

Dear Editor,

In the text below are our responses and author's changes in manuscript to comments of Referee 1 (page 2–10) and Referee 2 (page 11–19).

On behalf of the authors,

Dr Milena Jovašević-Stojanović

Response to the Reviewer's Comments #1

AC: The authors appreciate comments made by reviewers that helped us substantially to improve our manuscript. We have carefully addressed the comments in the revised manuscript. Here, we provided point-by-point responses below in this document. Author comments (AC) are in **blue** and parts that were changed in the manuscript are in **red**.

General comments

RC: The manuscript describes a PM₁₀ source apportionment study in Belgrade. The methodology is briefly described and the factor/sources are presented in detail. It is not clear why the study focuses on PM₁₀ while it is well known that PM_{2.5} is a better indicator of health impacts. More effort is needed to emphasize the scientific added value of this study compared to previous work and to place it in the broader context.

AC: Thank you very much for comments about manuscript in general, methodology and factors/sources.

This study focused on comprehensive representation of PM from a wider range of sources that hasn't been identified in Belgrade Metropolitan area so far. Although the methodology used in this study is well known, the inclusion of organic tracers in source apportionment allowed us to identify two biological sources (primary biological aerosol particles and biogenic secondary organic aerosol) for the first time in the Western Balkan and wider region. PBAP source comprise a heterogeneous group of particles (bacteria, fungi, plant debris, viruses), but the most abundant fraction represent fungal spores which are usually observed in the size range 2-10 µm (Bauer et al. 2008). Other sources of interest like mineral dust and desert dust events also have coarser grain size than it is PM_{2.5}.

You are right, PM_{2.5} is a better indicator of health impacts, but exposure to PM₁₀ that consist of fine (PM_{2.5}) and coarse fraction (PM_{2.5-10}) is also recognised as a standard metric for air quality assessment and regulation while WHO recommends monitoring impact of desert dust events in PM₁₀ (WHO, 2021). PM₁₀ include coarse fraction which has distinct health effects beyond those attributable to PM_{2.5} alone (Choi et al. 2026, Tian et al. 2020).

The importance of PM₁₀ monitoring depends on the objective of the assessment:

- If the goal is to estimate long-term mortality and the overall health burden, PM_{2.5} is usually sufficient and is the indicator recommended by organizations such as the World Health Organization and the European Environment Agency.
- If the goal is to assess short-term health effects, compliance with air quality standards, or the impact of coarse particles, PM₁₀ monitoring remains important (WHO, 2021).

The goal of this study was to cover sources of fine and coarse particles pollutants and we monitored PM₁₀.

References:

Bauer, H., Claeys, M., Vermeylen, R., Schueller, E., Weinke, G., Berger, A., and Puxbaum, H.: Arabitol and mannitol as tracers for the quantification of airborne fungal spores. *Atmos. Environ.*, 42, 588-593, <https://doi.org/10.1016/j.atmosenv.2007.10.013>, 2008.

World Health Organization: WHO global air quality guidelines: Particulate matter (PM_{2.5} and PM₁₀), ozone, nitrogen dioxide, sulfur dioxide and carbon monoxide. World Health Organization, Geneva, <https://iris.who.int/server/api/core/bitstreams/551b515e-2a32-4e1a-a58c-cdaecd395b19/content>, 2021.

In the manuscript we also addressed reviewer's comment to more clearly explained why we focused on PM₁₀ in our study:

Row 53-58

"Many studies demonstrated correlation between exposure to PM_{2.5} and cardiopulmonary and lung cancer mortality, making it the world's leading environmental risk factor (McDuffie et al. 2021, Burnett et al. 2018, Pope et al. 2002). However, some authors highlight that the health effects from coarse particulate matter should not be overlooked as the adverse health effects related to this fraction distinct beyond the attributable effects of PM_{2.5} alone. Therefore, the continuous monitoring of PM₁₀ is necessary as it includes both coarse and fine fraction (Tian et al. 2020, Choi et al. 2026)."

Row 413 - 419

"PBAP are found mainly in the coarse fraction of PM, with a maximum in a range from 5.6 to 10 µm which can contribute to the PM mass concentration to up to 5 µg/m³ in the summer period (Marcovecchio and Perrino, 2021). As this factor gathers the particles released into the atmosphere from living organisms, they are usually referred as bioaerosols (Fröhlich-Nowoisky et al. 2016). Dispersed in the air, bioaerosols may interact with PM which then serves as a carrier for bioaerosols. As a result, allergic sensitization and respiratory infections may occur and the incidence of these diseases is higher in areas with higher air pollution (Huang et al. 2024)."

Introduction

RC: The most appropriate citations for PMF are: Paatero P. and Tapper U.,1994 Envirometrics; Paatero P. and Hopke P., 2009 J. Chemometrics

AC: Thank you for the reminding us of these two important papers, we added these references in the introduction part where PMF model is described.

Row 104 - 108

"In light of this, the present study aimed to perform PM₁₀ source apportionment in Belgrade using PMF, a multivariate receptor model capable of resolving PM mass concentration into contributions of various source types (Paatero and Hopke, 2009) by utilizing error estimates of the species from the data matrix and implements strict non-negativity constraints for the factors (Paatero and Tapper, 1994)."

RC: The objective of the study should be clearly indicated in the introduction.

AC: Thank you for this comment, we rewrote the objective that explains our aim more clearly now.

Row 112 - 115

“The objective of the study is to offer a broader perspective on PM₁₀ sources by incorporating ions and elements, and for the first time number of tracers for biogenic aerosols as well as tracers for biomass burning together with OC and EC as input variables, and thereby quantify both natural, including biological, and anthropogenic sources at an urban background site in Belgrade.”

Methodology

RC: The authors should explain more clearly in the methodological section the procedure they followed to establishing the number of factors and attributing factors to sources including the model diagnostics and the use of independent external evidence (e.g. results from other studies) used to support their choices.

AC: The followed procedure to establish final number of factors was based on recommendations of the JRC publication “European guide on air pollution source apportionment with receptor models” (Belis et al. 2019a). The model diagnostic information and references from other SA studies that we used to confirm our factors are added.

Reference:

Belis, C. A., Favez, O., Mircea, M., Diapouli, E., Manousakas M-I., Vratolis, S., Gilardoni, S., Paglione, M., Decesari, S., Mocnik, G., Mooibroek, D., Salvador, P., Takahama, S., Vecchi, R., Paatero P.: European guide on air pollution source apportionment with receptor models – Revised version 2019, EUR 29816 EN, Publications Office of the European Union, Luxembourg, <https://data.europa.eu/doi/10.2760/439106>, 2019a.

The extended version in the manuscript with more clear explanation and references that support our factor choices as well as model diagnostic are described:

Row 188 - 206

“To determine the optimal number of factors, solutions with a total number of factors from 3 to 9 with random seed number and no applied factor constraints were examined. The final solution was derived from 100 base runs, with robustness evaluated according to the recommendations of “European guide on air pollution source apportionment with receptor models” (Belis et al. 2019a): (1) all factors’ chemical profile and temporal variability could have been interpreted, (2) Q_{true}/Q_{exp} ratio, (3) normal distribution of modelled species with more than 95% uncertainty-scaled residuals was within ± 3 , and (4) on displacement (DISP) and bootstrap (BS) analysis which confirmed the stability of the model.

