Assessment of wood burning versus fossil fuel contribution to wintertime black carbon and carbon monoxide concentrations in Athens, Greece

Authors Responses to referees' comments

The authors acknowledge both referees for critically reading the manuscript and for their contribution in improving and clarifying this study. The authors have compiled the responses as follows. Reviews from Referee 1 and Referee 2 are in blue and Brown font respectively, and have been grouped based on the section of the manuscript they refer to. Author responses are in black font numbered with [A0, A1, A2 …]. Italics and quotations are used for the information added in the revised manuscript.

General Comments

- Reviewer 1: This manuscript addresses up-to-date scientific questions within the scope of the journal, and may indeed be considered as relevant for the special issue dedicated to ChArMEx. Its overall presentation (including the title, the abstract and the figures) is appropriate, clear and globally well structured. It presents results of wintertime BC and CO source apportionment results obtained for Athens, Greece. To do so, authors claim they are using two different and independent methodologies. However, the "CO/NOx ratio" approach appears to be irrelevant in the present case, so that outputs are not used for the purpose of the study. My only major comment is related to this latter issue, and I would recommend presenting the use of the "CO/NOx ratio" approach in another way (or to simply skip it).

- Referee 2: The manuscript attributes the concentration-contribution of wood burning to air pollution in Athens and with that handles an important health related subject that needs attention. For the source apportionment of black carbon, the well-known technique based on wavelength dependence of the aerosol light absorption coefficient is used after application of necessary compensations. For CO apportionment two models are described. Model 1 relies on known emission ratios of NOx and CO and assumed similar atmospheric lifetimes. This model is not trusted by the authors and according to the authors this linear model always over-estimates the wood burning contribution. The results from model 1 are not researched enough to give recommendations to other scientific studies. It remains unclear why this model is included in this paper. A short discussion in the introduction could be enough.

- A0: Both referees major comment concerns the use and presentation of the CO-NOx linear model used for CO source apportionment. From their comments, we understand that the reason why the model was used seemed unclear since at the end, we give more confidence to the second model.
  However, we believe that since the CO/NOx ratio has been used in the past as a diagnostic ratio to characterize different type of emission sources (Fujita et al., 1992; Ravindra et al., 2006; Wahlina et al., 2001), it is interesting to discuss the output of the model 1 with respect to the output of the model 2. Additionally, this model could be of use in the case where no absorption measurements are available. This could be for instance the case at monitoring stations part of national networks where only regulated air pollutants are often measured. In order to make a clearer introduction to the reason why we have selected to use this model, we have added in the manuscript, section 2.4.1, the following:
  - "P5L29-32: "*The CO/NOx ratio has been used in the past as a diagnostic to characterize different type of emission sources* (Fujita et al., 1992; Ravindra et al., 2006; Saurer et al., 2009; Wahlina et al., 2001)*. It can serve as a useful tool for apportioning CO concentrations at monitoring stations part of national networks where only regulated air pollutants are often measured.*"

  We have also added some discussion about the conditions limiting the use of the model. Indeed, our results suggest that CO-NOx should be used with more caution in environments dominated by aged air masses. As a matter of fact, at the NOA urban background site, the difference between both models is of a factor of about 1.5, which can be considered rather acceptable given the level of uncertainty associated with source apportionment methods. Higher difference between both models are observed for the DEM suburban site. Finally, since this type of model is being used in other studies, we suggest that it is a benefit for future studies to keep the results of this comparative assessment against model 2 in order to have documented the results of the current evaluation.
  The following discussion was added in the manuscript
  - P10L01-08: "*The wood burning contribution to CO estimated using the CO-NOx linear model is higher compared to the estimations from CO-BCff-BCwb model, of a factor of about 1.5 for NOA, which can be considered as "acceptable" given the uncertainties associated with both models. A higher overestimation compared to model 2 of a factor of about 2.4 is found at DEM suburban station, which could be explained by the fact that the site is characterized by more aged air masses compared to the urban background NOA station. Consequently, ambient CO/NOx ratios might differ more significantly from emission ratios at DEM suburban station. These results suggest that CO-NOx linear model probably overestimate wood burning contribution to CO, especially in environments characterized by aged air masses were photochemical loss of NOx cannot be considered as negligible.*

- Model 2 for CO apportionment is based on multiple linear regression between CO and BC. This technique is well-known but in the conclusion section it is written that the method is new; or is the application to CO in combination to wood burning new? If new this fact should receive more attention earlier in the paper. The manuscript is not pushing scientific boundaries, but contains important numbers, e.g. 30% of BC is wood burning related.
  - We have taken into account the referee comments and added the following in the revised manuscript, in order to address what is the novelty about the method used.

9

- P6L38-40: *"While multiple linear regressions are known techniques for source apportionment, they have not yet been applied to investigate wood burning contribution to CO using the aethalometer's model results. The considerable increase in measurements carried out using aethalometers makes this technique an interesting and very useful methodology for apportioning CO concentrations."*

Specific comments

Abstract

- line 21: occasional significant impacts of long-range transport are not really discussed/demonstrated in the manuscript.
  - A1: The sentence "*and are only occasionally affected by long-range transport*" has been removed from the manuscript.

- 30% to the observed eBC and the CO concentrations (: : :.)' this doesn't read well and is confusing for CO.
  - A2: Corrected in the revised manuscript (P1L23).

1 Introduction

- Page 2, lines 16-23: it is not clear within which periods the discussed increases/decreases were observed (e.g., lines 16-18: a constant increase of 30% every year since 2012 ? or an increase of 30% for the period 2012-201x, compared to which period ? : : :).
  - A3: Precisions on the time periods discussed have added in the revised manuscript: P2L16,L18,L20

2 Material and Methods
2.1 Sampling Sites

- Page 3, line 9: how much "relatively far" from major roads?
  - A4: The station is at about 500 m from major roads (this information was added in the revised manuscript, P3L9). Within this radius of 500 m around the site, there are mainly pedestrian streets parks, hills. This is the reason why the site can be considered as an <u>urban background</u> and not an urban traffic site.

2.2 Measurements of aerosol light absorption and carbon monoxide

2.2.1 Aerosol light absorption and equivalent black carbon

- Page 3, lines 18-26: it may be worthy to indicate more clearly this data correction procedure was applied to AE42 (and AE31) datasets only.
  - A5: Added in the revised manuscript, P3L20, L35

- Also, what could be the uncertainties related to the use of f_ values that weren't estimated for this individual instrument /site?
- For compensation parameter f values given in Drinovec et al. (2015) were used. But Drinovec et al. describe that filter loading effects change with location and time. The values of Drinovec differ a lot from Sandradewi et al (2008) (reference in manuscript but not listed in References, make sure to find the correct paper) and Zotter et al (2017). The latter paper, that is known to the authors confirms the importance of proper compensation. I would like to see a more worked out compensation correction.
  - A6: We agree with both reviewers that f parameter depend on location and time and that uncertainties related to the use of f values should be estimated. f compensation parameter is expressed as: $f= a*(1 -w0) + 1$, with $w0$, the aerosol single scattering albedo and a, a constant parameter varying in the range 0.82–0.88 for the different wavelengths (950–370 nm). As a result, f depends mainly on the single scattering albedo. Since no simultaneous measurements of SSA were available, we chose default values based on Drinovec et al.(2015) because they were estimated for an urban environment where SSA is expected to be lower than background or remote environments characterized by aged aerosols. The f-values given in Drinovec et al., (2015) correspond to SSA values of about 0.75. Later measurements during the Athens smog ACTRIS JRA1 campaign indicated that wintertime SSA value at NOA exhibits an average value of 0.8±0.05. In order to estimate uncertainties related to the chosen f values, absorption coefficients calculated with f values taken from Drinovec et al., (2015) were compared with those using f values calculated for $w0$=0.8 (see Figure 1). Differences are found to be lower than 1% .Therefore, we estimate that on average the shadowing effect was correctly accounted for and therefore did not change the values in the manuscript. The following discussion has been added on the revised manuscript:
  - P3L28-30:*"The compensation parameter f_λ is a parameter that mainly depends on the single scattering albedo of aerosol (SSA). Because no simultaneous scattering coefficient measurements were available, f_λ values given in Drinovec et al.(2015) for an urban site with a single scattering albedo of about 0.75 were used for loading compensation at the urban background site.."*
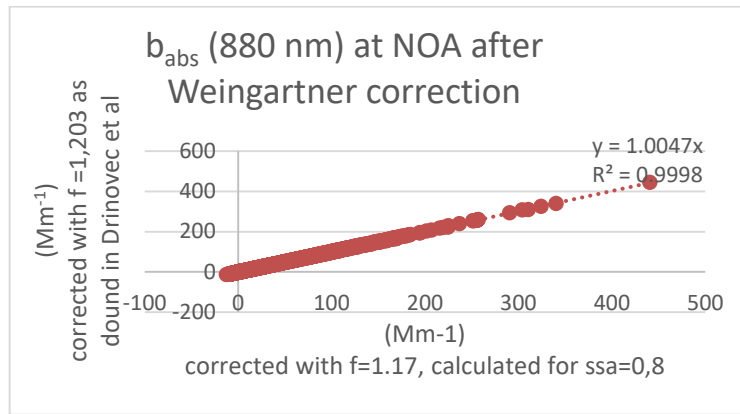
Figure 1 Scatter plot between absorption calculated using f_values of 1.17 (ssa=0.8) and 1.203 (Drinovec et al.2015) in the shadowing effect correction algorithm.

