopic growth, varied within the range (2.5–5.0)×10^{-4} (Veselovskii et al., 2021, 2022a,b; Hu et al., 2022). The Backscattering Angstrom Exponent (BAE) of smoke for 355/532

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Atmospheric Measurement Techniques Discussions

nm wavelengths, is about 2.0, and fluorescence capacity G_{472} in 472/32 nm channel (calculated for β_{355}) is expected to be in the range (0.8–1.6)×10^{-4}. For urban aerosol corresponding G_{472} should be (0.03-0.3)×10^{-4}. Here and below the fluorescence capacity will be provided for 472 nm, because in most of the cases fluorescence in this channel was maximal.

3.1. Fluorescence measurements during smoke episode

27-28 August 2022

Two-day backward trajectories from the NOAA HYSPLIT model for the air mass reaching Moscow on 28 August at 00:00 UTC are shown in Fig.2. Air masses observed at 1500 m, passed over the fire region, close to the ground, and should thus contain products of biomass burning. The relative humidity measured by the radiosonde, at 00:00 UTC, was about 35% at 1000 m and increased with height up to 70% at 3000 m. Temporal evolution of the aerosol backscattering coefficient, β_{355}, fluorescence backscattering, β_{F438}, and fluorescence capacity, G_{472}, are shown in Fig.3. Aerosols are localized mainly below 3000 m, while above 4000 m cloud layers can be seen. In the boundary layer the fluorescence backscattering inside the boundary layer is the strongest before 20:30 UTC. The fluorescence capacity exceeds 2.5×10^{-4}, which is the highest observed G_{472}. After 20:30 G_{472} decreases but remains above 1.0×10^{-4}, which, in principle, can be due to mixing of smoke with urban aerosol.

Vertical profiles of the fluorescence spectral backscattering coefficients B_λ are shown in Fig.4 for the period corresponding to maximum fluorescence capacity (19:00-20:00 UTC). Profiles of B_{472}, B_{513}, B_{560} are similar, indicating that fluorescence does not demonstrate significant spectral variations in 472-560 nm spectral range. The fluorescence capacity G_{472} is above 2.0×10^{-4}, in 1.0 km – 2.5 km height range, where β_{355} and B_λ are maximum. The ratios B_{472}/B_{438}, B_{472}/B_{513}, B_{472}/B_{560}, B_{472}/B_{614} do not demonstrate height dependence in 1000-2500 m range, thus, the fluorescence spectrum in this interval is not changed. Fig.5 shows spectra of fluorescence for two distinct temporal intervals. In the interval corresponding to high fluorescence capacity (19:00-20:00 UTC), the maximum fluorescence backscattering is observed in 513 nm channel, which agrees with spectrum of smoke fluorescence provided by Reichard et al. (2022). In the second interval (23:00-01:00 UTC), when fluorescence capacity is lower, the fluorescence is maximal at 472 nm and at longer wavelengths it decreases fast. The lidar ratios (S_{355}) for both time intervals are shown in the same figure. For the first interval (with maximum

Atmospheric Measurement Techniques Discussions

G_{472}) S_{355} is about 60 sr, while for the second interval S_{355} decreases to about 40 sr. Lidar ratio 60 sr is in agreement with S_{355} reported for fresh smoke (Adam et al., 2021), while values about 40 sr are usually observed for urban particles at low RH. The highest spectral fluorescence capacity of smoke (capacity per elementary spectral interval), reported by Reichard et al. (2022) for 455–535 nm range is about 8×10^{-6} nm^{-1}. This is very comparable with our value (11×10^{-6} nm^{-1}) calculated from data plotted in Fig.4 and 5 at 472 nm in 19:00-20:00 UTC time interval.

The variation of the fluorescence spectra with height is revealed by the ratio of the fluorescence backscattering coefficients at different wavelengths (e.g. B_{472}/B_{λ}). In particular, inside the aerosol plume in Fig.3 B_{λ} does not change significantly in 472 – 560 nm range, so the ratios B_{472}/B_{513}, B_{472}/B_{560} are close to 1.0. Temporal evolution of these ratios is shown in the right column in Fig.3. The intervals with the maximum G_{472} are well distinguished by minimum B_{472}/B_{513} and B_{472}/B_{560} ratios. At the same time, ratio B_{472}/B_{438} appears to be less sensitive to G_{472} changes. Actually, this ratio even increases inside the aerosol plume. Thus, the analysis of Fig.3 reveals two types of the particles. The first type having a high fluorescence capacity (G_{472}>2.0×10^{-4}) and a lidar ratio close to 60 sr can be classified as "pure" smoke. The second type, with lower fluorescence capacity (G_{472}~1×10^{-4}) and a smaller lidar ratio, can be a mixture of smoke and urban aerosol.