The input data included sets of chemical tracers that allowed identification of chemical profile and temporal variability connected to certain sources based on previously conducted studies. Therefore, levoglucosan, mannosan, galactosan, K, Rb, OC and EC were tracers for biomass burning (Yttri et al. 2011, Weber et al. 2019), sugars and sugar alcohols for primary biological aerosol particles (Bozzetti et al. 2016) and 2-methyl tetrols for biogenic secondary organic aerosol from isoprene (Srivastava et al. 2018) (Table 1). As mineral dust tracers were considered Al, Ti, Sr, Ca, Mg (Moreno et al. 2006, Tursun et al. 2025), As, Cd, Ni indicated industrial emission (Querol et al. 2007) and EC, Sb, Sn, Fe, Pb for exhaust and non-exhaust emissions (Amato et al. 2009, Srivastava et al. 2018). Q_{true} was 1574.62 and Q_{robust} 1574.66 which resulted in Q_{true}/Q_{exp} ratio of 1.03 which is less than 1.5 meaning the effect of outliers on the results was negligible (Belis et al. 2019a). In case of DISP test, no factor swaps were reported and the change in Q

value remained minimal (-0.013). BS analysis based on 100 runs is showed in Table 2. All factors had > 70 out of 100 mapped factors which is considered as appropriate solution (Belis et al. 2019a). The extra model uncertainty was 7%. The correlation between observed and modelled PM₁₀ concentrations was 0.92 indicating good reconstruction of PM₁₀ mass concentration.

RC: Also the way in which polar plots and backward trajectories is used should be explained in the methodological section.

AC: Thanks for this important point that we missed to add. In the methodology section of the manuscript, we added 2.7. section which addressed air mass transport modelling.

Row 211 - 230

“2.7. Air mass transport modelling

To examine and support the physical plausibility of the resolved PMF factors that they represent realistic local and transported sources influencing the monitoring site, backward trajectories and polar plots analysis were performed. To understand airmass transport to the Ada Marina station, the standard ATMO-ACCESS Research Infrastructure (<https://flexpart-request.nilu.no/data-access>) set-up was used for dust. Specifically, the Lagrangian particle dispersion model FLEXPART version 10.4 (Pisso et al. 2019) ran in the classic retroplume mode for 30 days backward in time for 3-hourly timesteps. The model was driven by ECMWF ERA5 reanalysis (Hersbach et al. 2019) with 0.5° spatial and hourly temporal resolution over 137 vertical levels. The resulting footprint emission sensitivity expresses the probability of potential emissions to arrive at Ada Marina, showing airmass origin, and can be converted to atmospheric concentrations at the receptor (Ada Marina) if combined with an emission dataset. For dust, emissions were first calculated using the FLEXDUST module (Groot Zwaftink et al. 2016). FLEXDUST uses input parameters, such as soil type, vegetation/snow cover, threshold friction velocity, particle-size classes combined with surface and meteorological conditions from ECMWF ERA5 data (0.25° resolution, hourly) to calculate gridded emission fluxes for 10 size-classes of dust particles from 0.2 to 20 µm.

Beside FLEXPART, air mass transport modelling was performed also by Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) transport and dispersion model developed by the National Oceanic and Atmospheric Administration (NOAA). The 24h back-trajectories used GFS Meteorological Data and vertical velocity model and were calculated at 100 m, 200 m and 500 m above ground level.

The directional dependence and temporal behaviour of each factor was examined using polarPlot function from the openair (version 2.18-2), R package (version 4.4.2) (Carslaw, 2012).”

Results and discussion

RC: Important publications regarding the study area should be considered in the discussion of results (e.g. Almeida et al., 2020 Environmental Pollution)

AC: We agree with your comment and in revised manuscript we discussed in more details all previous SA studies performed upon data sets collected at Belgrade central zone and Belgrade Metropolitan in both

introduction part as well as discussion. Also, we added Figure S1 where we marked monitoring sites of all studies performed in period of 2003-2015 and added contributions and species used for factor identification in these studies in Table S1.

Seven studies of SA were performed upon data sets collected in period 2003-2015. Paper of Almeida et al. (2020) used data set collected for period of 16 months that finished in August 2015. However, Todorović et al. (2020) took filters and results collected in one year campaign from Almeida et al. (2020) and performed additional analyses of ions. Todorović et al. (2020) performed separate SA analyses and obtain results that were partly different from Almeida et al. (2020). In the paper of Almeida et al. (2020) that was part of IAEA project in 16 cities, authors noted by themselves that combustion of oil fuel factor in Belgrade, contributing 38% to PM_{2.5} mass, was overestimated. This factor did not exist as separate in the study of Todorović et al. (2020) where factor local combustion sources and ammonium nitrate accounted by 29,7 % of PM_{2.5} mass. The genesis of differences between Almeida et al. (2020), Todorović et al. (2020), and our results may be explained by: time distance of campaigns (about eight years passed before WeBaSOOP campaign started); characteristics of sampling sites (Zeleno brdo vs. Ada Marina); nonidentical airborne PM fraction (PM_{2.5} vs. PM₁₀); additional analysed species used as input data for PMF analyses in Todorović et al. (2020) and this study in comparison to study of Almeida et al. (2020).

References:

Almeida, S., M., Manousakas, M., Diapouli, E., Kertesz, Z., Samek, L., Hristova, E., Šega, K., Padilla Alvarez, R., Belis, C. A., Eleftheriadis, K., The IAEA European Region Study Group: Ambient particulate matter source apportionment using receptor modelling in European and Central Asia urban areas. Environ. Pollut. 266, 115199, <https://doi.org/10.1016/j.envpol.2020.115199>, 2020.

Todorović, M. N., Radenković, M. B., Onjia, A. E., and Ignjatović, L. M.: Characterization of PM_{2.5} sources in a Belgrade suburban area: a multi-scale receptor-oriented approach. Environ. Sci. Pollut. Res, 27, 41717-41730, <https://doi.org/10.1007/s11356-020-10129-z>, 2020.

Here is the revised Table S1 in the Supplementary Material:

Table S1. Overview of the source apportionment studies conducted in Belgrade for the period 2003-2015.