- Finally, what could be the impact of the PM10 cut-off, compared to the PM2.5 used at the other site?
- A7: At NOA, TSP were collected and not PM10 as indicated in the original version of the manuscript. This information has been corrected in the revised manuscript (P3L18). As the inlet includes curved tubing, a significant aerosol loss of the coarse fraction is expected. However, as indicated in several studies, BC is mainly related to fine particles
  - *P3L17-20: "AE42 was used and aerosol sampling was performed with no size-cut. As BC mainly contributes to PM_1 (Laborde et al., 2013; Wang et al., 2015), differences in the eBC concentrations due to the different aerodynamic diameters of sampled aerosols are expected to be negligible".*

- About the instruments At DEM (AE33) at NOA(AE42). I understand that AE33 and AE31 are compared. At page 3 line29: 'and data from AE31 aethalometer with : :: : :to AE-42, which operates continuously in parallel with the AE33 at DEM station. So what instruments are compared and where is the AE-31 located?
  - A8: Since we could not compare directly AE33 and AE42, we decided to compare AE33 with an AE31-Aethalometer (with identical measurement settings to the AE42). Both instruments were running simultaneously from 1st August to 30th September 2014 at NCSR Demokritos station. We modified the following sentence for more clarity:
  - P3L35 *"The results indicated a very good agreement between the absorption measurements (Mm^{-1}) from the **AE33 and AE31** instruments after compensation, with R^2=0.79, a small intercept of -0.15 and a slope of 0.97."*

- The R-squared of 0.79 is not very convincing for aethalometers, I would like to see the plot. The intercept (what is the unit? Inverse Mm or ng/m3?) of 0.15 is interesting.
  - A9: The plot is shown below. The unit is Mm^{-1} and this information has been added in the revised manuscript. The intercept is **-0.15.** Please indicate if necessary to include this plot to the supplementary information
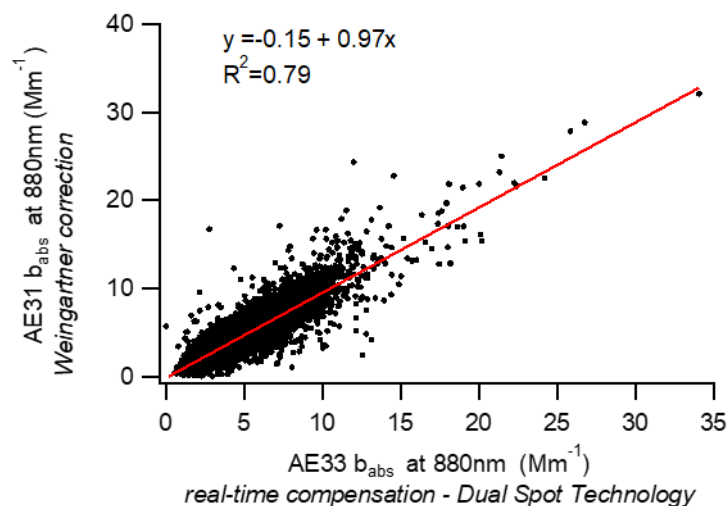

Figure 2 Linear regression between absorption coefficients at 880 nm measured simultaneously by AE33 and AE31 and corrected from loading and scattering effects using the dual Spot Technolgy and the Weingartner procedure respectively, from 1st August to 30th September 2014 at NCSR Demokritos station.

- Page 4, line 6-7: please indicate whether this value was also obtained using the 1.64 "ACTRIS correction factor" (as used by Zanatta et al., 2016)?
  - A10: As suggested by the reviewer, in the revised version of this manuscript the default C-factor for both aethalometers has been corrected with an additional correction factor. The need to use a compensation factor on top of the default value has also been confirmed by parallel measurements performed between AE31 and AE33 and a multi-angle absorption photometer (MAAP) (Model 5012, Thermo Electron Group,Waltham, MA,

11

USA) during 2011 at the DEM station (Diapouli et al., 2017). Absorption measurements have therefore been corrected with a factor of 1.64 as used in the ACTRIS community and proposed by the reviewer. This additional correction of our absorption measurements changes the MAC value derived from the intercomparison with EC measurements. The new corrected MAC at 880 nm value is therefore 4.6. However, correction on absorption coefficient and MAC compensate one another, and therefore final eBC values remain unchanged. The following changes have been made on the revised manuscript:

- o P3L26 "*The value of 3.5 was used for C_0 as recommended in [...]P4L2 eBC mass concentration was derived in this study by multiplying the b_{abs} coefficient at 880 nm with a constant value of mass absorption cross-section (MAC) of 4.6 m^2 g^{-1} (determined from the comparison with simultaneous measurements at DEM of elemental carbon)*" [...] *P4L4-8: :Assuming an absorption Ångstrom exponent of 1.0, the MAC used here is 6.13 when adjusted to 637 nm. Our MAC value is at the lower limit of the values reported by Zanatta et al., (2016), for nine rural background stations across Europe (7.5-13.3 m2 g-1, calculated for 637 nm), and within the range of values reported by Hitzenberger et al., (2006) for an urban background site in Vienna (5.9 -7.5 at 637 nm).*"

- I'm not sure, if it is interesting that 'BC is historically defined from aethalometer measurements at 880nm'. The important message should be that the whole spectral de- pendence approach depends on fixation somewhere. This is done at 880nm because it is believed that at that wavelength the MAC for wood burning and fossil fuel combustion is very close. Otherwise the DEC MAC cannot be applied at NOA. The whole fractitioning is based on the wavelength dependence that is somewhere fixed (Equation 10). The reader should be convinced of the choice that is supported by literature.
  - o A11: The following sentence was added in the revised manuscript:
  - o P3L40: "*At 880 nm, no significant difference in MAC at 880 nm between eBC originating from traffic or wood-burning emission is expected (Zotter et al., 2017)*"

- It is written '(MAC): : :. (determined from the comparison with concurrent measurements at DEM of elemental carbon)'. A bit later a reference to Diapouli et al. (2014) is included. Does this paper include the 7.5 m2 g-1? .
  - o A12: The paper of Diapouli et al. (2014) does not include absorption measurements, therefore no MAC value is presented. As indicated in the manuscript, the paper of Diapouli et al. (2014) includes an extensive description of EC/OC measurements at DEM.

- The angstrom exponent for absorption is measured why do the authors assume an exponent of 1.0 in line 6 (p4)?
  - o A13: As the reviewer mentions the absorption exponent is measured for both sites and exhibits spatial and temporal variability, with an average value superior to 1. However, this conventional value of 1 is used only at this point of the manuscript, where the scaling of the MAC calculated in this analysis based on the 880 nm wavelength absorption values, is needed to compare with the Zannata et al. 2016 paper, where MAC values from different sites were adjusted to 637 nm assuming an absorption Ångstrom exponent of 1.0.

2.2.2 Carbon monoxide and nitrogen oxides
- Page 4-5, BC and CO source apportionment: please discuss here possible interference from coal combustion emissions
  - o A14: Added in the manuscript, P5L18: "*It should also be noted that coal-burning organic aerosol is known to significantly absorb light at near UV wavelengths (Yang et al., 2009) and may thus interfere with $b_{abs}(λ_{UV})_{wb}$. Lignite coal is the single most important local energy source in Greece (Kavouridis, 2008). However, interferences from coal use are expected to be very low, as the lignite-fired power plants are located far away from Athens (>200 km distance).*"

2.3 Source apportionment of black carbon from fossil fuel and wood burning combustion.
- P4 line21 Reference to Sandradewi (please include the correct one in references).
  - o A15: Added

- Page 5, BC source apportionment: please justify/discuss a bit more the choice of _wb = 2 by comparison with value recently proposed by Zotter et al., 2017.
- Sandradewi discussed different Angstrom exponents depending on the chosen wavelengths. This wavelength dependence should be discussed in light of the choices given in line 32, or refer to other studies that use same wavelengths. The 470 nm channel was broken in that Sandradewi study, why does this study start at 470 nm (line 32) P5 top para. Exponents 0.9 (traffic) and 2.0 (wood) 'were used, based on the range of values.. reported'. The value of 2.0 is disqualified by Zotter et al., 2017, because is leads to differences with radiocarbon results. The exponents are crucial to the method,'based on' should be worked out.
  - o A16: In a previous study using the aethalometer model at DEM (Diapouli et al., 2017), calculations were made for different values of a_{wb}, in the range 1.1–3.0, by a step of 0.1. In order to identify an acceptable range of values for a_{wb}, the calculated babs(950)ff were correlated with NOx data, which are mainly related to fossil fuel combustion emissions. Values of a_{wb} below 1.7 produced either no correlation or weak correlations and were therefore not considered acceptable values (Pearson coefficients below 0.7). On top of that, during fire events, values of angstrom exponent up to 2 have been observed at DEM (Figure 3). We expect therefore that angstrom exponent from biomass burning to be at least as high as 2. In view of these results, a_{wb}=2 has been selected for the study. Discussion about the choice of a_{wb} has been added in the revised manuscript.
  - o P5L7-20: "*The application of the model requires the selection of suitable Ångström exponents for fossil fuel ($α_{ff}$) and wood burning ($α_{wb}$), since one of the greatest uncertainties of the model is associated with the a priori assumed α values for both types of emissions. Reported Ångström exponents range between 0.8-1.1 for pure traffic. For wood burning a wider range of values has been observed (0.9-3.5), even though αwb equal to 2.0 has long been considered a typical value for wood burning aerosol (Favez et al., 2009; Fuller et al., 2014;*