Forest fires stopped in the beginning of September, so during September – October the urban aerosols were predominant. Fig.6 shows corresponding fluorescence spectra, normalized to B_{472}. Measurements were performed during 07:00-09:00 UTC and averaged within the boundary layer between 500 m and 1000 m. For urban aerosols, fluorescence at wavelengths larger than 472 nm decreases fast. Presence of remaining smoke, however, may lead to some increase of B_{λ} in the 513 – 614 nm interval. For urban aerosol particles the fluorescence capacity G_{472} for urban particles varied within (0.1-0.4)×10^{-4} and the lidar ratios within 30-50 sr interval. Thus, a mixture of smoke and urban particles can explain the variability observed in fluorescence spectrum on Fig.5.

17 August 2022

The spatio – temporal intervals with high fluorescence capacity were observed also for other days. On August 17-18, 2022 between 18:00 – 19:00 UTC, fluorescence capacity at 472 nm, the G_{472}, within the aerosol plume increased above 1.0×10^{-4} (Fig.7). Simultaneously, the

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ratio B_{472}/B_{560} decreases to less than 0.8. Outside the plume, the fluorescence capacity is (0.4-0.7)×10^{-4} and the ratio B_{472}/B_{560} increases up to 1.5. Corresponding fluorescence spectra are shown in Fig.8. Inside the plume the fluorescence is maximal in the 560 nm channel, while outside the maximum is shifted to 472 nm. Similarly to the 27-28 August event (Fig.5), the lidar ratio S_{355} is about 60 sr inside the plume and decreases down to about 30 sr outside the plume. Thus, again, we conclude that in the interval having the highest G_{472}, smoke particles are predominant, while outside we very likely addressed a mixture of smoke and urban aerosol.

3.2. Analysis of fluorescence profiles observed in the presence of hygroscopic growth of aerosol.

Our previous studies with a single channel fluorescence lidar revealed, that the hygroscopic growth of aerosol particles decreases the fluorescence capacity, but does not affect the fluorescence backscattering coefficient (Veselovskii et all, 2021). Thus, when fluorescence spectra are available, one can expect that spectral dependence of fluorescence backscattering coefficients will preserve information about particle type (will not be influenced by water uptake). Below, we provide interpretation of the measurements performed during the nights August 21-22 and 23-24 2022. In both cases, RH increased with altitude and the hygroscopic growth is one possible contributor to the observed increase of particle backscattering coefficient. Our results show, that on August 21-22 the shape of the fluorescence spectrum (the set of B_{λ}/B_{472} ratios) did not exhibit any change with altitude, whereas, conversely, on August 23-24 the shape of the fluorescence spectrum has changed with altitude, indicating possible change of aerosol composition with height.

Fig.9. shows vertical profiles of the fluorescence spectral backscattering coefficients, B_{λ}, together with backscattering β_{355} coefficient, fluorescence capacity G_{472}, and B_{472}/B_{438}, B_{472}/B_{513}, B_{472}/B_{560} ratios on August 21 2022. Profiles of B_{472}/B_{614} ratio are noisier and not used for analysis. The profile of relative humidity measured by a radiosonde at Dolgoprudnii station, shows increase of RH with altitude from 30% to 80% within 1000-4500 interval. Inside 3000-4000 m range, the fluorescence backscattering does not demonstrate significant variations while elastic backscattering increases by two orders of magnitude (from approximately 1 $Mm^{-1}sr^{-1}$ to 100 $Mm^{-1}sr^{-1}$), which should be attributed to aerosol hygroscopic growth. The fluorescence capacity, G_{472}, decreases to less than 0.01×10^{-4} at 4000 m, however, the ratios B_{472}/B_{438},

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Atmospheric Measurement Techniques Discussions

B_{472}/B_{513}, B_{472}/B_{560} do not change with altitude, meaning that i) the spectrum (its shape) is not affected by water uptake process and that ii) aerosol composition remains constant.

