Interactive comment on "Source apportionment and seasonal variation of $PM_{2.5}$ in a Sub-Sahara African city: Nairobi, Kenya" by S. M. Gaita et al.

Responses to Anonymous Referee #1

We would like to thank the Anonymous Referee #1 for the critical and insightful review given to our manuscript.

The responses to his/her specific comments are listed herein;

1. Page 9566, line 24, and further within the manuscript (e.g., page 9567, lines 8-9; page 9567, lines 24-25; page 9568, lines 5-6): References within parentheses within the text should be placed in chronological order.

   Response: References have been ordered chronologically.

2. Page 9571, lines 1-4: How was BC obtained from the reflectometer reading? Some explanation or a literature reference is needed.

   Response: The BC concentration was analyzed using a FH62 1-N black smoke detector (ESM Emberline, Germany). The BC reflectometer utilizes the absorption and reflection properties of the PM loaded on the filter. The amount of reflected red light by the particles is inversely proportional to the amount of the BC present on the sample. The output parameter is normally voltage and the instrument is operated according to black smoke method, which categorizes the blackness of particle layer on a scale of 0 to 9 known as a black smoke number RZ (Gatari & Boman, 2003; Moosmüller et al., 2009).

3. Page 9571, lines 21 and 23: It is not specified what the index "i" indicates. Should it not be "A" instead of "i"?

   Response: The index "i" is supposed to be "A". The correction has been made.

4. Page 9573, lines 9-18: The average data for the $PM_{2.5}$ mass, BC and some elements of the two sites are compared here, but the data for the university site apply to a 2-year period and those for the UNEP site to a period of one year only. One cannot really draw conclusions from this comparison of different periods. It would be fairer to make the comparison for the one-year period that was is common for the two sites.

Response: The authors agree with your observation and have decided to implement your suggestion of comparing the common periods at the university and UNEP sites. Two new tables will be made:

a. Table 1: Summary of the results from all filter samples for the sampling period 22nd May 2008 to 30th March 2010: detection limits, range, mean concentrations (ng m^{-3}), standard deviations (SD) and percentage composition (%$PM_{2.5}$) for detected trace elements, BC and $PM_{2.5}$. N is the number of valid samples.

Elements	Detection limit (ng m^{-3})	Mean (ng m^{-3})	SD (ng m^{-3})	%$PM_{2.5}$	Range (ng m^{-3})	N
S	250	640	340	3.6	250 - 3800	459
Cl	110	480	200	2.7	110 - 1800	723
K	50	310	150	1.7	51 - 840	719
Ca	30	310	250	1.7	30 - 2700	713
Ti	14	54	25	0.3	14 - 180	570
Mn	9.5	41	23	0.2	10 - 190	722
Fe	10	530	350	2.9	11 - 1800	780
Ni	0.8	4	2	0.0	1 - 17	478
Cu	0.7	11	6	0.1	2 - 82	773
Zn	6.6	91	100	0.5	7 - 760	780
Br	2.5	12	21	0.1	3 - 340	667
Rb	0.5	2	1	0.0	1 - 5	383
Pb	1.5	22	18	0.1	2 - 160	525
BC	6	2700	1800	15	74 - 9900	767
$PM_{2.5}$ (µg m^{-3})	1	18	8.6		1.9 - 53	780

b. Table 2. Summary of the results from the University and the UNEP site for the sampling period 16th April 2009 to 30th Mar 2010: range, mean concentrations and standard deviations (SD) for detected trace elements, BC (in ng m^{-3}) and $PM_{2.5}$ (in µg m^{-3}). N is the number of valid samples.

	University			UNEP		
Elements	Range (ng m^{-3})	Mean (SD) (ng m^{-3})	N	Range (ng m^{-3})	Mean (ng m^{-3})	N
S	250 – 1600	660 (240)	132	250 – 1700	620 (280)	184
Cl	110 – 1300	520 (200)	253	110 – 1600	430 (170)	259
K	60 – 840	340 (160)	265	50 – 760	270 (160)	239
Ca	40 – 2700	340 (270)	268	30 – 1300	200 (150)	228
Ti	21 – 180	62 (27)	241	14 – 110	40 (18)	156
Mn	11 – 120	53 (23)	267	10 – 90	28 (14)	236
Fe	33 – 1700	730 (340)	270	11 – 1200	320 (240)	278
Ni	2 – 10	4 (1)	153	1 – 17	4 (2)	191
Cu	2 – 80	12 (7)	269	2 – 55	9 (4)	275
Zn	9 – 760	120 (120)	270	7 – 640	76 (97)	272
Br	3 – 340	16 (30)	240	3 – 70	7 (5)	215
Rb	1 – 5	3 (1)	160	1 – 5	2 (1)	123
Pb	2 – 80	23 (16)	202	2 – 79	17 (14)	186
BC	40 – 9500	3900 (800)	270	70 – 5700	1500 (1000)	267
$PM_{2.5}$ (µg m^{-3})	3 - 53	21 (95)	270	1.9 - 36	13 (7.3)	278