12

Herich et al., 2011; Petit et al., 2014; Sciare et al., 2011). Recently, Zotter et al., (2017) recommended to use αff=0.9 and αwb=1.68, obtained by fitting the model outputs (calculated with the absorption coefficients at 470 and 950 nm) against the fossil fraction of EC derived from 14C measurements. At DEM site, a previous study showed that values of awb below 1.7 were not appropriate for the specific site (Diapouli et al., 2017). On top of that, during fire events, Ångström exponent values up to 2 have been observed at DEM. Taking into consideration these results, absorption Ångström exponents of 0.9 and 2.0 for pure traffic (αff) and wood burning (αwb), respectively, were used.in this study"

- o *P4L36-39 "Even though different pairs of near-UV and near-IR wavelengths can be used, it is recommended to use the pair 470 nm versus 950 nm. The choice of 470 against 370 is even more critical as explained in Zotter et al (2017) since interference of VOCs or other absorbing non-BC particles can interfere with measurements with the 370 nm channel of aethalometer."*
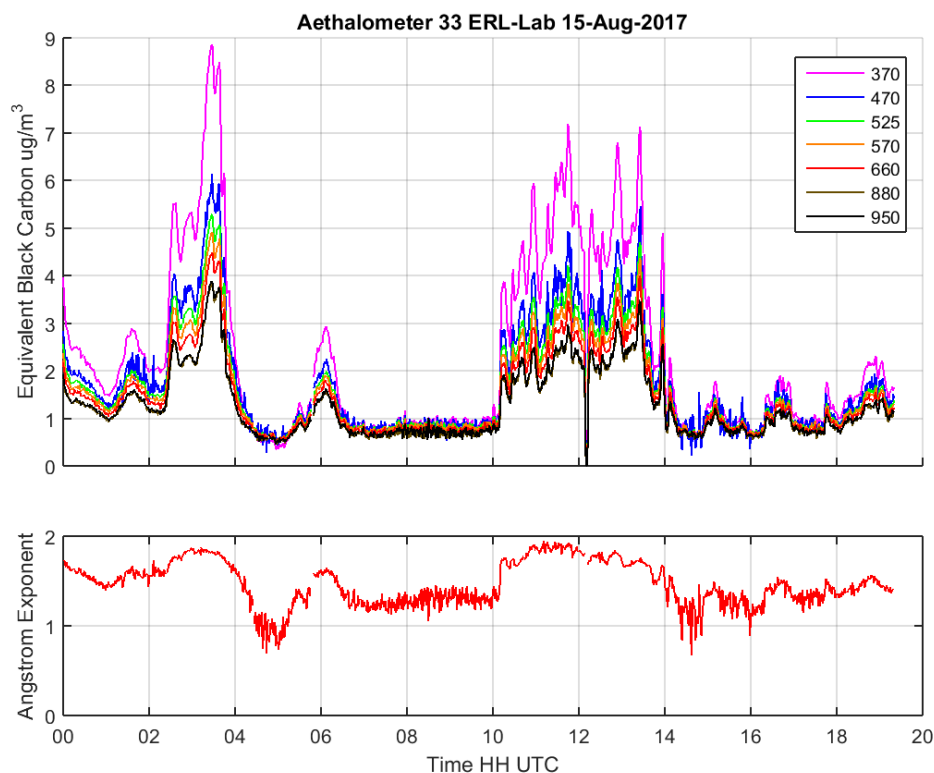

Figure 3 eBC and angstrom exponent measured at DEM station during summer forest fires.

2.4 Source apportionment of carbon monoxide from fossil fuel and wood burning combustion
2.4.2 Model 2: CO BCwb BCff multiple linear regression model   6

- P6 line 20 'the hypothesis of negligible photochemical chemistry is validated.' Where is it validated please include reference(s). Negligible what does that mean, negligible for the scale considered in this study? Or is the assumption that BC and CO have similar lifetimes? This para needs to be worked out to convince the reader that model2 is superior to model 1.
  - o A17, P6L36 "The sentence was corrected to "*the hypothesis of negligible photochemical chemistry is met for the time scale considered in this study*"

3. Results and Discussion
3.1 Levels and diurnal variations of black carbon and carbon monoxide

- Page 6, line 36 - Page 7, line 7: the expected diurnal cycle of the intensity of emissions could be discussed more deeply here.
  - o A18: Added in the manuscript P7L14: *Based on traffic volume data (Grivas et al., 2012), a first peak in the emissions from transportation is expected around 08:00 when people commute to work, followed by a plateau from 08:00-18:00, and a secondary peak until 21:00, after when traffic is decreasing. Wood burning emissions from residential heating are expected to increase during the evening, when temperatures drop and people are back-home.*

3.2 Source apportionment of BC and diurnal variability   7

- Page 7 line 9 'eBC in PM2.5' but at NOA a PM10 sampling head is installed, right?
  - o A19: This information has been corrected on the revised manuscript.

- Page7 line 11. Apparently the 1.25 percentile of a dataset can be used for background. Really would like to read that paper. Please include Kondo et al., 2006 in the references

13

- A20: p7L32,We have added the reference to the paper of (Kondo et al., 2006), that investigated temporal variations of elemental carbon in Tokyo. The same approach was used in (Verma et al., 2010) for determining the BC background concentration of black carbon in Guangzhou, China.

- P7L14 'relatively short lifetime of BC' please compare to P6L20
    - A21: We agree that there was a contradiction between statement in P7L14 and P6L20. In P6L20 we wanted to point out that both CO and BC are not chemically reactive, whereas in P7L14 we were referring to deposition losses. In order to avoid any misunderstanding we removed the sentence "*relative short lifetime*" in p7 l14.

- P7L34 how is the relative standard deviation defined in this case.
    - A22: It is defined as the interval of confidence in the coefficient values (slope and intercept) of the linear regression as calculated by Igor Pro software. The values are automatically calculated for each fitting.

- P7L39 '0.184' please include units if appropriate
    - A23: P8L19: Added

3.3.1 Using BCwb and BCff as tracers of fossil fuel and wood burning sources   7

- P8L4 the value 0.00137 is 0.7% of the best estimate 0.184. This is very small compared to values in Table 2. Please include discussion.
    - A24: 0.00137 is the standard deviation of the r_{ff} coefficient given from the multiple regression fitting for DEM station. This is very small compared to the range of values found in the literature (and given in Table 2) that have been calculated using different methodologies and for different type of transport fleet (size distribution and age of vehicle fleet, fuel consumption, environmental performance etc.). We assume that DEM and NOA experience similar vehicle fleet mix, and this is the reason why, the regression model was run for NOA using a fixed r'_{ff} according to values found in DEM station (and not based on the literature, P8L22). As a result, the error estimation of r_{ff} was made based on the standard deviation of the model for DEM, and not on values from the literature.

- Why is 0.00137 an useable value and why is the resulting uncertainty of 25% for the emission ratio 'rather reasonable' (not scientific terminology)
    - A25: 0.00137 was the uncertainty calculated for DEM station. When fixing r'_{ff} at NOA, we did a sensitivity analysis using r'_{ff} values ranging from the lowest (0.184-0.00137) to the highest (0.184+0.00137) around the determined r'_{ff}, and the resulting r'_{wb} variated as much as 25%. We corrected the uncertainty in eq.21 and removed the statement "can be considered rather reasonable" from the revised manuscript.

- P8L13 background or intercept values are 109 and 147 how do these differences related to 'cannot differ significantly' line 1 of this page?
    - A26: Considering a uniform/similar vehicle fleet in terms of type of vehicle and driving patterns, the **emission ratio** between BC/CO from traffic should not differ. However, absolute <u>concentrations</u> of CO vary between the urban and suburban sites.

- P8L14 background concentrations of CO with a reference to Goldstein and Schade (2000), this work contains some informations on background but not on CO. Howshould the reader interpret the reference, please modify.
    - A27: The reference was about background estimation using regression's intercept values. In order to avoid any confusion, we removed the reference

- P8L14etc The resulting background concentration are in very good agreement with : : :1.25 percentile. Really want to learn more. For me it sounds like abracadabra.
    - A28: The estimation of background using the 1.25 percenrtile of an extended long term dataset of atmospheric concentration has been documented in previous studies with good results (Kondo et al., 2006; Verma et al., 2010). It is based on the fact that within the observed variability the minimum values of the dataset represent what we can consider background levels for this environment. It is meaningful to consider here.