Temporal evolution of the particle parameters on the August 23-24 night is presented in Fig.10. The relative humidity increases with height and during 18:00-20:00 time interval a cloud was formed at ~3000 m. After 20:00 the fluorescence capacity inside 2000-3000 m height range is low (below 0.2×10^{-4}), however low values of G_{472} can also be explained by particle hygroscopic growth, thus one can not yet conclude that aerosol composition has changed, because the two effects (RH + aerosol changes) can occur simultaneously. Meanwhile, B_{472}/B_{560} ratio decreases above 2000 m, which can be an indication of aerosol composition change. Profiles of aerosol properties for the time interval 20:30-23:30 are shown in Fig.11. In accordance with the radiosonde measurements the relative humidity reaches 80% at 3000 m at 00:00 UTC. At 1000 m height, where RH is low (~35%), G_{472} is about 0.4×10^{-4}, hence, urban aerosol type is predominant. Both B_{472}/B_{513} and B_{472}/B_{560} ratios decrease above 2000 m, while B_{472}/B_{438} increases. As mentioned above, such behavior can be an indication that contribution of smoke rises with height.

Normalized fluorescence spectra for two height intervals, 1000-1500 m and 2500-3000 m are shown in Fig.11c. In the second interval, the spectrum is shifted towards longer wavelengths, which corroborates that smoke fraction in the aerosol mixture increases above 2000 m. Thus, the analysis of this episode demonstrates that multi-spectral fluorescence backscattering provides opportunity for particle identification even in the presence of hygroscopic growth.

Conclusions and perspectives

Observations performed with a five-channel fluorescence lidar allow estimation of atmospheric aerosol fluorescence spectrum. For urban aerosol type the maximum of fluorescence is observed at 472 nm. However, for smoke particles, the maximum is shifted toward longer wavelengths and the fluorescence backscattering coefficients in the 472 nm, 513 nm and 560 nm channels are comparable. Hence, the ratios B_{472}/B_{513} or B_{472}/B_{560}, allow identification of the smoke layers because, for smoke, these ratios are smaller than for urban particles.

During strong forest fires in August 2022 we regularly observed over Moscow aerosol plumes, characterized by high fluorescence capacity (G_{472}>1.0×10^{-4}). Inside these plumes, lidar ratio S_{355} increased up to 60 sr simultaneously with a shift of the fluorescence maximum to 513

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Atmospheric Measurement Techniques
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Discussions

nm or 560 nm. Particles inside plume are very likely composed of "pure" smoke, while outside the plume, a smoke/urban mixture is probable. Classification of aerosol particles based on single channel fluorescence measurements has limitations at high RH because the fluorescence capacity is decreasing due to water uptake. However, our experimental database of fluorescence backscattering ratios does not evidence noticeable dependence with RH, which means these ratios allow us to identify smoke layers even in the presence of hygroscopic growth.

In our measurements, the laser emitted only 355 nm radiation, however, for aerosol detailed characterization it is important to use 532 nm and 1064 nm wavelengths as well. Such Laser Induced Fluorescence Exploratory instrument (LIFE) is currently under construction and will start operation in 2023, at LOA, ATOLL platform (France), in the frame of the OBS4CLIM project and AGORA-Lab research and development activities. More generally, it seems promising to upgrade widely-used multiwavelength Mie-Raman high performance lidars with a couple of fluorescence channels. According to our results, at least for smoke, the 472 nm and 513 nm channels can be considered. The wavelengths of aniti-Stokes components of nitrogen and oxygen stimulated by 532 nm radiation are 473 nm and 491 nm respectively. The oxygen component is blocked by the filter, while the nitrogen one is inside the transmission band of the 472 nm channel. The power of anti-Stokes scattering increases with temperature, but even at 30C^0 its contribution to the fluorescence signal is insignificant. Estimations show that for backscattering coefficient β_{355}=1.0 Mm^{-1}sr^{-1} and β_{F513}=0.2×10^{-4} Mm^{-1}sr^{-1} (urban aerosol), the relative contribution of the nitrogen anti-Stokes component to the fluorescence at 1000 m height is below 4×10^{-4}.