5. Page 9673, lines 22-23: There is an inconsistency here; the percentages of 17 % and 14 % add up to 31 %, which is larger than the 29 % given in line 19.

   Response: BC accounted for 15% and not 17% as indicated. The error has been corrected.

6. Page 9674, lines 2-3, with regard to Fig. 2: It is unclear what the percentage data in the figure denote. Percent of what? Perhaps percent of the sum of the concentrations of the three elements, whereby the BC data were divided by ten? In any case, this should be made clear.

   Response: The authors have reorganized the manuscript and thus felt that the information presented by the said Fig. 2 will be captured and be represented by the new Table 1 and 2 (see comment 4) which will be included in the revised manuscript. Therefore the said figure and corresponding section have been omitted.

7. Page 9575, lines 20-27: The interpretation of the third factor is hard to follow and not convincing at all. The presence of K, Mn, Ni, Cu, Zn, Rb, and BC in this factor do not point to secondary formation processes. This factor looks to me like a mixed factor of biomass burning aerosol (indicated by the presence of K, Zn, Rb) with perhaps some secondary aerosol (part of the S on this factor may be derived from gaseous SO_2 that is emitted by biomass burning).

   Response: After a thorough relook of the third factor, the authors agree with the referee that the factor can be considered to be a mixed factor of secondary aerosol and biomass burning.

8. Page 9577, line 17: It is noteworthy that the Br/Pb ratio of 0.64 in the aerosol is lower than the ratio of 0.77 expected for fresh vehicular exhaust. This could indicate that part of the Br from the leaded gasoline emissions was present in the vapor phase. In their study for the city of Butare, Rwanda, where TEL-B was also used as antiknock agent, Maenhaut and Akilimali (1987) found that the Br/Pb ratio in the aerosol was, on average, 0.68_0.11 (n = 18) during the night versus 0.43_0.03 (n = 16) for the day. The difference was attributed to much more Br being present in the vapor phase during the warm day than during the cool night, and it was stated that this suggests that significant exchange takes place between particulate and gaseous Br. The same is likely also the case for Nairobi.

   Response: The authors agree with the referee's observations and will incorporate the given information in the manuscript.

9. Page 9579, line 3: Although contribution from soil Pb and other anthropogenic sources of Pb may have been partly responsible for the low Br/Pb ratio of 0.43 at the UNEP site, it should not be discounted that part of the automotive Br may have been in the vapor phase, as was discussed in the previous comment.

   Response: The authors are grateful for the referee's input and comments. The said comments will be incorporated into the manuscript.

10. Technical and other minor corrections:

    Response: The highlighted corrections have been worked on.

References

Gatari, M. J., & Boman, J. (2003). Black carbon and total carbon measurements at urban and rural sites in Kenya, East Africa. *Atmospheric Environment*, *37*(8), 1149-1154. doi: http://dx.doi.org/10.1016/S1352-2310(02)01001-4

Maenhaut, W., & Akilimali, K. (1987). Study of the atmospheric aerosol composition in equatorial Africa using PIXE as analytical technique. *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, 22*(1–3), 254-258. doi: http://dx.doi.org/10.1016/0168-583X(87)90338-7

Moosmüller, H., Chakrabarty, R. K., & Arnott, W. P. (2009). Aerosol light absorption and its measurement: A review. *Journal of Quantitative Spectroscopy and Radiative Transfer*, *110*(11), 844-878. doi: http://dx.doi.org/10.1016/j.jqsrt.2009.02.035

Responses to Anonymous Referee #2
We would like to thank the Anonymous Referee #2 for the insightful and in-depth review s/he has given to our manuscript.