- Page 8, line 25 (% COwb): please discuss these percentage regarding previous studies/results.
  A29: While there have been numerous studies in the last years investigating the contribution of different sources to black carbon surface concentrations, similar studies are very limited for carbon monoxide. Saurer et al., (2009) used the stable isotope composition of CO (δ^{13}C and δ^{18}O) for the characterization of different CO sources at 3 sites in Switzerland during winter (along with other indicators for traffic and wood combustion such as NO_x-concentration and aerosol light absorption at different wavelengths) and estimated the wood burning contribution to night-time CO concentrations at 70%, 49% and 29% for a village site dominated by domestic heating, a site close to a motorway and a rural site respectively. These differences reflect the spatial variability in the wood burning use within the same region depending on the type of site, as well as between countries depending on the country and the heating practices. This discussion is added in the revised manuscript (P9L13-18).

3.3.2 Comparison the CO BCwb BCff linear model vs the CO NOx linear model   8

- P8L41 'using a best fit line' If this is a fit how was the data selected? This was not clear from the references literature.
    - A30: In the reference literature there are no explanation on the methodology used to draw these two slopes. In this study, in order to o draw the minimum and maximum slopes, the 10th percentile and 90th percentile of (CO-CObgd)/NOx ratio have been calculated. To draw the minimum slope, fitting was applied for data where

CO/NOx ratio was below the calculated 10th percentile. To draw the maximum slope, fitting was applied to data where CO/NO$_X$ ratio was above the calculated 90th percentile. However, these fitted lines are just indicative of the expected range of values of CO/NOX ratios for each emission source. This information has been added in the revised manuscript (P9L29).

- P9Line4 informs us that the ratio is larger than : : :please explain
  - A31: Wood burning lines from figure 11, exhibit slopes of 20 and 25. However we do not expect to have 100% contribution of wood burning at any time of the day. We can therefore estimate that r$_{wb}$ is superior to both these values. Modifications in the manuscript: "*Nevertheless, based on "wood burning" lines from Fig. 11, and assuming that emission ratios from wood burning are similar between NOA and DEM, we estimate a r$_{wb}$ ratio for the area of Athens, larger than 25 ppbv ppbv 1.*"

- P9L9 'values found in the literature' please include references
  - A32: We removed the sentence 'values found in the literature'. The references are given in the following sentence.

- P9L10 2-3% where should I look to see the supporting material?
  - A33: An additional column in Table 4 with the COwb% resulting from the sensitivity analysis test has been added in the revised manuscript.

4. Conclusion
- Page 9, line 25-26: here, it sounds like wind speed is controlling the diurnal patterns. Please consider rephrasing this sentence.
  - A34: Modified in the manuscript: *"Both BC and CO displayed a clear bimodal diurnal pattern, in which morning peaks were observed due to morning inversion and rush-hour traffic, while evening peaks were attributed to combustion sources (evening traffic rush-hour, residential heating) combined with the effects of a shallow nocturnal boundary layer. Highest concentrations were observed during low wind speeds, suggesting that both combustion products were not related to regional transport but instead originated from sources within Athens."*

Acknowledgements
References

- Figure axes: please homogenize the use of "BC" / "eBC".
  - A35: Corrected

- Figure 7, right panel: legend of the y-axis seems inaccurate
  - A36: Corrected

- Table 4 Regression Slope between model 1 and model 2: what model outcomes are regressed? Are we looking at COwb/totalCO?
  - A37: Yes, this information is added in the Table

- Typos-suggestions P3 line26 'this purpose' ! for loading compensation (corrected), P4 L9 ratios were (corrected) , P4 line 25 lambda is bold (corrected) in equation P4 eq 5 lambda1 should be lambda2 in Denominator (corrected). P7L40 last ff should be sub (corrected), P8L28 diurnal variabilities : : :are (corrected),Comparison of A and B Figure 7 caption or axis titles are wrong for right bottom figure (corrected)

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Assessment of wood burning versus fossil fuel contribution to wintertime black carbon and carbon monoxide concentrations in Athens, Greece

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Abstract

The scope of this study was to estimate the contribution of fossil fuel and wood burning combustion to black carbon (BC) and carbon monoxide (CO) during wintertime, in Athens. For that purpose, in-situ measurements of equivalent Black Carbon (eBC) and CO were simultaneously conducted in a suburban and an urban background monitoring site in Athens during three months of winter 2014-2015. For the deconvolution of eBC into eBC emitted from fossil fuel (BC_{ff}) and wood burning (BC_{wb}), a method based on the spectral dependency of the absorption of pure black carbon and brown carbon was used. Thereafter, BC_{wb} and BC_{ff} estimated fractions were used along with measured CO concentrations in a multiple regression analysis, in order to quantify the contribution of each one of the combustion sources to the ambient CO levels. For an independent evaluation of the results, we additionally estimated the wood-burning and fossil fuel contribution to CO, calculated on the basis of their CO/NO_x emission ratios. The results indicate that during wintertime BC and CO are mainly emitted by local sources within the Athens Metropolitan Area (AMA). Fossil fuel combustion, mainly from road traffic, is found to be the major contributor to both eBC in $PM_{2.5}$ and CO ambient concentrations in AMA. However, wintertime wood burning makes a significant contribution to the observed eBC (of about 30%) and CO concentrations (on average, 11 % and 16 % of total CO in the suburban and urban background sites respectively). Both, BC and CO from biomass burning (BC_{wb} and CO_{wb}, respectively) present a clear diurnal pattern with highest concentrations during night, supporting the local domestic heating as their main source.

1 Introduction

Air pollution, which is originating largely from combustion processes, is a very important environmental concern in Athens, like in other large urban agglomerations around the world. High population (3.75 million in the metropolitan area) and the confinement of commercial and industrial activities in a relatively small area (approximately 450 km^2), has led to severe environmental degradation. Over the years high loadings of atmospheric pollutants have been documented (Chaloulakou et al., 2005; Eleftheriadis et al., 1998, 2014; Kalabokas et al., 1999; Theodosi et al., 2011). Combustion processes used for transportation, power generation and other human activities produce a complex mixture of chemical pollutants (Cohen et al., 2004), which at any given location have characteristics depending on the relative contributions of the different sources of pollution and on the effects of the local geo-climatic factors. Black carbon (BC) aerosol and carbon monoxide (CO) are two major products of incomplete combustion and are important atmospheric components because of their substantial impact on

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health (Ostro et al., 2015), including respiratory and cardiovascular effects, as well as on climate (Zanatta et al., 2016). BC refers to the absorbing components of soot and is the second most significant contributor to climate change (Andreae and Gelencsér, 2006; Bond et al., 2013). On the other hand, CO strongly influences the oxidative capacity of the atmosphere (by reacting with the OH radicals), and thereby alters the lifetime of methane and other greenhouse gases (Seinfeld and Pandis, 2012). The potential adverse health and climate effects associated with exposure to high levels of BC and CO, motivates a thorough characterization of their emission from different sources. In urban environments, fossil fuel combustion is the major source of BC and CO, mainly related to motor vehicle exhausts. However, biomass combustion, from forest fires (especially in summer; Diapouli et al., 2014), or from domestic heating (in winter) may also contribute significantly to their ambient levels. Improvement of air quality in Athens after measures adopted during the last decades are described by Kanakidou et al. (2011) and are in line with proposed mitigation strategies (Aleksandropoulou et al., 2012). Vrekoussis et al. (2013) used satellite observations over Athens for NO_2 and SO_2, to show that the economic crisis resulted in acceleration of the reduction of air pollutants in Athens. In the recent years, a resurgence in the use of biofuels over more expensive fuels for heating has been observed in Europe (Denier van der Gon et al., 2015; Gonçalves et al., 2011), especially in Greece where the economic crisis has tripled the fossil fuel cost in a few years (Saffari et al., 2013). The technology of domestic wood burning in Athens is known to suffer from low burning efficiency. The extensive use observed in recent years resulted in considerable emissions of incomplete combustion, i.e. CO, hydrocarbons and soot particles during cold months. Paraskevopoulou et al.(2015), reported the impact of wood combustion (dominant fuel for domestic heating) on air quality in Athens, as an almost 30 % increase of the contribution of particulate organic matter to the urban aerosol mass, from winter 2012 to winter 2013. At the same time, a long term analysis of EC concentrations in Athens (Paraskevopoulou et al., 2014) revealed a significant increase in wintertime EC in the period 2011-2013. Respectively, a significant increase in winter evening CO level has been reported for the period 2012-2015 by Gratsea et al., (2017) and attributed to the increase in wood burning use. On the other hand, during summertime a consistent decrease is encountered in the last decade as a result of the simultaneous reduction in traffic and industrial activity due to the economic crisis in Greece (Diapouli et al., 2017b).

Even though biomass burning from domestic heating has been recognized as a main source of atmospheric pollutants in Southern Europe (Denier van der Gon et al., 2015; Giannoni et al., 2012; Gonçalves et al., 2011; Paglione et al., 2014; Saffari et al., 2013) emission estimates are still scarce and the associated uncertainty remains high. This is because wood consumption statistics are difficult to obtain since wood is often non-commercial and emission factors vary greatly with wood type, combustion equipment and flame temperature. As a matter of fact, reported emission factors of PM for different types of residential combustion appliances range between 10-2000 mg per MJ (Mega Joule) of fuel burnt (Kocbach Bølling et al., 2009). In a similar way, CO emission factors from fireplaces and traditional or eco-labelled woodstoves range typically from 30-120 g kg^{-1} (ratio of the mass of CO emitted related to the mass of the burnt fuel) (AIRUSE, 2015). The spatial variability of the carbonaceous aerosol pollutants is also of great interest with respect to the health impacts of their major contributing sources in the urban PM_{10}.