PM fraction	Sampling site	Period	N	PM concentration (µg/m ³)	Chemicals analyzed	Factors resolved	Model used	Reference
1 PM _{2.5} , PM ₁₀	1. 44°49'06.7"N 20°27'27.3"E 2. 44°47'39.8"N 20°27'56.3"E	Jun 2003 - Jul 2005	PM _{2.5} : 64; -PM ₁₀ : 209	PM _{2.5} : 61.4 PM ₁₀ : 68.4	Pb, Cu, Zn, Mn, Fe, Cd, Ni, V, Al, Cr	PM _{2.5} : resuspended road dust (Zn, Al, Mn, Fe) (29%), traffic and oil refineries (Cr, Pb) (17.8%), oil combustion (V, Ni) (17.7%), diesel fuel and local industry (Cu, Cd) (13.5%) PM ₁₀ : road dust (Mn, Zn, Fe, Al, Ni) (26.1%), fuel oil (V, Ni) (17.4%), road traffic emission (Cu, Cd, Pb) (16.8%), traffic exhaust (Cr, Pb) (13.2%)	PCA	Rajšić et al. 2008
2 PM ₁₀	1. 44°49'06.7"N 20°27'27.3"E 2. 44°47'39.8"N 20°27'56.3"E	Jul 2003 - Dec 2006	277	70.1	Al, V, Cr, Mn, Fe, Ni, Cu, Zn, Cd, Pb	Fossil fuel combustion (V, Ni, Fe, Cu, Mn) (34), traffic exhaust/regional transport from industry (Zn, Fe, Mn, Cu, Ni) (26%), traffic related particles/site specific industrial processes (Cu, Pb, Mn, Cd) (21%) , mineral/crustal matter (Al, Fe, Cu, Mn, Ni, Cd) (19%)	Unmix USEPA	Mijić et al. 2012
3 Dp ≤ 0.49 µm 0.49 < Dp ≤ 0.95; 0.95 < Dp ≤ 1.5; 1.5 < Dp ≤ 3.0; 3.0 < Dp ≤ 7.2; Dp ≥ 7.2 µm	44°49'14.25"N 20°27'44.81"E	Jun - Dec 2008		Dp < 0.49 µm: 7.9 0.49 < Dp ≤ 0.95: 2.7 0.95 < Dp ≤ 1.5: 1.8 1.5 < Dp ≤ 3.0: 2.0 3.0 < Dp ≤ 7.2: 3.3 Dp ≥ 7.2 µm: 1.3	Na ⁺ , NH ₄ ⁺ , K ⁺ , Mg ²⁺ , Ca ²⁺ , Cl ⁻ , NO ₃ ⁻ , SO ₄ ²⁻ , PO ₄ ³⁻	Ammonium sulphate (SO ₄ ²⁻ , NH ₄ ⁺ , Cl ⁻ , Mg ²⁺) (16.4%); marine aerosol (Na ⁺ , Cl ⁻) (14.9%); construction activities (Ca ²⁺) (10%); fertilizer plant (PO ₄ ³⁻) (8.5%); industrial zone (Cl ⁻ , SO ₄ ²⁻ , NH ₄ ⁺ , K ⁺) (8.1%); biomass burning (K ⁺) (8%)	PCA	Đorđević et al. 2012

4	PM ₁₀	1. 44°38'42.15" N, 20°26'52.48" E 2. 44°36'11.74" N, 20°06'09.30" E 3. 44°48'03.5" N, 20°27'57.8" E	2010 – 2011	–	1. Summer: 31.86 Winter: 80.31 2. Summer: 26.16 Winter: 62.38 3. Summer: 44.37 Winter: 88.46	Nap, Acy, Ace, Flu, Phe, Ant, Fit, Pyr, BaA, Chry, BbF, BkF, B[a]P, Ind, DahA, BghiP	*Diesel and gasoline exhaust (traffic 1) (BbF, BkF, B[a]P, Ind, DahA, BghiP) (55.2% winter, 38.5% summer); Unburned petroleum from vehicles (traffic 2) (Nap, Ace, Phe) (13.5% winter, 17.4% summer); Stationary sources (Fit, Pyr, BaA, Chry, BkF, BbF) (31.3% winter, 43.9% summer)	USEPA PMF 3.0	Cvetković et al. 2015
5	PM ₁₀	44°49'00.42"N 20°28'12.85"E	2011 – 2015	254	60.51	B[a]P, As, Cd, Cr, Mn, Ni, Pb, Cl, Na ⁺ , Mg ²⁺ , Ca ²⁺ , K ⁺ , NO ₃ ⁻ , SO ₄ ²⁻ , NH ₄ ⁺ , OC, EC	Solid fuel burning (B[a]P, As, OC, SO ₂ , CO, NO ₂) (29.8%); Industrial emissions (Cd, Pb) (21.9%); Secondary aerosols (NH ₄ ⁺ , SO ₄ ²⁻ , NO ₃ ⁻) (19.5%); vehicle derived and particle resuspension (EC, NO _x , soot) (28.7%)	Unmix USEPA	Stojić, et al. 2016
6	PM _{2.5}	44°47'12.17"N 20°31'16.63"E	May 2014 – May 2015	133	20.8	Al, Si, P, S, Cl, K, Ca, Ti, V, Cr, Mn, Fe, Ni, Cu, Zn, Br, As, Ba, Pb, NH ₄ ⁺ , NO ₃ ⁻ , SO ₄ ²⁻	Biomass burning (K, Cl, S, Zn) (14.5%); -Traffic (Fe, Pb, Mn, Cu, Zn) (3.9%); secondary sulphate from regional combustion sources (S, NH ₄ ⁺) (28.8%); local combustion sources and ammonium nitrate (V, Ni, NO ₃ ⁻ , NH ₄ ⁺) (29.7%); soil (Si, Ca, Ti, Fe, Mn) (5.4%); unaccounted (17.8%)	USEPA PMF 5.0	Todorović et al. 2020
7	PM _{2.5}	44°47'12.17"N 20°31'16.63"E	Apr 2014 – Aug 2015	166	20.7	Al, Si, S, Cl, K, Ca, Ti, V, Mn, Fe, Cu, Zn, Pb, Ni, P, Cr, As, Br, Ba	Soil (Al) (8%); Biomass burning (Cl, K, Zn, Pb) (15%); Traffic (Ca, Si, Fe, Ti, Mn) (3%); fuel oil combustion (V, Ni) (38%); secondary sulfate (S, Pb, Cu, Ti) (3%); unaccounted (33%)	USEPA PMF 5.0	Almeida et al. 2020
8	PM ₁₀	44°47'25.4"N 20°25'02.5"E	Jun 2023 – May 2024	84	23.9	OC, EC, Na, Mg, Al, K, Ca, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Ga, As, Se, Rb, Sr, Cd, Ba, Pb, P, Ti, Zr, Mo, Sb, Sn, Cl, NO ₃ ⁻ , SO ₄ ²⁻ , NH ₄ ⁺ , galactosan, mannosan, levoglucosan, 2-methylerythritol, 2-methylthreitol, glucose, fructose, mannitol, arabitol, trehalose	Biomass burning (galactosan, mannosan, levoglucosan, K, Cl, Rb, OC) (21%); Long-range transport and road-salt/local combustion (Na, NO ₃ ⁻ , Cl) (9%); Mineral dust (Al, Ti, Sr, Mg, Ca) (17%); Primary biological aerosol particles (glucose, fructose, trehalose, mannitol, arabitol) (10%); Biogenic secondary organic aerosol from isoprene (2-methylerythritol, 2-methylthreitol) (10%); Ammonium sulphate (SO ₄ ²⁻ , NH ₄ ⁺) (18%); Traffic/industry (EC, Fe, Sb, Cu, Sn, Mn, Pb, V, Cd, As) (15%)	USEPA PMF 5.0	This study

N – number of samples

*factors resolved in sampling site in urban zone of the city (Slavija)

Here is the added Figure S1 in the Supplementary Material:



Figure S1. Map of Belgrade with monitoring sites included in the studies from the Table S1.

Rajšić et al. 2008, Mijić et al. 2012: Roof of Rector's Office (1), Faculty of Veterinary Medicine (2); Đorđević et al. 2012: Knjeginje Ljubice 21 (3); Cvetković et al. 2015: Lazarevac (4.1.), Grabovac (4.2.) Slavija (4.3.), Stojić et al. 2016: Institute of Public Health Belgrade (5); Todorović et al. 2020, Almeida et al. 2020: Zeleno brdo (6, 7); this study: Ada Marina (8).