The responses to his/her specific comments are listed herein;

1. Page 9566, line 4, "particles" should be "particulate"

   Response: The suggested change has been effected.

2. Page 9569, section 2.1 could be summarized:

   Response: The authors have shortened the section by removing the last paragraph which had explained the developmental plans for the sampling area.

3. Section 2.2 could be shortened:

   Response: The authors concur with the referee and the said section has been shortened.

4. Page 9570, line 12: 3 lpm is a very low flow, did the authors take positive artefacts for OC into account? They did not measure OC (which is a pity), but this may have affected particle mass.

   Response: The authors have noted the valid point with regard to lack of OC measurement. In order to correct for the positive artefacts for OC, concentration values from the field blank filters were subtracted from the measured samples' values.

5. Page 9570, line 16: what was the total number of valid samples collected for each location? Were they daily samples?

   Response: The number of valid sample filters collected at both sites was 780 and is indicated in page 9570, line 23.

6. Page 9572, section 3.1: does any Kenyan legislation exist? If so, what are the limit values?

   Response: There is the Draft Air Quality Regulation, 2008 which is referred to as "The Environmental Management and Coordination (Air Quality) Regulations, 2008" (NEMA, 2013).The said regulation is still in the draft form as there is no scientific knowledge which is specific to Kenya that is available to back any suggested air quality guidelines.

7. Page 9574, line 13: shouldn't there be larger biomass burning contributions in the background area than in the city centre? If not, please clarify here why.

   Response: The background area site (UNEP) recorded lower BC concentration since it was shielded by two forests (Karura and Gigiri) which inadvertently are located in the same direction as the local wind and regional air mass back trajectories.

8. Page 9574, line 16: what sort of combustion?

   Response: The likely combustion process is the use of biomass based fuel in domestic energy generation.

9. Page 9576, lines 1-7: the profile of this source could be mistaken for traffic based on its tracers. Do the back-trajectories support this interpretation?

   Response: The back trajectories supports these observations in that their general direction lies between east and south, which is the same direction as the industrial area as well as the low income households (where biomass based fuel is used and open burning of trash is common (Karanja & Makau, 2012).

10. Page 9577, line15: what is the mean $Pb/PM_{2.5}$ ratio?

    Response: The mean $Pb/PM_{2.5}$ ratio was 0.001375

11. Page 9577, lines 26-27: please remove "due to prevailing.....(Querol et al., 2001)" and substitute with "due to the S emissions from vehicles, as described in sections above."

    Response: The referee's suggestion has been implemented.

12. Page 9579, lines 1-2: "traffic factor compared to other sources...", but this is the background site, how do the authors explain that the $Pb/PM_{2.5}$ ratio is higher at UNEP? Shouldn't this ratio be higher in the city centre?

    Response: In the view of banning lead in gasoline by the Kenyan government in 2006, it is expected that the Pb concentration in the soil dust will last for long period and somewhat be constant (Datko-Williams et al., 2014; Xu et al., 2012). In absolute values, the university site had higher concentration value (23 ± 16 ng m^{-3}) compared to the UNEP site (17 ± 14 ng m^{-3}). More so, since the university site is close to the city center and therefore it is influenced heavily by PM sources as characterized by the reported 50% higher $PM_{2.5}$ concentration than the value reported at the UNEP site.

13. Page 9579, line 8: Does this factor correlate with the traffic one, then? They should if this interpretation is correct.

Response: The interpretation of the third factor has high uncertainty. As highlighted by the referee (see comment 16), it has contribution from mixed sources such as biomass burning and industrial emission. Therefore, this factor will be reviewed and discussed as a mixed factor.

14. Page 9579, lines 8-9: this statement is too vague, please elaborate or remove

    Response: The said statement has been removed.

15. Page 9580, lines 2-3: But the authors stated above that they are 2 independent factors, and that road dust is included in the traffic source. Then why does the mineral source decrease on the weekends? If this is regional dust then there should be no weekly trend.

    Response: The authors see the point raised by the referee and agree that the specific anthropogenic sources should be indicated in the text to avoid confusion with road dust. The implied anthropogenic sources of mineral dust that lead to weekly trend include quarrying activities and road construction which as employment activities follow a weekly trend.