In this context, the scope of the present study is to investigate, based on ambient measurements, the impact of biomass burning versus fossil fuel use on the air pollution observed in Athens during wintertime. For that purpose, three-months of continuous and simultaneous measurements of equivalent Black Carbon (eBC) by aethalometers and CO at a suburban and an urban background site of Athens were analyzed and compared. The measured eBC was deconvoluted into two fractions using a model based on the different spectral dependencies of light absorption by pure black carbon (related to fossil fuel) and brown carbon (linked to wood-burning emissions) (Sandradewi et al., 2008). For simplicity we refer to these light absorbing carbon fractions as "BC" with an additional index for specifying the wood burning (BC_{wb}) or fossil fuel (BC_{ff}) origin. Two independent methods based on the relations between CO and co-products of combustion processes were used and compared for the estimation of CO originated from traffic and wood combustion.

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2 Material and Methods

2.1 Sampling Sites

Simultaneous measurements of eBC and CO were performed at the National Center of Scientific Research (NCSR) Demokritos (DEM) and at the National Observatory of Athens (NOA), from December 6th 2014 until March 10th 2015 (Figure 1). The
5 campus of Demokritos is situated at the foot of Mount Hymmettus in Aghia Paraskevi and covers an area of 600 acres in a forest of pine trees. Situated at 7 km NNE from Athens centre (Triantafyllou et al., 2016), the GAW-Demokritos measurement station (37.99 N, 23.82 E, 270 m a.s.l) is considered representative of the suburban areas of the Athens Metropolitan Area (AMA). NOA's station is located at its central premises at Thission, in the center of Athens and on the top of Nymphs Hill (38.0 N, 23.7 E, 107 m a.s.l.). Its central setting, still relatively far (further than 500 m) from main traffic lines, can be
10 considered ideal for monitoring the air pollution urban background of Athens.

2.2 Measurements of aerosol light absorption and carbon monoxide

2.2.1 Aerosol light absorption and equivalent black carbon

The aerosol light absorption coefficient, b_{abs}, was retrieved at each station by means of a 7-wavelength (370, 470, 520, 590, 660, 880 and 950 nm) aethalometer (Magee Scientific Corp., Berkeley, CA 94703, USA) with a 5-min temporal resolution. At
15 DEM, the new generation AE33 aethalometer model was used, which provides a real-time compensation for multiple scattering in the filter matrix and loading effects using the DualSpot Technology® (Drinovec et al., 2015). The AE33 sampled aerosol through a PM$_{2.5}$ cut-off inlet. At NOA, a Portable Aethalometer® Model AE42 was used and aerosol sampling was performed with no size-cut. As BC mainly contributes to PM$_1$ (Laborde et al., 2013; Wang et al., 2015), differences in the eBC concentrations due to the different aerodynamic diameters of sampled aerosols are expected to be negligible. Raw absorption coefficients at a given wavelength
20 λ ($b_{aeth,\lambda}$) from AE42 dataset were corrected from loading and scattering effects following the procedure introduced by Weingartner et al. (2003).

$$b_{abs,\lambda} = \frac{b_{ATN,\lambda}}{C_0 \times R(ATN)_\lambda} \tag{1}$$

$$R(ATN)_\lambda = \left(\frac{1}{f_\lambda} - 1\right) \times \frac{\ln(ATN_\lambda) - \ln 10}{\ln 50 - \ln 10} + 1 \tag{2}$$

As described in Eq. (1), a C_0 constant was used to correct for multiple scattering by the filter fibers and the scattering of the
25 aerosols embedded in the filter, whereas a $R(ATN)$ function enabled to compensate the loading effect, i.e. the fact that the attenuation increases as light absorbing particles accumulate in the filter (Eq. (2)).The value of 3.5 was used for C_0 as recommended in Zanatta et al., (2016). The compensation parameter f_λ is a parameter that mainly depends on the single scattering albedo of aerosol (SSA). Since no simultaneous scattering coefficient measurements were available during this campaign, f_λ values given in Drinovec et al.(2015) for an urban site with a single scattering albedo of about 0.75 were used for
30 loading compensation at the urban background site.

In order to investigate systematic differences between the processed outputs by the two types of instruments, an inter-comparison exercise was performed between data from the new generation AE33-aethalometer compensated in real-time, and data from an AE31-Aethalometer (with identical measurement configuration and settings to the AE42) which operates continuously in parallel with the AE33 at DEM station. A two-month period of data was found reasonable for this exercise with
35 AE31 data compensated by post-processing using the Weingartner algorithm (N=8784). The results indicated a very good agreement between the absorption measurements from the AE33 and AE31 instruments after compensation, with R^2=0.79, a small intercept of -0.15 (Mm^{-1}) and a slope of 0.97.

Eventually, aerosol light absorption coefficients were converted into mass concentration of the equivalent BC (eBC) as defined by Petzold et al. (2013). BC is historically defined from aethalometer measurements at 880 nm. At 880 nm, no significant

difference in MAC at 880 nm between eBC originating from traffic or wood-burning emission is expected (Zotter et al., 2017). eBC mass concentration was derived in this study by multiplying the b_{abs} coefficient at 880 nm with a constant value of mass absorption cross-section (MAC) of 4.6 m^2 g^{-1}(determined from the comparison with simultaneous measurements at DEM of elemental carbon). An extensive description of EC/OC measurements at DEM is available in Diapouli et al. (2014). Assuming

5 an absorption Ångstrom exponent of 1.0, the MAC used here is 6.13 when adjusted to 637 nm. Our MAC value is at the lower limit of the values reported by Zanatta et al., (2016), for nine rural background stations across Europe (7.5-13.3 m^2 g^{-1}, calculated for 637 nm), and within the range of values reported by Hitzenberger et al., (2006) for an urban background site in Vienna (5.9 -7.5 at 637 nm).

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10 **2.2.2 Carbon monoxide and nitrogen oxides**

Ambient CO mixing ratios were measured at DEM station at a time resolution of 1 Hz using a Cavity Ring-Down Spectroscopy analyzer (Model G2401, Picarro, CA, USA), which provides high resolution and low detection limit CO, CO$_2$ and CH$_4$ ambient mixing ratios in line with GAW standards. Air was pulled through a 5-m line at about 0.4 L min^{-1}, and water was removed from the sample using a Nafion^{TM} copolymer membrane dryer (http://www.permapure.com/resources/all-about-nafion-and-faq/). CO

15 measurements were obtained with a typical precision (one sigma) of about ±4 ppbv in a 1-s measurement for concentrations ranging between 75 and 300 ppbv. Additionally, hourly measurements of NO$_x$ were available from the monitoring station of the Greek Ministry of Environment and Energy (www.ypeka.gr) situated 300 m from DEM station.

CO and NO$_x$ were determined at the NOA station with a 1-min, integration time using a Horiba APMA-360 series automatic gas analyser (NDIR technique, scale: 0-20 ppmv, lower detectable limit: 0.05 ppmv) and a Horiba APNA-360 series

20 (chemiluminescence technique, scale: 0-1000 ppbv, lower detectable limit: 0.5 ppbv) respectively.

2.3 Source apportionment of black carbon from fossil fuel and wood burning combustion.

Source apportionment of the ambient BC concentrations was based on the method developed by Sandradewi et al. (2008) and successfully applied in several studies (Favez et al., 2009; Fourtziou et al., 2017; Fuller et al., 2014; Petit et al., 2014; Sciare et al., 2011). This model relies on the first assumption that the total absorption at a wavelength λ, $b_{abs}(\lambda)$, is a combination of

25 absorption due to fossil fuel ($b_{abs}(\lambda)_{ff}$) and wood burning ($b_{abs}(\lambda)_{wb}$) aerosols:

$$\boldsymbol{b_{abs}(\lambda)} = \boldsymbol{b_{abs}(\lambda)_{ff}} + \boldsymbol{b_{abs}(\lambda)_{wb}} \ , \tag{3}$$

Secondly, it is based on the difference in the dependency of the absorption coefficient on wavelength assuming that absorption from fossil fuel and biomass burning emissions follow different spectral dependencies. The wavelength dependent absorption of light b_{abs} by aerosols is proportional to $\lambda^{-\alpha}$ where α is the absorption Ångström exponent such that:

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$$\frac{b_{abs}(\lambda_1)_{ff}}{b_{abs}(\lambda_2)_{ff}} = \left(\frac{\lambda_1}{\lambda_2}\right)^{-\alpha_{ff}} \ , \tag{4}$$

And respectively:

$$\frac{b_{abs}(\lambda_1)_{wb}}{b_{abs}(\lambda_2)_{wb}} = \left(\frac{\lambda_1}{\lambda_2}\right)^{-\alpha_{wb}} \ , \tag{5}$$