Below are the paragraphs added to the manuscript (both introduction and discussion) regarding discussion of the results:

Row 94 - 104

"In addition, sampling sites where daily (24h) filter samples were collected, were in Belgrade city area, in triangle of 20 km² as it is presented at Figure S1. For one of SA study, Cvetković et al. (2015), one site was

in the medium of triangle and another two sites were out off triangle nearby thermal power plants in Metropolitan area of Belgrade far away for several tens of kilometres from the city centre. Only studies of Todorović et al. (2020) and Almeida et al. (2020) overlap with the period of sampling and sampling site as filter samples were collected at the urban background area at Zeleno brdo (Figure S1). Furthermore, species used in these SA studies were different (Table S1). Some studies were performed only upon analyses of elements (Mijić et al. 2012, Rajšić at. 2008, Almeida et al. 2020), ions (Đorđević et al. 2015) or PAHs (Cvetković et al. 2015). Almeida et al. (2020) for SA study used data collected for 16 months and concentrations of elements while Todorovic et al. (2020) as input data set used one year of Almeida et al. (2020) data set and performed additional analyses of ions.”

In the Section 3.2.1:

Row 329 - 335

“In the previous SA studies performed for Belgrade region and Metropolitan, biomass and/or wood burning were identified as separate or mix factor. In the study of Đorđević et al. (2012) this factor was identified as separate factor based on the dominant presence of K^+ (8%) while Cvetković et al (2015) verified it by PAHs Nap, Acy and Ace (10.4%). In the studies of Todorović et al. (2020) and Almeida et al. (2020) biomass burning was identified with Cl, K, Zn, Pb and S with contribution of about 15% in both studies. In this study biomass burning was 21% of PM_{10} mass concentration, and was identified based on OC, organic tracers (levoglucosan, mannosan and galactosan) and Rb, that is, beside K, one of the alternative tracers for this factor (Massimi et al. 2020, Pereira et al. 2025).“

In the Section 3.2.3:

Row 386 - 388

“However, factor soil, in this study titled mineral dust, was identified in the studies of Almeida et al. (2020) and Todorović et al. (2020), contributed to PM_{10} mass concentration with 8% and 5% respectively.“

In the Section 3.2.6:

Row 479 - 497

“In the study of Todorović et al. (2020), factors secondary sulphate from regional combustion sources (S , NH_4^+) (28.8%) and local combustion sources and ammonium nitrate (V , Ni , NO_3^- , NH_4^+) (29.7%) accounted for around 2/3 of PM_{10} total mass concentration. For the same sampling site, Almeida et al. (2020) identified sulphate factor with contribution of 3%, which was separated from oil fuel combustion (38%). Comparing their results to ammonium sulphate contribution in our study (18%), differences may be explained by nonidentical PM fraction, SA with PM_{10} identified factors that are not only from combustion sources, the chemicals analysed and used as input data in PMF, time period when studies were conducted as well as long-term trends that indicate airborne PM decrease (de Hoogh et al. 2025). Almeida et al. (2020) analysed 19 elements (Table S1) while Todorovic et al. (2020) analysed also ions beside the 19

elements (Table S1). Furthermore, Todorovic et al. (2020) as well as Almeida et al. (2020) had sampling campaign in the period from 2014-2015. Their studies represent the last SA studies in Belgrade until WeBaSOOP sampling campaign. In the time span of eight years, the sources in Belgrade changed due to: substantial changes in traffic routes in Belgrade central zone, industrial activities, observed reductions in PM₁₀ concentrations during the 2010s. The PM₁₀ decrease likely reflect the combined effects of the long-term replacement of coal- and oil-fired boiler houses with district heating supplied predominantly by natural gas, together with the gradual phase-out of small local boiler plants and other emission control measures (https://beoelektrane.co.rs/saopstenja/veliki-doprinos-beogradskih-elektrana-u-borbi-zacistiji-vazduh-i-smanjenje-zagadenja-u-glavnom-gradu/?utm_source=chatgpt.com). Finally, Almeida et al. (2020) emphasised that in their study contributions of some tracers were not well defined which led to overestimation of oil combustion and underestimation of other factors.”

Conclusions

RC: The conclusion section should be revised to match ACP guidelines for authors

AC: We appreciate indicating discrepancies between our conclusion and ACP conclusion guidelines. In the manuscript, the conclusion is improved according to the ACP guidelines, with clear and concise summary and synthesis of the obtained results, explained and summarized consistencies and inconsistencies with other SA studies performed in Belgrade are, limitations and explanation of contribution of our paper to understanding of the monitoring and mitigation measures of PM₁₀.

Row 538 - 545

“Eight SA studies were conducted in the past in Belgrade urban and Metropolitan area upon data sets collected in the period from 2003 and 2015 and WeBaSOOP year-long campaign in 2023-2024. Although WeBaSOOP study was conducted upon data set collected eight years after the last study and having different, broader range of, species used for SA, factors traffic, industry, different combustion sources, mineral/soil dust and secondary inorganic aerosol were identified in all studies in the past and ours. This indicates a continuity of these factors throughout the years on air quality in Belgrade. One study performed on data sets collected 15 years ago identified marine aerosol also but with higher contribution than in our, WeBaSOOP, study. However, in contrast to other studies, this was the first one that identified factors from biological origin (PBAP and BSOA_{Isoprene}).”

Row 563

“Our results showed influence of both, local (biomass burning, traffic, biogenic aerosols) and regional sources (mineral dust, salt from long-range transport) on PM₁₀ concentration in this area.”

Row 567 - 569

“However, further work for better understanding of PM₁₀ regional and local sources in Belgrade is needed by performing SA study at least for two fractions of airborne PM represent by fine and coarse fraction as well as combination of offline and online PMF analysis and long-term measurements.”

Row 570 - 580

“Mineral dust events, marine aerosol and biogenic aerosols contribute to the background concentration of PM_{10} and $PM_{2.5}$ and are largely beyond the scope of emission control measures. Although sea salt was not extracted as a separate factor in WeBaSOOP study, its contribution to PM_{10} mass may be accounted as $1-2 \mu\text{g}/\text{m}^3$, but in case of mineral dust, contribution is estimated to be around $4 \mu\text{g}/\text{m}^3$. In WeBaSOOP study, mineral dust represents mix of both natural and anthropogenic sources from local and long-range transport, while 1/5 of PM_{10} mass (around $5 \mu\text{g}/\text{m}^3$) was attributed to primary and secondary airborne particulate matter of biogenic sources. As emissions from these sources are beyond controllable measures compliance with ambient air quality limit values consequently requires sufficient reductions in controllable anthropogenic emissions to offset the irreducible natural background. Where legislation permits, documented contributions from specific natural sources, such Sahara dust events and sea salt, may be excluded from compliance assessment. However, routine exclusion of biogenic aerosol contributions is generally not possible to be applied without measurements such WeBaSOOP study enabled.”

Response to the Reviewer's Comments #2

AC: The authors are thankful for this review and comments that we followed to substantially improve our manuscript. Here, we provided point-by-point responses below in this document. Author comments (AC) are in **blue** and parts that were changed in the manuscript are in **red**.