The results presented in this study are preliminary. We focused mainly on the fresh smoke analysis. However, smoke particle fluorescence properties depend on its chemical composition, in particular, on its organic carbon fraction. In addition, smoke fluorescence may be influenced by the burning process and transportation conditions. Thus, fluorescence spectra appears to be a relevant information to differentiate fresh from aged smoke particles. More observation campaigns, at different locations, are needed to clarify this. In the coming Spring – Summer period analysis of fluorescence spectra of different aerosol types, in particular, the pollens, is planned. At present, the system used in this study is being modified to include depolarization capability.

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Data availability. Lidar measurements are available upon request (philippe.goloub@univ-lille.fr).

Author contributions. IV assembled the lidar and wrote the paper. NK and MK performed the measurements. QH, and PG analyzed data and helped with paper preparation. TP helped with lidar design, DL participated in paper preparation.

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

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Atmospheric Measurement Techniques Discussions

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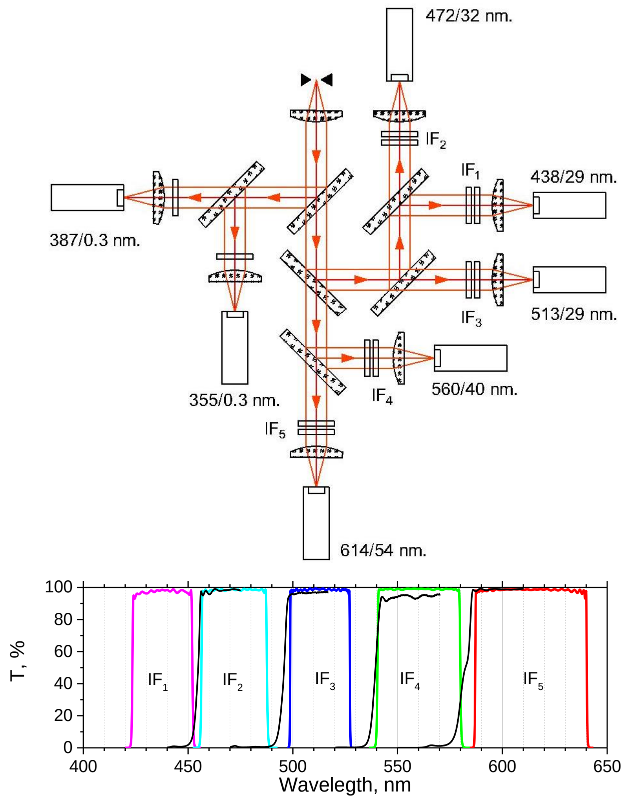

Fig.1. Optical scheme of the receiving module of the lidar together with transmissions of interference filters IF_1-IF_5 in the fluorescence channels. Black lines show the transmissions of the 45 degree dichroic beam splitters used for separation of fluorescence spectral components.

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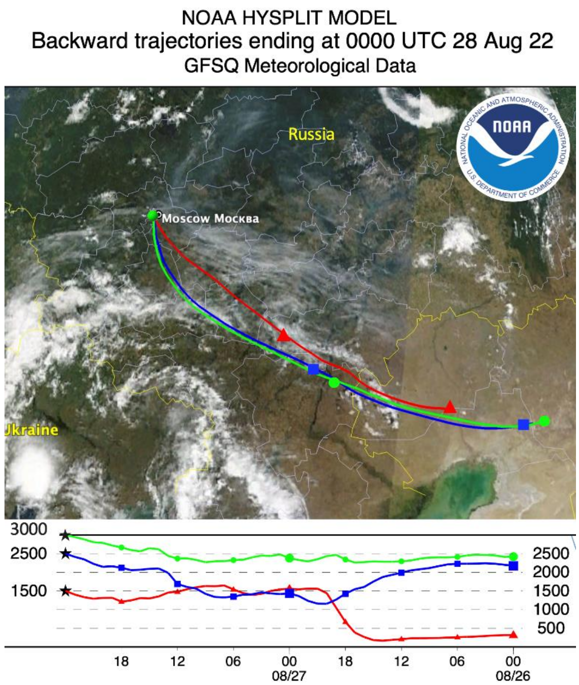

Fig.2. Two-day backward trajectories from the NOAA HYSPLIT model for the air mass in Moscow on 28 August at 00:00 UTC. The basemap is the Earth's true color image observed by MODIS Terra for the same period.