Light absorption measurements at $\lambda_1 = 470 \ nm \ (UV)$, and $\lambda_2 = 950 \ nm \ (IR)$ are used in this approach due to the fact that when compared to BC from fossil fuel combustion (BC$_{ff}$), wood burning aerosols (BC$_{wb}$) exhibit greater absorption in the near

35 ultraviolet. This enhanced absorption at near UV for wood burning aerosols is due to the presence of absorbing organic molecules, especially polycyclic aromatic hydrocarbons and humic-like substances (Hoffer et al., 2006). Even though different pairs of near-UV and near-IR wavelengths can be used, it is recommended to use the pair 470 nm versus 950 nm. The choice of 470 against 370 is even more critical as explained in Zotter et al (2017) since VOCs or other absorbing non-BC particles can interfere with measurements with the 370 nm channel of aethalometer. By solving equations 2-5, unique values of $b_{abs}(\lambda_{UV})_{wb}$,

40 $b_{abs}(\lambda_{IR})_{wb}$, $b_{abs}(\lambda_{UV})_{ff}$ and $b_{abs}(\lambda_{IR})_{ff}$, can be calculated, thus leading to the determination of BC$_{wb}$ and BC$_{ff}$:

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$$b_{abs}(\lambda_{UV})_{wb} = \frac{1}{1-\left(\frac{\lambda_{UV}}{\lambda_{IR}}\right)^{-\alpha_{ff}} * \left(\frac{\lambda_{UV}}{\lambda_{IR}}\right)^{\alpha_{wb}}} \times \left(b_{abs}(\lambda_{UV}) - \left(\frac{\lambda_{UV}}{\lambda_{IR}}\right)^{-\alpha_{ff}} * b_{abs}(\lambda_{IR}) \right), \tag{6}$$

$$b_{abs}(\lambda_{IR})_{wb} = \left(\frac{\lambda_{UV}}{\lambda_{IR}}\right)^{\alpha_{wb}} * b_{abs}(\lambda_{UV})_{wb} , \tag{7}$$

$$b_{abs}(\lambda_{UV})_{ff} = b_{abs}(\lambda_{UV}) - b_{abs}(\lambda_{UV})_{wb}, \tag{8}$$

$$b_{abs}(\lambda_{IR})_{ff} = b_{abs}(\lambda_{IR}) - b_{abs}(\lambda_{IR})_{wb} , \tag{9}$$

$$BC_{ff} = \frac{b_{abs}(\lambda_{IR})_{ff}}{b_{abs}(\lambda_{IR})} \times EBC , \tag{10}$$

$$BC_{wb} = EBC - BC_{ff} , \tag{11}$$

The application of the model requires the selection of suitable Ångström exponents for fossil fuel (α_{ff}) and wood burning (α_{wb}), since one of the greatest uncertainties of the model is associated with the a priori assumed α values for both types of emissions. Reported Ångström exponents range between 0.8-1.1 for pure traffic. For wood burning a wider range of values has been observed (0.9-3.5), even though α_{wb} equal to 2.0 has long been considered a typical value for wood burning aerosol (Favez et al., 2009; Fuller et al., 2014; Herich et al., 2011; Petit et al., 2014; Sciare et al., 2011). Recently, Zotter et al., (2017) recommended to use α_{ff}=0.9 and α_{wb}=1.68, obtained by fitting the model outputs (calculated with the absorption coefficients at 470 and 950 nm) against the fossil fraction of EC derived from 14C measurements. At DEM site, a previous study showed that values of a_{wb} below 1.7 were not appropriate for the specific site (Diapouli et al., 2017a). On top of that during fire events, Ångström exponent values up to 2 have been observed at DEM. Taking into consideration these results, absorption Ångström exponents of 0.9 and 2.0 for pure traffic (α_{ff}) and wood burning (α_{wb}), respectively, were used in this study.

It should also be noted that coal-burning organic aerosol is known to significantly absorb light at near UV wavelengths (Yang et al., 2009) and may thus interfere with $b_{abs}(\lambda_{UV})_{wb}$. Lignite coal is the single most important local energy source in Greece (Kavouridis, 2008). However, interferences from coal use are expected to be very low, as the lignite-fired power plants are located far away from Athens (>200 km distance).

2.4 Source apportionment of carbon monoxide from fossil fuel and wood burning combustion

The partitioning of CO ambient concentrations into different sources has been investigated in a limited number of studies and was mainly based on the variable isotopic composition of CO (Gros et al., 2002; Kato et al., 1999; Saurer et al., 2009). In the absence of isotopic analysis, we use two different models for the source apportionment, based on the correlations between CO and other combustion tracers.

2.4.1 Model 1: the CO-NO$_x$ linear model.

The CO/NO$_x$ ratio has been used in the past as a diagnostic to characterize different type of emission sources (Fujita et al., 1992; Ravindra et al., 2006; Saurer et al., 2009; Wahlina et al., 2001). It can serve as a useful tool for apportioning CO concentrations at monitoring stations part of national networks where only regulated air pollutants are often measured. The CO-NOx linear model, introduced by Saurer et al. (2009), relies on the fact that both CO and NO$_x$ are common products of combustion processes. Assuming that the only significant combustion processes in urban environments are traffic and wood burning for residential heating (in addition to the regional background, and a minor contribution by industrial processes), the concentrations of NO$_x$ and CO can be expressed as:

$$[NO_x] = [NO_x]_{bgd} + [NO_x]_{ff} + [NO_x]_{wb} , \tag{12}$$

$$[CO] = [CO]_{bgd} + [CO]_{ff} + [CO]_{wb} , \tag{13}$$

where $[X]_{ff}$, $[X]_{wb}$ represent the concentration of the tracer X resulting from fossil fuel (mainly traffic) and wood-burning, respectively, whereas $[X]_{bgd}$ represent the background concentration of X.

The CO-NO$_x$ linear model is based on the distinct CO/NO$_x$ ratios for the two emission sources, where the wood-burning emission ratio, r_{wb}, is much larger than the one for traffic, r_{ff}. Considering that photochemical processes do not substantially affect the ambient concentrations of CO and NO$_x$ in winter, the ratios of the concentrations can be regarded as approximately the same as their respective emission ratios, $[CO]_{ff}/[NOx]_{ff} \approx r_{ff}$ and $[CO]_{wb}/[NOx]_{wb} \approx r_{wb}$. Based on this assumption, we can consider that r_{ff} and r_{wb} are given, and as a consequence Eq. (12) can be rewritten as:

$$[NO_x] = [NO_x]_{bgd} + \frac{[CO]_{ff}}{r_{ff}} + \frac{[CO]_{wb}}{r_{wb}}, \tag{14}$$

Equations 13 and 14 allow $[CO]_{ff}$ and $[CO]_{wb}$ to be determined. The concentration of CO originating from wood burning emissions can be expressed as:

$$[CO]_{wb} = \frac{r_{wb}}{r_{ff}-r_{wb}} \times \left[[CO]_{bgd} - [CO] + r_{ff}([NO_x] - [NO_x]_{bgd}) \right], \tag{15}$$

Defining the emission ratios r_{wb} and r_{ff} is a crucial step for the source apportionment of CO. The methodology used for their selection is presented in section 3.3.2

It is important here to mention the limitations of this model for CO apportionment. Firstly, it requires an *a priori* knowledge of the emission ratios r_{ff} and r_{wb}. Secondly, it is based on the hypothesis that the CO/NO$_x$ ratio remains constant, while in fact it could be affected by photochemistry. CO is a long-lived species with an atmospheric lifetime of several days to several weeks; hence photochemical processes influence CO concentrations on a limited extent. In contrast NO$_x$, are much more reactive species. Consequently, any change in reactive nitrogen compounds, mainly by photochemistry, would alter the CO/NO$_x$ ratio.

2.4.2 Model 2: CO-BC$_{wb}$-BC$_{ff}$ multiple linear regression model

The second model for CO source apportionment is based on the existing relation between the concentrations of CO and BC, introducing advantages in order to overcome the limitations of the previously presented CO-NO$_x$ linear model.

In a similar manner to model 1, considering both CO and BC exclusively produced by combustion processes and that in the urban environment the CO/BC ratios can be regarded as equivalent to their source emission ratio, the CO concentration can be expressed as:

$$[CO] = [CO]_{bdg} + r'_{ff} \times [BC]_{ff} + r'_{wb} \times [BC]_{wb}, \tag{16}$$

where $r'_{ff} = [CO]_{ff}/[BC]_{ff}$, and $r'_{wb} = [CO]_{wb}/[BC]_{wb}$ the relevant emission ratios at the source. The difference of our approach in this second model resides in the way that this equation is solved. Unlike the CO-NO$_x$ linear model, here *a priori* knowledge of r_{wb} and r_{ff} emission ratios is not required. Instead, BC$_{ff}$ and BC$_{wb}$ are known variables (determined previously using the method presented in section 2.2), and r'_{ff} and r'_{wb} can be calculated by a multiple linear regression model applied on Eq. (16).