General Comment

RC: The authors are presenting a source apportionment study based on the PM₁₀ chemical composition data obtained at an urban background site in Belgrade, Serbia. There were numerous source apportionment studies conducted for the city in the past covering the sampling period from 2003 to 2015. Therefore, the presented study aims to identify the PM₁₀ using recent filter samples collected between June 2023 and May 2024, and a broader spectra of the tracers. However, it is a solid work, the used approach of collecting 24h PM₁₀ filter samples even not every day for a year and analyse them for the standard compounds/tracers is not very innovative and up-to-date. Additionally, this approach doesn't allow a precise differentiation of the PM sources. Therefore, further work for better understanding of PM sources in Belgrade will be needed.

AC: We appreciated and carefully considered the comments regarding our study performed upon data set collected in the Belgrade background site in the framework of WeBaSOOP campaign.

The approach in WeBaSOOP campaign was to collect daily (24h) PM₁₀ filter samples every second day for a year and analyse them for 27 elements, 4 ions and OC and EC. To prepare input data for PMF analysis and to include in addition 10 organic tracers in the PMF, 84 exposed filter samples and 6 field blanks were chosen for the analysis according to the procedure described in the study of (Platt et al. 2026). With this, source discrimination was supported by a comprehensive set of chemical variables, including elemental composition, water-soluble ions, OC/EC, biomass-burning tracers, and specific molecular tracers of biogenic aerosol. The combination of these complementary source indicators provides substantially greater chemical constraints than conventional PM₁₀ source-apportionment approaches based only on major ions, elements, and carbonaceous aerosols. Therefore, this was the first study in Belgrade Metropolitan area that used levels of polyols and 2-methyltetrols to identify PBAP and BSOA from isoprene sources, which would otherwise be difficult to distinguish, as well as organic tracers for biomass burning.

We agree with reviewer comment that 24-hour sample collection and used methodology aren't innovative, but the substantial contribution of our work was identification of broader spectra of the sources, biogenic aerosols, that haven't been identified so far and which contributed with 20% in total to PM₁₀ mass in our study performed for Belgrade urban background sampling site. Therefore, the main added value of the present approach is therefore not improved temporal resolution but improved chemical resolution through the integration of source-specific organic tracers with conventional elemental, ionic and carbonaceous measurements.

Based on the studies found in the literature that were conducted with similar approach, it is well known that 24-hour filter sampling can't resolve diurnal variations, so final solution may result in mixed factors. In paper (Cvetković et al. 2015), where dataset consisted of PAHs, there were identified three factors related to traffic. In addition, in paper of Ćirović et al. (2026), input data consisted of online measured particle size number distribution of ultrafine particles, main pollutants and BC, there were also identified

three factors related to traffic. So, we agree that future work is needed, and it would include performing SA study with at least for two fractions of airborne PM (fine and coarse fraction) as well as combination of offline and online PMF analysis. Combining offline methods, with inclusion of biological tracers, with high-time-resolution measurements of ultrafine particles and equivalent black carbon would improve the identification, more precise differentiation, and quantification of PM sources in Belgrade and of course, the contribution of unregulated biogenic aerosols (Via et al. 2023, Via et al. 2026). There are spectra of instruments for online measurements of organic aerosols suitable for identifying different OA sources as well as for elemental analysis that we plan to include in upcoming studies, depending on our capacity.

References:

Cvetković, A., Jovašević-Stojanović, M., Marković, D., and Ristovski, Z.: Concentration and source identification of polycyclic aromatic hydrocarbons in the metropolitan area of Belgrade, Serbia. *Atmos. Environ.*, 112, 335-343, <https://doi.org/10.1016/j.atmosenv.2015.04.034>, 2015.

Ćirović, Ž., Stojanović, D. B., Davidović, M., Onjia, A., Garcia-Marlès, M., Lozano, N. P., Alastuey, A., and Jovašević-Stojanović, M.: Concentrations and Estimation of Sources of Ultrafine Particles in the City of Belgrade at Ada Marina Urban Background Site. *Environments*, 13, 47, <https://doi.org/10.3390/environments13010047>, 2026.

Platt, S. M., Davidović, M., Bartonova, A., Ćirović, Ž., Eckhardt, S., Evangeliou, N., Gundersen, H., Jovanović, M., Jovašević-Stojanović, M., Močnik, G., Petrović, B., Schneider, P., and Yttri, K. E.: Measurement report: Sources of carbonaceous aerosol in a South-East European metropolis, *EGUsphere* [preprint], <https://doi.org/10.5194/egusphere-2026-1708>, 2026.

Via, M., Yus-Díez, J., Canonaco, F., Petit, J.-E., Hopke, P., Reche, C., Pandolfi, M., Ivančič, M., Rigler, M., Prévôt, A. S. H., Querol, X., Alastuey, A., and Minguillón, M. C.: Towards a better understanding of fine PM sources: Online and offline datasets combination in a single PMF. *Atmos. Environ.*, 177, 108006, <https://doi.org/10.1016/j.envint.2023.108006>, 2023.

Via, M., Demšar, J., Hao, Y., Manousakas, M., Rusanen, A., Jiang, J., Grange, S. K., Jaffrezo, J.-L., Dinh, V. N. T., Uzu, G., Močnik, G., and Daellenbach, K. R.: Chemical sparsity in Bayesian receptor models for aerosol source apportionment, *Atmos. Meas. Tech.*, 19, 2175–2195, <https://doi.org/10.5194/amt-19-2175-2026>, 2026.

2. Material and methods

RC: The section is quite brief and some information/parts are missing e.g. detailed information about filter sampling as duration and frequency, meteorological measurements, FLEXPART and HYSPLIT model description and settings.

AC: We addressed reviewer's comments in manuscript by adding more information regarding filter sampling:

Row 135 - 137

“Daily filter samples were collected for 24 hours. The field campaign lasted for one year, and for PMF analysis seven representative samples for each month were used which yielded in 84 PM₁₀ samples.”

meteorological parameters:

Row 118 - 121

“Our sampling campaign was performed at an urban background monitoring site Ada Marina (44.790166° N, 20.4169° E; 71 m above sea level) which is a part of the local air quality network in Belgrade Metropolitan (Fig. 1) where main air pollutants and meteorological parameters (temperature, relative humidity, wind speed, wind direction and atmospheric pressure) have been measured.”

and we added the section 2.7. named Air mass transport modelling where we described FLEXPART and HYSPLIT settings used:

Row 211 – 230

2.7. Air mass transport modelling

“To examine and support the physical plausibility of the resolved PMF factors that they represent realistic local and transported sources influencing the monitoring site, backward trajectories and polar plots analysis were performed. To understand air mass transport to the Ada Marina station, the standard ATMO-ACCESS Research Infrastructure (<https://flexpart-request.nilu.no/data-access>) set-up was used for dust. Specifically, the Lagrangian particle dispersion model FLEXPART version 10.4 (Pisso et al., 2019) ran in the classic retroplume mode for 30 days backward in time for 3-hourly timesteps. The model was driven by ECMWF ERA5 reanalysis (Hersbach et al., 2019) with 0.5° spatial and hourly temporal resolution over 137 vertical levels. The resulting footprint emission sensitivity expresses the probability of potential emissions to arrive at Ada Marina, showing air mass origin, and can be converted to atmospheric concentrations at the receptor (Ada Marina) if combined with an emission dataset. For dust, emissions were first calculated using the FLEXDUST module (Groot Zwaaftink et al., 2016). FLEXDUST uses input parameters, such as soil type, vegetation/snow cover, threshold friction velocity, particle-size classes combined with surface and meteorological conditions from ECMWF ERA5 data (0.25° resolution, hourly) to calculate gridded emission fluxes for 10 size-classes of dust particles from 0.2 to 20 µm.