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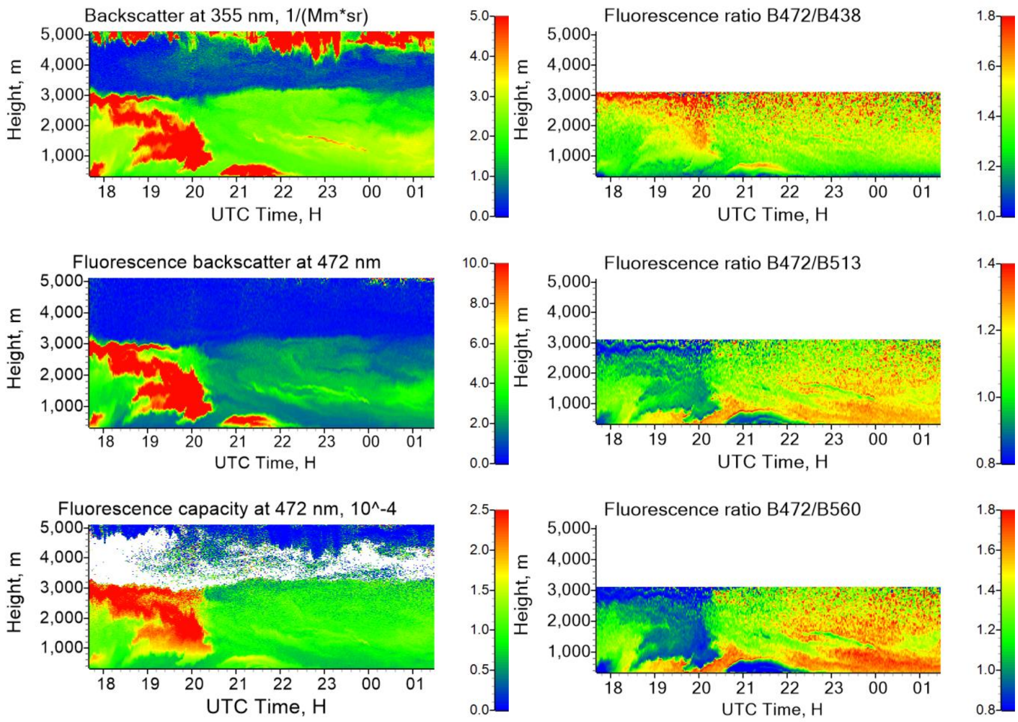

Fig.3. Spatio – temporal distribution of particle parameters on the night 27-28 August 2022. (left column) Aerosol backscattering coefficient β_{355}, fluorescence backscattering β_{F472} (in 10^{-4} $Mm^{-1}sr^{-1}$), fluorescence capacity G_{472}. (right column) Ratios of fluorescence spectral backscattering coefficients B_{472}/B_{438}, B_{472}/B_{513}, B_{472}/B_{560}.

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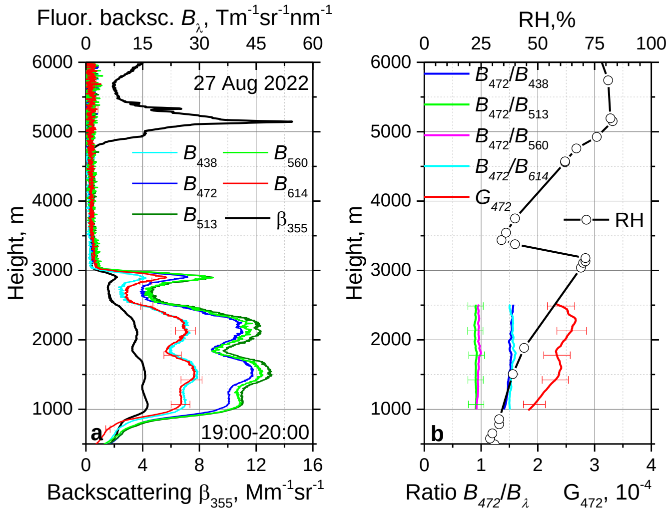

Fig.4. Observations on 27 August 2022 for period 19:00-20:00 UTC. (a) Fluorescence spectral backscattering coefficients B_λ at 438, 472, 513, 560, 614 nm and the aerosol backscattering coefficient β_{355}. (b) The ratios B_{472}/B_{438}, B_{472}/B_{513}, B_{472}/B_{560}, B_{472}/B_{614} and the fluorescence capacity G_{472}. Symbols show the relative humidity measured by a radiosonde at 00:00 UTC on 28 August.