Using r'_{ff} and r'_{wb} resulting from the model, the concentration of CO attributed to fossil fuel and wood burning sources can be estimated such that:

$$CO_{ff} = r'_{ff} \times [BC]_{ff}, \tag{17}$$

and,

$$CO_{wb} = r'_{wb} \times [BC]_{wb} \tag{18}$$

Moreover, the hypothesis of negligible photochemical chemistry is met for the time scale considered in this study and for the long-lived species BC and CO, and therefore should not have a significant impact on their ambient ratio.

While multiple linear regressions are known techniques for source apportionment, they have not yet been applied to investigate wood burning contribution to CO using the aethalometer's model results. The considerable increase in measurements carried out using aethalometers makes this technique an interesting and very useful methodology for apportioning CO concentrations.

3. Results and Discussion

3.1 Levels and diurnal variations of black carbon and carbon monoxide

Statistical summary of eBC and CO levels at NOA and DEM stations, as well as their respective time series are displayed in Table 1 and Fig. 2, respectively. Median eBC and CO levels were, respectively, 2.3 and 1.7 times higher at NOA station compared to DEM station. In particular, on days with stagnant atmospheric conditions (low wind speed), concentrations of both combustion tracers were up to 10 times higher at NOA compared to DEM. During days with more turbulence, the levels of eBC and CO were similar at both stations, as a result of intensive mixing and uniform horizontal pollutants' dispersion in the Athens valley. As shown in Fig. 3, eBC mass concentrations observed at NOA station are similar to previously reported values in various urban background sites of European highly populated cities, whereas eBC concentrations at DEM are of the same order of magnitude than in residential urban or suburban areas in Europe.

Diurnal cycles of eBC and CO, as well as wind speed and temperature have been calculated as 1-h mean values and are shown in Fig. 4. eBC and CO exhibit similar diurnal variability. At both stations, maximum concentrations of eBC and CO occur during morning hours (between 08:00-09:00 a.m) and late evening (between 08:00-09:00 p.m), suggesting common emission sources. Based on traffic volume data (Grivas et al., 2012), a first peak in the emissions from transportation is expected around 08:00 when people commute to work, followed by a plateau from 08:00-18:00, and a secondary peak until 21:00, after when traffic is decreasing. Wood burning emissions from residential heating are expected to increase during the evening, when temperatures drop and people are back-home. As a result, the first peak in eBC and CO concentrations occurs during morning traffic rush hours, while the surface boundary layer is still shallow. At NOA peaks are quite more pronounced compared to DEM, suggesting that each site is under the influence of different small scale dynamics in the Athens valley (Tombrou et al., 2007). It is also interesting to observe that the average minimum of concentrations at NOA occurs during midday due to a higher boundary layer height (BLH) and corresponding aerosol dilution during daytime, when both sampling sites are under the same well-mixed atmosphere, winds are stronger, and consequently the pollutants are more homogeneously dispersed in the metropolitan area. The second peak at NOA during night-time is the result of the Nocturnal Boundary Layer (NBL) formation, with the site (elevation 107 m) well within the nocturnal boundary layer (Kassomenos and Koletsis, 2005), leading to an accumulation of atmospheric pollutants from combustion sources active at night. During the late hours of the night, the minimum of the 24-h concentrations are observed at the periphery of the basin (DEM), where during stagnant conditions advection from the urban pollution sources is reduced. Occasional downslope winds (katabatic winds) from Hymettus Mountain (Amanatidis et al., 1992) may enhance air exchange from outside the nocturnal boundary layer (NBL), at the same time induce a build up, and increase in concentrations at the Athens Basin.

3.2 Source apportionment of BC and diurnal variability

Following the deconvolution of BC (see section 2.3), on average BC_{wb} represents 33 % and 29 % of total eBC in PM, at DEM and NOA, respectively. BC_{ff} and BC_{wb} fractions comprise the background concentration of BC (BC_{bgd}). Nevertheless, it was estimated that BC_{bgd}, defined as the 1.25 percentile of the dataset (Kondo et al., 2006), is below 10% of the arithmetic mean concentration for both stations (Table 1). As a matter of fact, regional BC background concentrations are expected to be low compared to ambient levels in urban and suburban environments due to the low emission intensity of widespread sources.

Wood burning contribution to total eBC is similar as in other European cities. Indeed, wintertime wood burning contribution of about 23-25 % has been reported for urban and suburban areas in Paris (Favez et al., 2009; Petit et al., 2014; Sciare et al., 2011), (24±11) % in Zurich downtown (Herich et al., 2011), and 23 % in London (Fuller et al., 2014).

Figure 5 and Fig. 6 present the diurnal cycle of BC_{wb}, BC_{ff}, BC_{total} (=eBC) as well as the relative contribution of wood burning aerosols to the total BC (*WB%*). BC_{wb}, as well as *WB%* show a clear diurnal trend, with values from 20-25 % early in the morning to peaks at 40 % during night-time, suggesting a large contribution of wood burning domestic sources spread over the

7

region of Athens, in addition to the enhancement of concentrations at ground level because of the suppression of the boundary layer height. Other sources like industry and power generation are considered negligible as at European scales both consume less than 1 % of the total amounts of wood used annually (Denier van der Gon et al., 2015; IEA, 2008). Fossil fuel source is nevertheless the main contributor to black carbon concentrations in both areas. In particular, during morning rush hours, it represents up to 70 % and 90 % of total eBC at DEM and NOA, respectively.

3.3 Source identification of CO

3.3.1 Using BC$_{wb}$ and BC$_{ff}$ as tracers of fossil fuel and wood burning sources

The association between CO concentration, BC$_{wb}$ and BC$_{ff}$ were examined using multiple linear regressions. Regression analysis between CO, BC$_{wb}$ and BC$_{ff}$ are shown for both sites in Fig. 7. Regressions were carried out using 10-minutes averaged data which represented a sample size of 13259 and 7474 values for DEM and NOA, respectively. The best-fitted linear equation to observed data, and the partial regression coefficients of the model r'_0, r'_{ff} and r'_{wb} were calculated so that:

$$[CO] = r'_0 + r'_{ff} \times [BC]_{ff} + r'_{wb} \times [BC]_{wb} \,, \tag{18}$$

The model was run with no constraint for DEM, and the determined regression coefficients (r'_{ff} and r'_{wb} for DEM) were found with a relative standard deviation below 2 %. However, for NOA, a constraint was applied in order to achieve a solution mathematically and physically meaningful. This choice was made because of the simultaneous advection of aerosols, resulting in a significant correlation between BC$_{wb}$ and B$_{ff}$ (Fig. 7), thus making more difficult the separation of different sources based on their variability. Since the variability of the emission ratios is greater for wood burning emissions (the emission ratio strongly depends on type of biofuel and appliances used), the choice was made to constrain the emission ratio of fossil fuel r'_{ff}. The r'_{ff} value for NOA was set identical to the one predicted by the model for DEM (i.e equal to 0.184 ppbv ng^{-1} m^3, see Eq. 19). This is an approximation based on the assumption that BC and CO are chemically inert and their emission ratio r'_{ff} cannot differ significantly within the same urban area due to an uniform vehicle fleet mix (size distribution and age of vehicle fleet, environmental performance, driving behaviour etc.). We acknowledge that this assumption might introduce some level of uncertainty. The latter is difficult to be estimated with accuracy. A sensitivity analysis for the NOA emission ratios was made, based on the statistical error of determined r'_{ff} at DEM. r'_{wb} for NOA was re-calculated using not only a single constraint value, but a range of values from the lowest (0.184-0.00137) to the highest (0.184+0.00137) around the determined r'_{ff} value from the multilinear regression analysis at DEM. An uncertainty of 25% was finally estimated from this exercise for the calculated r'wb value at NOA. The results of the multiple regression analysis applied at the two sites are presented in Fig. 8.

$$CO_{ff-DEM}(ppbv) = (0.184 \pm 0.00137) \, x \, BC_{ff-DEM}\left(ng \, m^{-3}\right) \rightarrow (BC/CO)_{ff-DEM} = 5.4 \, ng \, m^{-3}/ppbv \,, \tag{19}$$

$$CO_{wb-DEM}(ppb) = (0.114 \pm 0.00216) \, x \, BC_{wb-DEM}\left(ng \, m^{-3}\right) \rightarrow (BC/CO)_{wb-DEM} = 8.8 \, ng \, m^{-3}/ppbv, \tag{20}$$

$$CO_{wb-NOA}(ppb) = (0.131 \pm 0.03275) \, x \, BC_{wb-NOA}\left(ng \, m^{-3}\right) \rightarrow (BC/CO)_{wb-NOA} = 7.6 \, ng \, m^{-3}/ppbv, \tag{21}$$

The resulting regression coefficients were applied to estimate the fraction of CO attributed to fossil fuel and biomass burning combustion sources whereas the intercept values (108.5±0.64 and 146.8±2.5 ppbv and for DEM and NOA, respectively) were regarded as the background concentrations of CO. The resulting background concentrations are in very good agreement with those calculated as 1.25 percentile of the dataset (see Table 1). It is noteworthy to mention here that CO background levels are very significant with regard to the ambient concentrations, representing about 26% and 46% of the arithmetic mean concentration at NOA and DEM respectively. As a matter of fact, widespread natural sources of CO, such as plants, oceans and oxidation of hydrocarbons, in combination with its long atmospheric lifetime are known to maintain a significant background concentration even outside urban areas. These results show that the BC/CO ratio is higher for emission related to biomass burning compared to fossil fuel combustion, which is consistent with literature values (Pan et al., 2012). The determined values for DEM and NOA for wood burning are very similar, with a (BC/CO)$_{wb}$ ratio of 7.6-8.8 ng m^{-3} ppbv^{-1}. These values are also

in the low range of emission ratios found in the literature for both transport and domestic heating (using biofuel) sources (see Table 2).