Beside FLEXPART, air mass transport modelling was performed also by Hybrid Single Particle Lagrangian Integrated Trajectory (HYSPLIT) transport and dispersion model developed by the National Oceanic and Atmospheric Administration (NOAA). The 24h back-trajectories used GFS Meteorological Data and vertical velocity model and were calculated at 100 m, 200 m and 500 m above ground level.

The directional dependence and temporal behaviour of each factor was examined using polarPlot function from the openair (version 2.18-2), R package (version 4.4.2) (Carslaw, 2012).”

2.6. PMF model

RC: The section has to be revised.

- RC: First and only equation of the paper quoted with number “4”.

AC: Thanks for this correction, we corrected it with number “1”.

- RC: Glojek et al., 2024 is not an original paper see Glojek et al., 2024.

AC: We now changed the document we cited previously in this section.

Row 176 - 177

“For those species below LOD, the uncertainties were calculated as 5/6 of the LOD (Polissar et al. 1998).”

- RC: Table S2 not cited at all in the main text.

AC: Thanks for pointing this out. As we lengthened the methodology part regarding PMF modelling, we moved Table S2 from the Supplement Material to manuscript and cited it now in the text as Table 2.

Row 202 - 203

“In case of DISP test, no factor swaps were reported and the change in Q value remained minimal (-0.013). BS analysis based on 100 runs is showed in Table 2.”

- RC: Table S4 cite earlier than Table S3 in the main text.

AC: You are right and, as Figure S1 was analogue to Table S4, we removed Table S4 from the Supplement Material at all. Furthermore, as we removed Table S2 from the Supplement Material to manuscript in 2.6. PMF modelling section, previous Table S3 became Table S2 in revised Supplement Material.

- RC: Sentence 151-151 is not easy to follow.

AC: We addressed this comment trying to paraphrase the sentence to be clearer.

Row 175 - 177

“In the model, if the concentrations of the species were assigned as “below LOD”, a value equal to 1/2 of the LOD was entered. For those species below LOD, the uncertainties were calculated as 5/6 of the LOD (Polissar et al. 1998).”

RC: Questions:

What are the S/N ratios and LODs for Rb, Sr, Cd, Sb and Sn?

How was the PM10 uncertainty calculated?

Was the total variable (PM10) considered as “weak”?

AC: In the Table below, we summarised the S/N ratios and LODs for Rb, Sr, Cd, Sb and Sn:

	S/N ratio	LOD
Rb	3.2	0.1 ng/m ³
Sr	3.7	0.1 ng/m ³
Cd	2.3	0.04 ng/m ³
Sb	1.7	0.5 ng/m ³
Sn	2.4	1 ng/m ³

PM₁₀ was considered as total variable, as “strong” and uncertainty was calculated by multiplying PM₁₀ concentration value by 4.

3. Result and discussion

RC: I recommend to present the average values with SD and use same number of decimal numbers in the whole manuscript.

AC: Thank you for this recommendation. We corrected number of decimal places in the whole manuscript to be the same for all decimal numbers and the average values with SD are shown in Table S2 where seasonal levels of analysed species are shown.

The Table S2 in the Supplement Material:

Table S2. Seasonal levels of analysed species (ng m⁻³) in Belgrade during WeBaSOOP campaign (N=84).

Species	N	Average (± SD)	Spring (± SD)	Summer (± SD)	Autumn (± SD)	Winter (± SD)	NH (± SD)	H (± SD)
PM ₁₀ *	84	23943 (± 14867)	20107 (± 9724)	20289 (± 7754)	23283 (± 19876)	32537 (± 17456)	19272 (± 7750)	28189 (± 18259)
OC	84	8185 (± 6489)	5288 (± 1790)	6412 (± 2326)	8441 (± 8330)	12996 (± 8313)	5936 (± 2255)	10230 (± 8227)
EC	84	1384 (± 1030)	927 (± 450)	933 (± 362)	1636 (± 1106)	2140 (± 1371)	955 (± 492)	1774 (± 1225)
OM	84	11459 (± 9085)	7403 (± 2506)	8977 (± 3257)	11818 (± 11662)	18194 (± 11638)	8310 (± 3157)	14322 (± 11518)
Cl ⁻	84	135 (± 185)	70 (± 119)	25 (± 49)	178 (± 169)	285 (± 237)	26 (± 39)	234 (± 208)
NO ₃ ⁻	84	1294 (± 1498)	615 (± 345)	364 (± 131)	1647 (± 1486)	2709 (± 1894)	478 (± 364)	2035 (± 1740)
SO ₄ ²⁻	84	2531 (± 1874)	2140 (± 1194)	3201 (± 2176)	2213 (± 2564)	2532 (± 1296)	2967 (± 2174)	2135 (± 1467)
NH ₄ ⁺	84	673 (± 541)	444 (± 299)	776 (± 609)	672 (± 652)	815 (± 522)	716 (± 572)	634 (± 514)
Na	83	158 (± 132)	156 (± 159)	74 (± 31)	196 (± 123)	211 (± 135)	82 (± 73)	225 (± 137)
Mg	84	109 (± 105)	128 (± 174)	82 (± 49)	107 (± 80)	117 (± 61)	79 (± 69)	135 (± 125)
Al	83	409 (± 426)	572 (± 694)	347 (± 219)	282 (± 253)	412 (± 291)	338 (± 303)	471 (± 506)
K	84	353 (± 385)	219 (± 162)	142 (± 67)	411 (± 439)	672 (± 488)	157 (± 88)	531 (± 459)
Ca	84	492 (± 413)	611 (± 643)	432 (± 252)	395 (± 246)	507 (± 328)	416 (± 320)	561 (± 476)
V	84	1.67 (± 1.48)	1.35 (± 1.27)	0.91 (± 0.57)	1.67 (± 1.21)	2.83 (± 1.89)	0.91 (± 0.69)	2.37 (± 1.66)
Cr	66	2.59 (± 2.41)	4.62 (± 2.80)	1.24 (± 0.94)	0.84 (± 0.90)	3.21 (± 2.22)	1.67 (± 1.90)	3.42 (± 2.53)
Mn	81	7.29 (± 5.20)	7.82 (± 6.66)	6.09 (± 3.20)	6.59 (± 4.02)	8.66 (± 6.10)	5.87 (± 3.79)	8.49 (± 5.92)