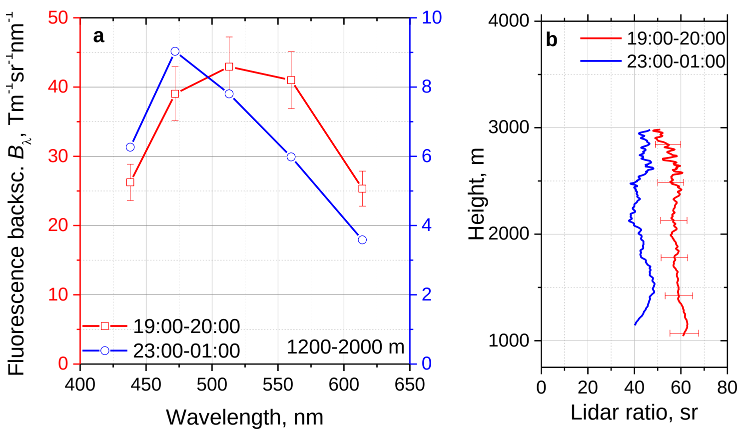

Fig.5. (a) Spectrum of fluorescence backscattering B_λ on the night 27-28 August 2022 for 19:00-20:00 and 23:00-01:00 UTC intervals. Results are averaged inside 1200-2000 m height range. (b) Profiles of lidar ratios at 355 nm for the same temporal intervals.

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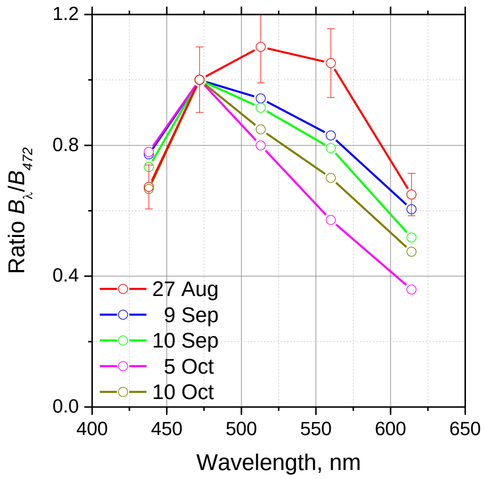

Fig.6. Fluorescence spectra measured in September - October 2022, when forest fires were over. Fluorescence backscattering coefficients B_λ were averaged inside 500 – 1000 m height range and normalized on B_{472}. For comparison, the fluorescence spectrum in smoke plume on 27 August from Fig.5 is also presented.

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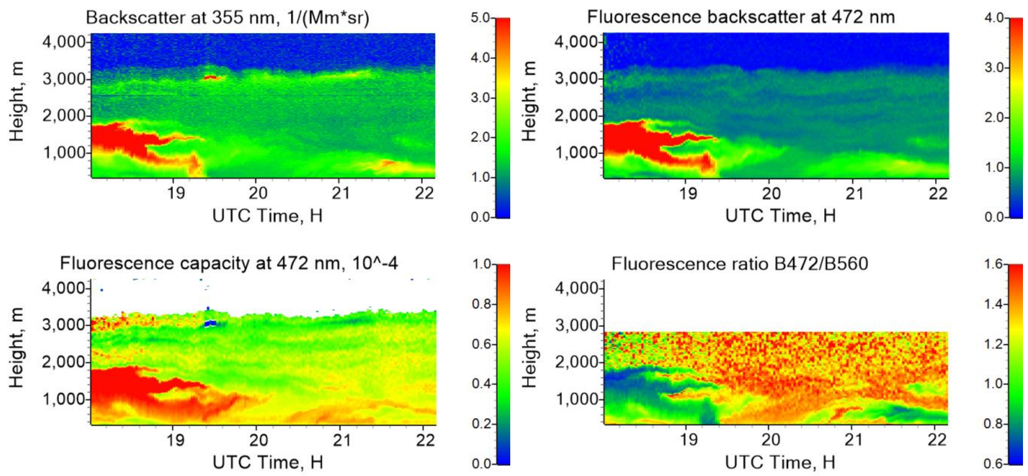

Fig.7. Observations on 17 August 2022. (left column) Aerosol backscattering coefficient β_{355} and fluorescence capacity G_{472}. (right column) Fluorescence backscattering coefficient β_{F472} (in 10^{-4} $Mm^{-1}sr^{-1}$) and the ratio of fluorescence spectral backscattering coefficients B_{472}/B_{560}.