16. Page 9580, line 14: A similar situation here: it was stated that S from traffic was included in the traffic source, therefore it cannot be included again in the secondary aerosol factor. If the secondary aerosol factor is of regional (or possibly industrial) origin, then it should not have a weekly trend. The interpretation of this source should be revised

    Response: Once again the authors agree with the referee and as stated in comment 13, the said factor will be reviewed and discussed afresh.

17. A deeper analysis of back-trajectories vs. sources would be extremely helpful to further understand and confirm the nature of the sources. I would suggest adding a section on this.

    Response: The proposed discussion will be included in the results as well as in the discussion section.

18. Page 9580, line 23: "value", which value?

    Response: The referred value is the concentration value from Gatari et al. (2009).

19. Page 9582, line 12: I think "but lower" should be "and thus higher"?

    Response: The authors agree with the suggested change of phrase.

20. Page 9582, line 18: "mineral dust", what are the natural and anthropogenic sources of the mineral dust factor? This should be clarified earlier in the text.

    Response: The authors agree with the referee and will clarify the natural and anthropogenic sources of mineral dust. In this regards, the natural source of mineral dust in Kenya include windblown dust from local soil (indicated by presence of Fe, Ca and Ti). The anthropogenic sources of mineral dust include quarrying activities which have gained momentum due to increased road construction and infrastructure development in Kenya especially during the sampling period.

21. Page 9582, line 22: this is an interesting conclusion, how would it be done (reducing the lead content)?

    Response: Reducing lead content will entail strict implementation of emission control from industrial sources (Were et al., 2012).

22. Page 9583, lines 3-4: also an interesting recommendation.

    Response: Authors are grateful for the positive comment.

References

Datko-Williams, L., Wilkie, A., & Richmond-Bryant, J. (2014). Analysis of U.S. soil lead (Pb) studies from 1970 to 2012. *Science of The Total Environment*, *468–469*(0), 854-863. doi: http://dx.doi.org/10.1016/j.scitotenv.2013.08.089

Gatari, M. J., Boman, J., & Wagner, A. (2009). Characterization of aerosol particles at an industrial background site in Nairobi, Kenya. *X-Ray Spectrometry*, *38*(1), 37-44. doi: 10.1002/xrs.1097

Karanja, I. W., & Makau, J. (2012). Nairobi Slum Inventory: http://www.irinnews.org/pdf/nairobi_inventory.pdf

NEMA. (2013). Draft Air Quality Regulation, 2008. Retrieved 12 Feb, 2013, from http://www.nema.go.ke/index.php?option=com_content&view=article&id=141&Itemid=493

Were, F. H., Kamau, G. N., Shiundu, P. M., Wafula, G. A., & Moturi, C. M. (2012). Air and Blood Lead Levels in Lead Acid Battery Recycling and Manufacturing Plants in Kenya. *Journal of Occupational and Environmental Hygiene*, *9*(5), 340-344. doi: 10.1080/15459624.2012.673458

Xu, H. M., Cao, J. J., Ho, K. F., Ding, H., Han, Y. M., Wang, G. H., Chow, J. C., Watson, J. G., Khol, S. D., Qiang, J., & Li, W. T. (2012). Lead concentrations in fine particulate matter after the phasing out of leaded gasoline in Xi'an, China. *Atmospheric Environment*, *46*(0), 217-224. doi: http://dx.doi.org/10.1016/j.atmosenv.2011.09.078

Responses to Anonymous Referee #3

We would like to thank the Anonymous Referee #3 for the insightful review given to our manuscript.

The responses to his/her specific comments are listed herein;

1. Abstract should be partially rewritten to reflect the major changes in the text

   Response: The authors agree with the referee about revising the abstract after making the suggested changes.

2. P. 9568 lines 3-8: Chapter should be extended significantly by adding discussion about biomass burning episodes, see e.g. (Swap et al., 2003; Vakkari et al., 2014) and domestic combustion, see e.g. (Venter et al., 2012).

   Response: The authors have included discussion about biomass burning especially the Southern African Regional Science Initiative – SAFARI 1992 and SAFARI 2000 campaigns (Lindesay et al., 1996; Swap et al., 2003).

3. Wind rose/roses including the wind velocities for the both measurement sites would be valuable

   Response: The meteorology data was collected from Jomo Kenyatta Airport which is approximately 13 km to the southeast of the university site. Therefore, the author will include only one wind rose to represent the wind condition during the sampling period.