Fe	80	497 (± 375)	512 (± 444)	412 (± 234)	463 (± 291)	603 (± 477)	391 (± 246)	584 (± 439)
Co	80	0.12 (± 0.12)	0.14 (± 0.17)	0.10 (± 0.08)	0.12 (± 0.13)	0.13 (± 0.10)	0.08 (± 0.08)	0.15 (± 0.14)
Ni	84	2.07 (± 1.24)	2.49 (± 1.20)	1.43 (± 0.86)	1.94 (± 0.97)	2.42 (± 1.55)	1.67 (± 0.84)	2.44 (± 1.43)
Cu	64	6.00 (± 7.06)	2.67 (± 2.58)	2.66 (± 2.18)	9.38 (± 8.20)	8.49 (± 8.91)	2.40 (± 2.14)	8.46 (± 8.16)
Zn	54	19.17 (± 20.80)	3.52 (± 4.02)	6.93 (± 6.82)	26.38 (± 18.70)	24.48 (± 25.36)	9.22 (± 13.21)	23.00 (± 22.02)
Ga	71	0.10 (± 0.10)	0.17 (± 0.18)	0.07 (± 0.05)	0.07 (± 0.07)	0.09 (± 0.05)	0.08 (± 0.07)	0.11 (± 0.12)
As	80	1.01 (± 0.90)	0.59 (± 0.48)	0.57 (± 0.39)	1.28 (± 0.77)	1.63 (± 1.21)	0.62 (± 0.52)	1.34 (± 1.01)
Se	82	0.33 (± 0.17)	0.32 (± 0.19)	0.36 (± 0.11)	0.32 (± 0.20)	0.34 (± 0.17)	0.33 (± 0.15)	0.33 (± 0.18)
Rb	84	0.86 (± 0.88)	0.68 (± 0.75)	0.49 (± 0.27)	0.87 (± 0.95)	1.44 (± 1.10)	0.45 (± 0.34)	1.24 (± 1.04)
Sr	84	1.97 (± 2.13)	2.67 (± 3.48)	1.46 (± 1.10)	1.71 (± 1.46)	1.98 (± 1.22)	1.61 (± 1.33)	2.31 (± 2.62)
Cd	84	0.16 (± 0.15)	0.09 (± 0.08)	0.08 (± 0.06)	0.17 (± 0.15)	0.29 (± 0.17)	0.08 (± 0.06)	0.22 (± 0.17)
Ba	83	11.24 (± 8.38)	5.78 (± 2.95)	8.05 (± 4.74)	15.84 (± 6.67)	16.35 (± 11.29)	7.41 (± 5.04)	14.80 (± 9.32)
Pb	81	3.27 (± 2.90)	2.60 (± 2.46)	2.39 (± 1.58)	3.50 (± 2.56)	4.64 (± 3.99)	2.36 (± 2.12)	4.04 (3.21)
P	84	19.31 (± 12.32)	25.73 (± 16.60)	21.62 (± 7.63)	11.22 (± 7.75)	16.80 (± 9.78)	21.20 (± 11.05)	17.59 (± 13.26)
Ti	81	20.09 (± 27.58)	35.83 (± 46.59)	16.30 (± 9.64)	12.33 (± 11.82)	16.81 (± 9.67)	17.08 (± 15.11)	24.63 (± 34.94)
Zr	58	1.98 (± 1.60)	2.76 (± 1.72)	1.98 (± 1.40)	1.54 (± 1.87)	1.65 (± 1.32)	2.07 (± 1.59)	1.92 (± 1.62)
Mo	66	12.46 (± 12.25)	11.56 (± 5.24)	26.50 (± 14.37)	7.01 (± 12.48)	7.79 (± 7.14)	20.66 (± 13.66)	6.04 (± 5.42)
Sb	83	1.11 (± 0.92)	1.14 (± 1.03)	0.82 (± 0.52)	0.96 (± 0.70)	1.50 (± 1.15)	0.76 (± 0.52)	1.41 (± 1.08)
Sn	74	6.41 (± 6.79)	3.15 (± 2.40)	2.73 (± 2.58)	11.65 (± 8.77)	7.76 (± 6.68)	3.32 (± 4.15)	8.52 (± 7.45)
Galactosan	84	12.51 (± 22.34)	1.76 (± 3.10)	0.57 (± 0.37)	16.21 (± 25.82)	33.60 (± 26.91)	0.90 (± 1.12)	23.05 (± 26.89)
Mannosan	84	55.3 (± 103.3)	7.9 (± 14.1)	2.1 (± 1.2)	65.6 (± 116.1)	154.0 (± 128.8)	3.6 (± 4.9)	102.2 (± 125.9)
Levogluconan	84	413.0 (± 682.3)	74.8 (± 116.7)	34.3 (± 15.5)	545.7 (± 779.6)	1066.4 (± 804.1)	48.4 (± 59.1)	744.4 (± 812.0)
2-methylerythritol	84	5.01 (± 7.97)	3.51 (± 4.58)	14.44 (± 9.75)	1.01 (± 1.50)	0.21 (± 0.10)	10.15 (± 9.14)	0.35 (± 0.34)
2-methylthreitol	84	2.05 (± 2.78)	1.43 (± 1.51)	5.51 (± 3.14)	0.78 (± 0.85)	0.21 (± 0.09)	3.97 (± 3.03)	0.31 (± 0.28)
Glucose	84	39.69 (± 25.93)	46.60 (± 25.94)	60.27 (± 24.71)	31.97 (± 15.09)	17.16 (± 10.43)	58.46 (± 23.73)	22.62 (± 12.72)
Fructose	84	10.16 (± 8.46)	15.37 (± 8.73)	15.09 (± 7.56)	6.41 (± 4.76)	2.51 (± 1.44)	16.32 (± 7.54)	4.57 (± 4.41)

Mannitol	84	39.50 (± 32.85)	45.73 (± 27.52)	74.03 (± 28.88)	24.81 (± 16.04)	9.12 (± 5.58)	66.68 (± 27.15)	14.80 (± 10.14)
Arabitol	84	34.84 (± 26.85)	43.67 (± 25.22)	57.73 (± 24.05)	25.02 (± 16.57)	9.63 (± 5.55)	56.75 (± 21.63)	14.93 (± 10.73)
Trehalose	84	16.17 (± 11.51)	20.41 (± 13.15)	25.17 (± 9.36)	11.07 (± 5.26)	6.48 (± 3.49)	24.51 (± 11.17)	8.59 (± 4.37)
Inositol	77	3.15 (± 2.16)	3.55 (± 2.48)	3.83 (± 1.77)	2.92 (± 1.55)	1.71 (± 2.28)	3.96 (± 2.12)	2.26 (± 1.85)
Erythritol	84	4.36 (± 5.17)	4.08 (± 5.07)	8.19 (± 7.13)	2.77 (1.99)	2.00 (1.34)	6.95 (± 6.42)	2.00 (± 1.54)

RC: Fig. 2 I recommend to change y axis to $\mu\text{g}/\text{m}^3$. Please discuss the difference in “unaccounted” part during the seasons.

AC: Thanks for this comment as it substantially improved this part of the manuscript. We changed y axis to $\mu\text{g}/\text{m}^3$ and the “unaccounted” part is discussed in the end of the second paragraph of the 3.1. PM₁₀ mass concentration and chemical composition section.