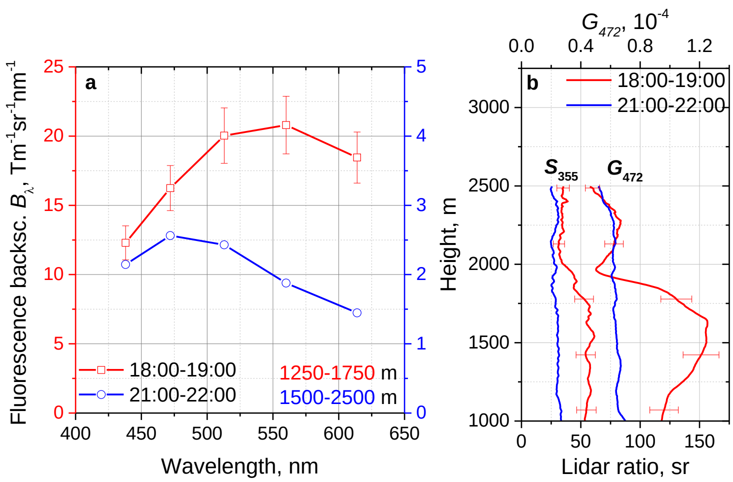

Fig.8. (a) Spectra of fluorescence backscattering B_λ on 17 August 2022 for 18:00-19:00 UTC and 21:00-22:00 UTC periods. Results are averaged within 1250-1750 m and 1500-2500 m height ranges respectively. (b) Profiles of lidar ratio S_{355} and fluorescence capacity G_{472} for the same temporal periods.

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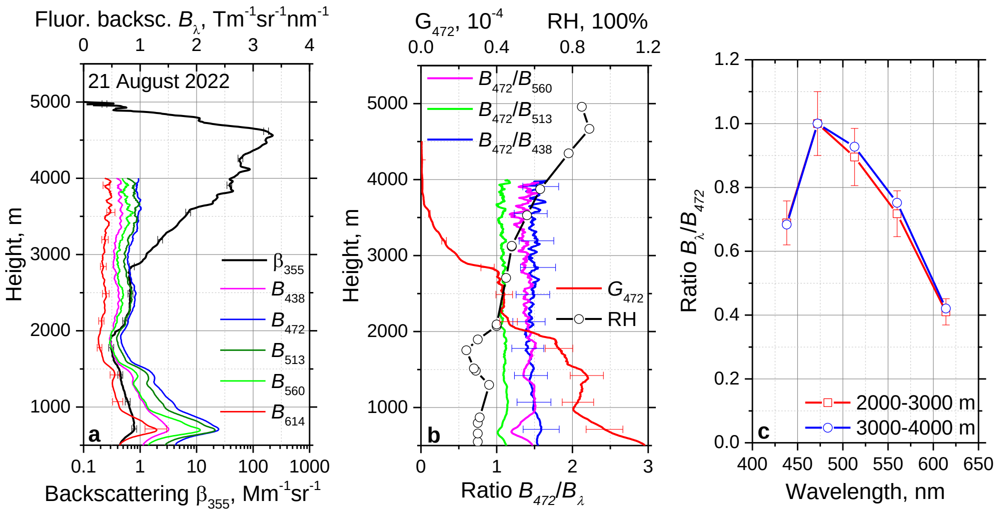

Fig.9. Vertical profiles of the particle parameters on 21 August 2022 for period 22:00-24:00 UTC. (a) The fluorescence spectral backscattering coefficients B_λ at 438, 472, 513, 560, 614 nm and the aerosol backscattering coefficient β_{355}. (b) The ratios B_{472}/B_{438}, B_{472}/B_{513}, B_{472}/B_{560} and the fluorescence capacity G_{472}. Symbols show the relative humidity measured by a radiosonde at 00:00 UTC on 22 August. (c) Spectrum of the fluorescence backscattering coefficient B_λ for height intervals 2000-3000 m and 3000-4000 m. Values of B_λ are normalized on B_{472}.