4. Supporting material is needed to confirm PMF solutions, see e.g. (Comero et al., 2009) including at least:
   a. Analysis of residuals and fpeak
   b. Q/Qexp and MaxRotMat vs. factor number plot
   c. G space plotting

   Response: The requested supporting materials will be included in the supplementary material.

5. Show the PMF results of the different number of factors (e.g. 4-6) in supplementary material and add discussion about the results when the number of sources/factors has been changed.

Response: As stated above, the requested supporting materials will be included in the supplementary material.

6. I propose that $PM_{2.5}$ mass, elemental concentration and mass concentration variation (seasonal/weekdays) results are in the same chapter and trajectory + PMF analysis are in the new chapter named as "$PM_{2.5}$ source apportionment".

   Response: The authors are grateful for the proposed outlines of the manuscript and will reorganize it in a manner that captures the said proposal.

7. Add a new table for the dry season/wet season comparison (mean concentrations)

   Response: Given that during the sampling period (2009) there was a drought, the information in the suggested tables will not give an accurate picture. Instead the authors are of the opinion that inclusion of new graphs (see comment 9) will give a clearer picture of PM in Nairobi.

8. Plot separate ternary diagrams for the dry and wet seasons and use more easily distinguishable colors/markers (Fig 2).

   Response: The authors have decided to omit the ternary diagrams and instead include two the new tables which will be included in the revised manuscript. One table will have all the data and the second one will have separate data from university and UNEP site during the common sampling period.

9. Add new graph for $PM_{2.5}$, BC and major trace element concentrations (time series) including mean percentage seasonal compositions (see Figs. 9, 10 and 11).

Response: The suggested graphs will be included in the revised manuscript.