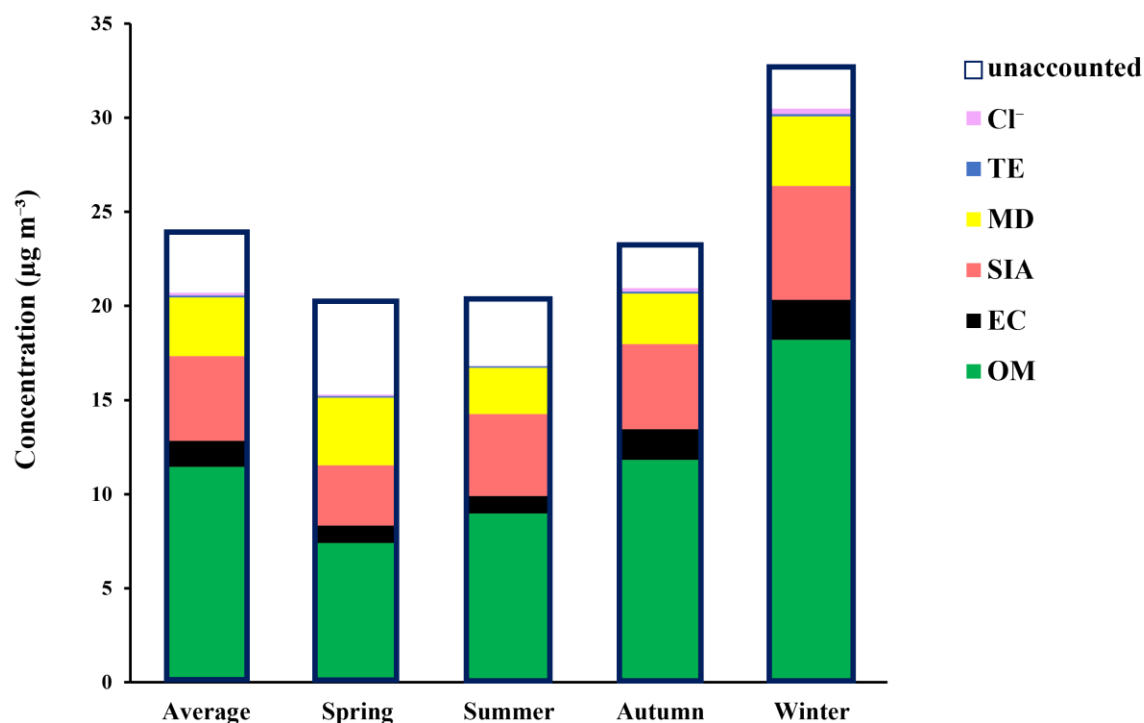


Figure 2. Major composition of PM₁₀ in Belgrade on annual level and during different seasons. Every bar represents total PM₁₀ on annual and seasonal average concentration. Major PM₁₀ reconstructed components were: OM – organic matter, EC –

elemental carbon, SIA – secondary organic aerosol, MD – mineral dust, TE – trace elements. (Row 260)

Here is the part of the manuscript where we discussed “unaccounted” mass:

Row 252 - 256

“The unaccounted PM₁₀ mass concentration on average was 3.2 µg m⁻³ which is around 16%. During spring, the unaccounted PM₁₀ mass was the highest, 4.8 µg m⁻³ while during winter was two times lower (2.0 µg m⁻³). The higher fraction of unaccounted mass might be attributed to the particle-bound water content of PM₁₀, and/or conversion factors adopted for OM and mineral dust which represent simplified calculations and may lead to uncertainties (Terzi et al. 2010).”

RC: Fig. S1 is analogue to Tab. S4.

AC: You are right, we removed Table S4 as it showed the same information as Figure S2. Figure S2 used to be Figure S1 but we added Fig. S1 with sampling sites of the studies conducted in Belgrade for the period 2003 – 2015 in the Supplement Material and changed ordinary numbers of the figures accordingly.

RC: Fig. 3 and 4 used abbreviations, which should be clarified in the figure’s legend.

AC: Thanks for pointing this out, the abbreviations in the captions of Figures 3 and 4 are added now.

Row 274

“Figure 3. Chemical profiles of the PMF factors in Belgrade Ada Marina. The names of the species are shown on x-axis, on y-axis are shown chemical concentrations of the species in ng m⁻³ with mean DISP values (white dots) and DISP confidence intervals (error bars). On the secondary y-axis are shown relative contributions of the species apportioned by the factor (black dots). Biomass burning (BB); Long range transport and local combustion (NaCl/COMB); Mineral dust (MD); Primary biological aerosol (PBAP); Biogenic secondary organic (BSOAIsoprene); Traffic/ Industry (TRA/IND).”

Row 281

“Figure 4. Daily factor contribution to PM₁₀ mass concentration during one-year campaign (left) and wind polar plots with normalized concentration of the apportioned PMF factors (right). Biomass burning (BB); Long range transport and local combustion (NaCl/COMB); Mineral dust (MD); Primary biological aerosol (PBAP); Biogenic secondary organic (BSOA_{Isoprene}); Traffic/ Industry (TRA/IND).”

RC: Questions:

How was “mineral dust” calculated?

What represent the whiskers in the Fig. 4?

AC:

Mineral dust was calculated according to the formula from (Querol et al. 2001):

$$MD = [Ca] \times 1,5 + [Al]/0.53 \times 2.5 + [Al]/0.53 + [Na] + [Mg] + [K] + [Fe]$$

Reference:

Querol, X., Alastuey, A., Rodriguez, S., Plana, F., Ruiz, C.R., Cots, N., Massagué, G., Puig, O.: PM₁₀ and PM_{2.5} source apportionment in the Barcelona Metropolitan Area, Catalonia, Spain. *Atmos. Environ.*, 35, 6407–6419. [https://doi.org/10.1016/S1352-2310\(01\)00361-2](https://doi.org/10.1016/S1352-2310(01)00361-2), 2001.

The whiskers in the Fig. 4 represent min, mean and max of DISP values obtained from the PMF output.

4. Conclusion

RC: Most of the text is rather summary than conclusion(s).

AC: You are right. We rewrite the conclusion following the ACP guidelines for comment section.

Row 538 - 545

“Eight SA studies were conducted in the past in Belgrade urban and Metropolitan area upon data sets collected in the period from 2003 and 2015 and WeBaSOOP year-long campaign in 2023-2024. Although WeBaSOOP study was conducted upon data set collected eight years after the last study and having different, broader range of, species used for SA, factors traffic, industry, different combustion sources, mineral/soil dust and secondary inorganic aerosol were identified in all studies in the past and ours. This indicates a continuity of these factors throughout the years on air quality in Belgrade. One study performed on data sets collected 15 years ago identified marine aerosol also but with higher contribution

than in our, WeBaSOOP, study. However, in contrast to other studies, this was the first one that identified factors from biological origin (PBAP and BSOA_{Isoprene}).”

Row 563

“Our results showed influence of both, local (biomass burning, traffic, biogenic aerosols) and regional sources (mineral dust, salt from long-range transport) on PM₁₀ concentration in this area.”

Row 567 - 569

“However, further work for better understanding of PM₁₀ regional and local sources in Belgrade is needed by performing SA study at least for two fractions of airborne PM represent by fine and coarse fraction as well as combination of offline and online PMF analysis and long-term measurements.”

Row 570 - 580

“Mineral dust events, marine aerosol and biogenic aerosols contribute to the background concentration of PM₁₀ and PM_{2.5} and are largely beyond the scope of emission control measures. Although sea salt was not extracted as a separate factor in WeBaSOOP study, its contribution to PM₁₀ mass may be accounted as 1-2 µg/m³, but in case of mineral dust, contribution is estimated to be around 4 µg/m³. In WeBaSOOP study, mineral dust represents mix of both natural and anthropogenic sources from local and long-range transport, while 1/5 of PM₁₀ mass (around 5 µg/m³) was attributed to primary and secondary airborne particulate matter of biogenic sources. As emissions from these sources are beyond controllable measures compliance with ambient air quality limit values consequently requires sufficient reductions in controllable anthropogenic emissions to offset the irreducible natural background. Where legislation permits, documented contributions from specific natural sources, such Sahara dust events and sea salt, may be excluded from compliance assessment. However, routine exclusion of biogenic aerosol contributions is generally not possible to be applied without measurements such WeBaSOOP study enabled.”