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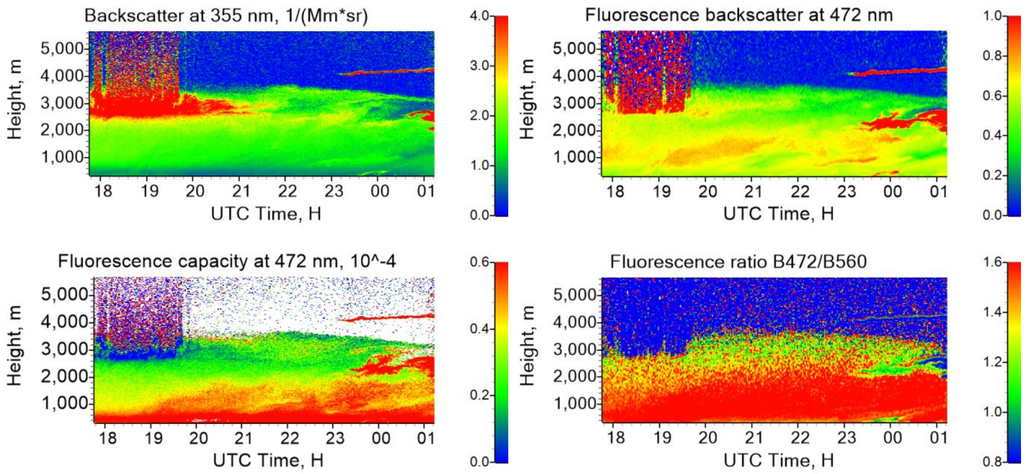

Fig.10. Spatio-temporal distributions of the particle parameters on the night 23-24 August 2022. (left column) The aerosol backscattering coefficient β_{355} together with the fluorescence capacity G_{472}. (right column) The fluorescence backscattering coefficient β_{F472} (in 10^{-4} $Mm^{-1}sr^{-1}$) and the ratio B_{472}/B_{560}.

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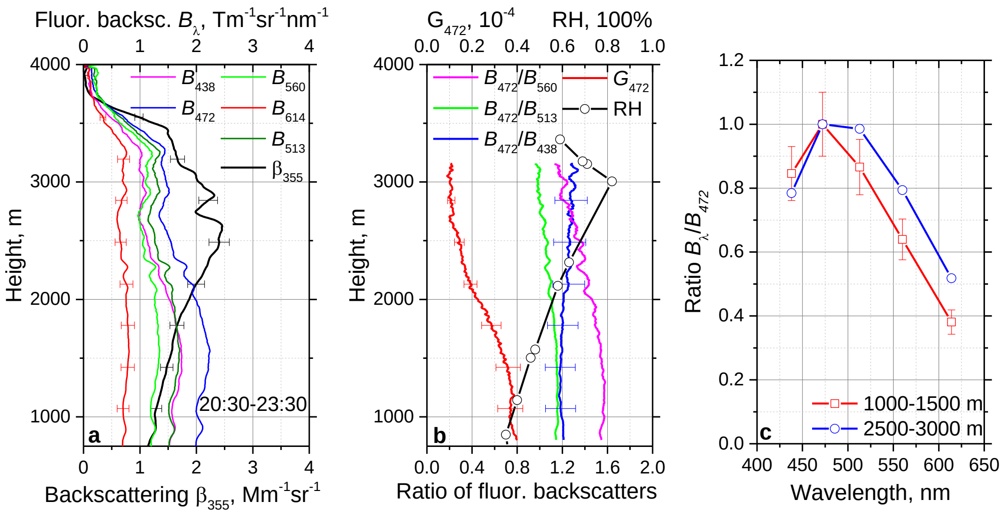

Fig.11. Vertical profiles of the particle parameters on 23 August 2022 for period 20:30-23:30 UTC. (a) The fluorescence spectral backscattering coefficients B_λ at 438, 472, 513, 560, 614 nm and the aerosol backscattering coefficient β_{355}. (b) The ratios B_{472}/B_{438}, B_{472}/B_{513}, B_{472}/B_{560} and the fluorescence capacity G_{472}. Symbols show the relative humidity measured by a radiosonde at 00:00 UTC on 24 August. (c) Spectrum of the fluorescence backscattering coefficient B_λ for height intervals 1000-1500 m and 2500-3000 m. Values of B_λ are normalized on B_{472}.