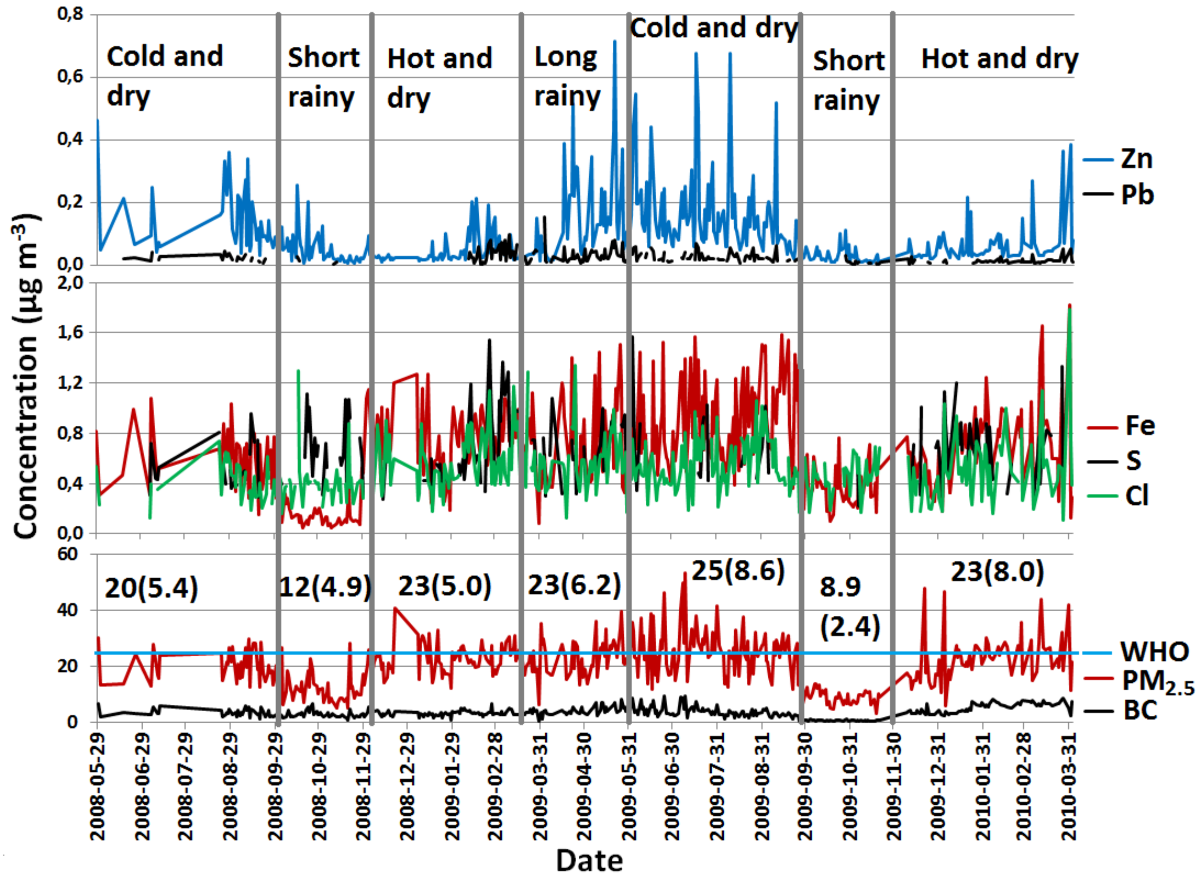

Fig. 1: Seasonal variation of $PM_{2.5}$ and some elements sampled at the university site. Included in the figure are the seasonal averages and standard deviations (enclosed in brackets) as well as the WHO air quality guideline for a 24 h period.

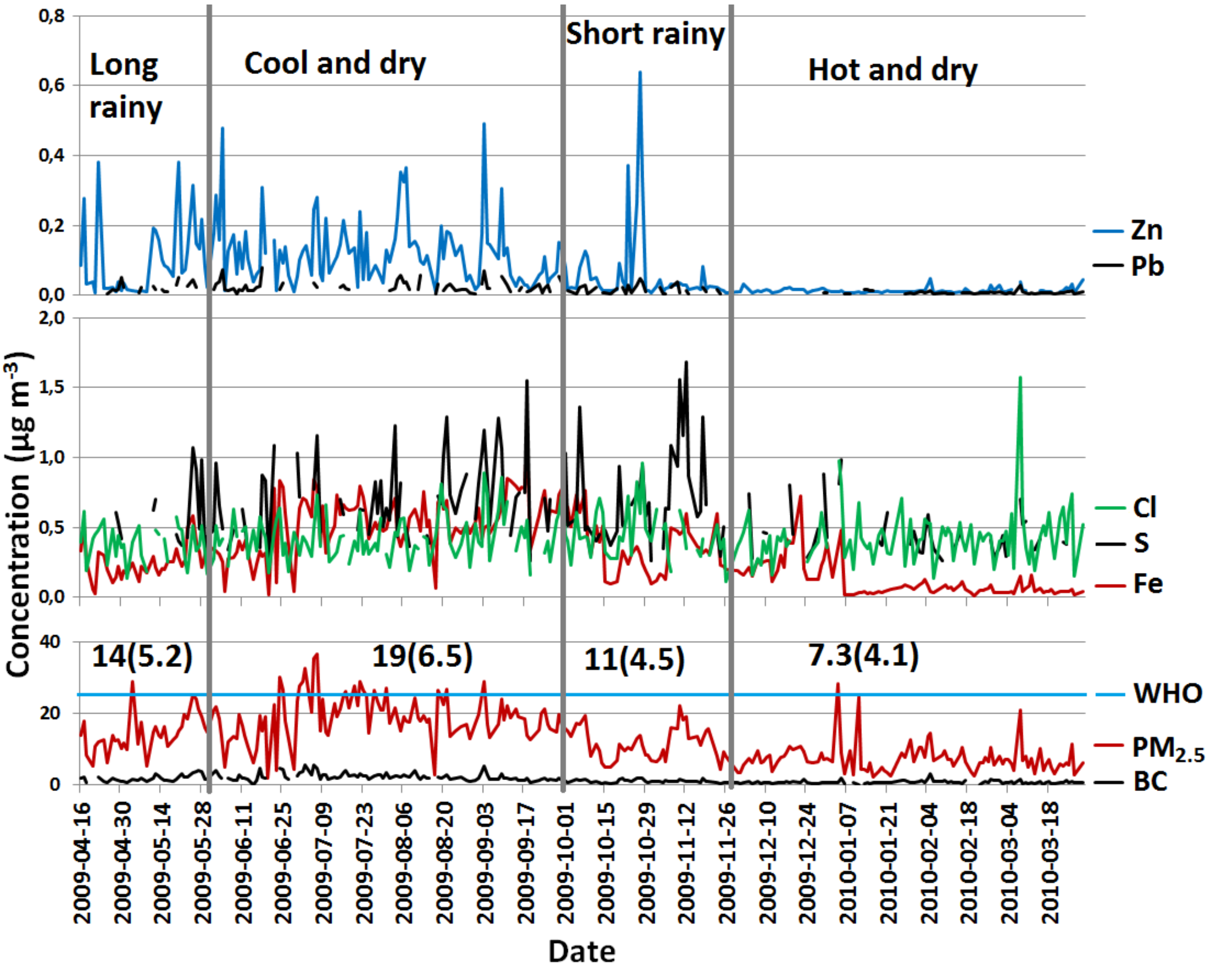

Fig. 2: Seasonal variation of $PM_{2.5}$ and some elements sampled at the UNEP site. Included in the figure are the seasonal averages and standard deviations (enclosed in brackets) as well as the WHO air quality guideline for a 24 h period.

10. Add more trajectory analysis, e.g. try to find typical time periods for the sources like biomass burning events traffic, dust event and domestic burning and compare these source identified results to other results like seasonal averages.

    Response: More trajectories will be added to the revised manuscript and analyzed with respect to PM sources.

11. Check PMF analysis carefully with the supporting information and rewrite results/conclusions when necessary.

    Response: Authors will have a thorough relook of the PMF analysis as suggested by the referee.

12. Add percentage compositions for each period to Figs 10 and 11.

Response: The percentage composition for each period in the said figures will be added as part of the results in the revised manuscript.

13. Present the relationships between the source contributions and wind directions, see e.g. (Zhou et al., 2005).

Response: The said relationship will be presented in the revised manuscript.

References

Comero, S., Capitani, L., & Gawlik, B. M. (2009). Positive An introduction to the chemometric evaluation of environmental monitoring data using PMF *JRC Scientific and Technical Reports, EUR 23946 EN-2009*. Ispra, Italy.

Lindesay, J. A., Andreae, M. O., Goldammer, J. G., Harris, G., Annegarn, H. J., Garstang, M., Scholes, R. J., & van Wilgen, B. W. (1996). International geosphere-biosphere programme/international global atmospheric chemistry SAFARI-92 field experiment: Background and overview. *Journal of Geophysical Research: Atmospheres, 101*(D19), 23521-23530. doi: 10.1029/96JD01512

Swap, R. J., Annegarn, H. J., Suttles, J. T., King, M. D., Platnick, S., Privette, J. L., & Scholes, R. J. (2003). Africa burning: A thematic analysis of the Southern African Regional Science Initiative (SAFARI 2000). *Journal of Geophysical Research: Atmospheres, 108*(D13), 8465. doi: 10.1029/2003JD003747

Vakkari, V., Kerminen, V.-M., Beukes, J. P., Tiitta, P., van Zyl, P. G., Josipovic, M., Venter, A. D., Jaars, K., Worsnop, D. R., Kulmala, M., & Laakso, L. (2014). Rapid changes in biomass burning aerosols by atmospheric oxidation. *Geophysical Research Letters, 41*(7), 2014GL059396. doi: 10.1002/2014GL059396

Venter, A. D., Vakkari, V., Beukes, J. P., van Zyl, P. G., Laakso, H., Mabaso, D., Tiitta, P., Josipovic, M., Kulmala, M., Pienaar, J. J., & Laakso, L. (2012). An air quality assessment in the industrialised western Bushveld Igneous Complex, South Africa. *S Afr J Sci., 108*, 10. doi: 10.4102/sajs.v108i11/12.1059

Zhou, L., Hopke, P. K., Stanier, C. O., Pandis, S. N., Ondov, J. M., & Pancras, J. P. (2005). Investigation of the relationship between chemical composition and size distribution of airborne particles by partial least squares and positive matrix factorization. *Journal of Geophysical Research: Atmospheres, 110*(D7), D07S18. doi: 10.1029/2004JD005050

Relevant changes in the manuscript

The manuscript has been revised as per the referees’ suggestions and the changes are as follows:

1. The secondary aerosol factor in the original manuscript has been renamed to mixed factor (assumed to be composed of secondary aerosol and biomass burning component).
2. The table in the original manuscript has been removed and replaced by two tables; one for the statistics of all the data and a second one with data covering the common period at the university and UNEP sites.
3. New figures have been included which cover
    a. Wind speed and direction from the weather data
    b. Seasonal variation of $PM_{2.5}$, BC and some selected elements.
    c. Weekly variation of $PM_{2.5}$, BC and some selected elements