The time series of the deconvolution of CO into three fractions, namely CO_{ff}, CO_{wb} and $CO_{background}$, are shown in Fig. 9. According to our results, the wood-burning fraction of CO, represents on average 11 % and 16 % of total CO for DEM and NOA, respectively. In terms of concentrations, CO_{wb} ranges between 5-52 ppbv ($\approx$ 25 ppbv on average) at DEM and between 2-406 ppbv ($\approx$ 135 ppbv on average) at NOA (Table 3). During night-time (20:00-02:00), this contribution is estimated at 15% and 25% respectively.

Diurnal variabilities of CO_{ff} and CO_{wb} at each site are presented in Fig. 10 (*NB*: different vertical scales are used for each station). As expected, CO_{ff} presents similar variability with that of BC_{ff}, i.e a pronounced bimodal distribution, with higher concentrations during rush hours. Along the same line, the diurnal variability of CO_{wb} shows a unimodal pattern with increasing concentrations after 18:00, due to the combination of enhanced wood burning emission which is a source more active during evening hours and lower ambient temperature and BLH, as discussed previously.

Comparison with other European cities is limited by the very few number of studies investigating the carbon monoxide concentrations sources. Saurer et al., (2009) used the stable isotope composition of CO ($\delta^{13}C$ and $\delta^{18}O$) for the characterization of different CO sources at 3 sites in Switzerland during winter (along with other indicators for traffic and wood combustion such as NO_x-concentration and aerosol light absorption at different wavelengths) and estimated the wood burning contribution to night-time CO concentrations at 70%, 49% and 29% for a village site dominated by domestic heating, a site close to a motorway and a rural site respectively. These differences reflect the spatial variability in the wood burning use within the same region depending on the type of site, as well as between countries depending on the country and heating practices.

3.3.2 Comparison the CO-BC_{wb}-BC_{ff} linear model vs the CO-NO_x linear model

The results of the multiple-regression model were compared with those from the CO-NO_x linear model. As presented in section 2, an *a priori* knowledge of the emission ratio of CO/NO_x from traffic (r_{ff}) and wood burning (r_{wb}) emissions is required for the CO-NO_x model and therefore the choice of their value is of major importance.

In Fig. 11, the scatter plot of CO versus NO_x is shown for the data recorded at DEM and NOA. The data set is mostly comprised between two well defined slopes and the range of values of CO/NO_x observed in actual air samples is 7-25 ppbv ppbv^{-1} (after subtraction of the CO_{bgd} concentration) for DEM and NOA stations and depends on the contribution of each of the sources. As applied in other studies for similar purposes (Rodríguez and Cuevas, 2007; Saurer et al., 2009), these slopes were estimated using two best fit lines, the first to the points aligned in the lower edge of CO versus NO_x scatter charts, and the second one to the points aligned in the upper edge respectively. More precisely, they have been calculated by fitting only data below the 10th percentile and above the 90th percentile respectively of CO/NO_x data. Knowing that lowest ratios are obtained when traffic emissions dominate (and when the contribution of woodburning is insignificant), an r_{ff} value of 7 ppbv ppbv^{-1} was estimated. Higher ratios were obtained typically late in the night-time, when traffic emission decreased and domestic heating increased. However, as we do not expect a contribution of domestic heating close to 100 % at any time of the day in Athens, it is impossible to estimate with accuracy the r_{wb} ratio based solely on this data. Nevertheless, based on "wood burning" lines from Fig. 11, and assuming that emission ratios from wood burning are similar between NOA and DEM, we estimate a r_{wb} ratio for the area of Athens, larger than 25 ppbv ppbv^{-1}.

A sensitivity analysis of the CO-NO_x model was performed using the experimentally determined r_{ff} (at 7 ppbv ppbv^{-1}) and by varying the r_{wb}. Measurements performed directly at the emission source and close to the chimney exhausts during controlled wood-burning experiments, indicated ratios in the range of 50-150 ppbv ppbv^{-1}(Albinet et al., 2015; Nalin, 2014). As a result, the choice was made to vary the r_{wb} parameter from 50 to 150 ppbv ppbv^{-1}. The results of the analysis are presented in Table 4. The influence of increasing r_{wb} at a constant r_{ff} resulted in a relatively minor reduction in the calculated contribution from wood-burning of 2-3 %. A good correlation was found between both models, with coefficients of determination R^2 of 0.52 and 0.85

at DEM and NOA, respectively. The wood burning contribution to CO estimated using the CO-NO_x linear model is higher compared to the estimations from CO-BC_{ff}-BC_{wb} model, of a factor of about 1.5 for NOA, which can be considered as "acceptable" given the uncertainties associated with both models. A higher overestimation compared to model 2 of a factor of about 2.4 is found at DEM suburban station, which could be explained by the fact that the site is characterized by more aged air masses compared to the urban background NOA station. Consequently, ambient CO/NO_x ratios might differ more significantly from emission ratios at DEM suburban station. These results suggest that CO-NO_x linear model probably overestimate wood burning contribution to CO, especially in environments characterized by aged air masses were photochemical loss of NOx cannot be considered as negligible.

4. Conclusion

In this study we performed a comprehensive field campaign at two surface stations in a suburban and a central area of Athens during winter 2014-2015 in order to investigate the impact of fossil fuel and biomass combustion on the urban air quality. We report measurements of particulate black carbon and CO and NO_x gaseous components performed simultaneously at the monitoring station of Demokritos (DEM), representative of suburban areas of the Athens Metropolitan Area and at the National Observatory of Athens (NOA), typical of urban background conditions. More precisely, black carbon particles were concurrently measured using two 7-wavelength aethalometers, whereas mixing ratios of CO were measured with an infrared absorption analyzer at NOA and by wavelength-scanned cavity ring down spectrometry at DEM.

The median BC concentrations were 528 ng m^{-3} at DEM and 1198 ng m^{-3} at NOA. In a similar way, median CO mixing ratios were 195 ppbv at DEM and 324 ppbv at NOA. These differences have been explained by the location of the two sites with respect to the proximity from sources and local atmospheric dynamics in the Athens valley. Both BC and CO displayed a clear bimodal diurnal pattern, in which morning peaks were observed due to morning inversion and rush-hour traffic, while evening peaks were attributed to combustion sources (evening traffic rush-hour, residential heating) combined with the effects of a shallow nocturnal boundary layer. Highest concentrations were observed during low wind speeds, suggesting that both combustion products were not related to regional transport but instead originated from sources within Athens.

Source apportionment of BC was carried out using a model based on the absorbance spectral differences of black carbon (related to fossil fuel) and brown carbon (related to biomass burning). Our results suggest that even though fossil fuel combustion is the major contributor to BC in PM$_{10}$, woodburning makes an important contribution of about 30% to wintertime BC concentrations at both sites (on average 33 % at DEM and 29 % at NOA, respectively, but this difference lies within the uncertainty range of the calculations). BC from biomass burning displayed a clear unimodal diurnal pattern with the highest concentrations during night, confirming that its main source was local domestic heating.

As both datasets showed significant BC and CO correlations, we used observations of CO mixing ratios along with the fraction of BC_{wb} and BC_{ff} to quantify the percentage of observed CO which originates from fossil fuel and wood burning sources. This analysis led to the conclusion that the wood-burning fraction of CO from local emissions, represents on average 11-16 % of total CO in Athens during wintertime. The method proposed here for the source apportionment of CO was compared to a previously reported method based on the CO-NO_x ratios. From our results, it appears that the CO-NO_x linear model over-estimates the contribution of wood burning to CO concentrations, especially in environments characterized by aged air masses, likely due to the fact that the hypothesis of negligible photochemical loss of NO_x is not always met.

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Table 1. Statistical summary of eBC and CO concentrations at DEM and NOA stations for the period between 6th December 2014 and 10th March 2015.

	Arithmetic mean ± stdv	Geometric mean	Median	90th percentile	10th percentile	1.25th percentile**	Number of datapoints (10-min averaged)
eBC (DEM) ng.m⁻³	656±519	497	528	1265	179	71	13259
eBC (NOA) ng.m⁻³	2655±3554	1372	1198	6963	352	57	7474
CO (DEM) ppbv	214±95	199	195	315	125	101	13259
CO (NOA) ppbv	555±570	404	324	1282	196	143	12127
*NOx (DEM)	6.17±3.47		5.56	9.93	3.66	3.13	2238
NOx (NOA)	29.6±42.7	12.4	11.4	84.5	1.9	1.2	12127

*NOx measurements were available from the monitoring station of the Greek Ministry of Environment and Energy (www.ypeka.gr) situated 300 m from DEM station

**Background concentration levels estimated as in Kondo et al., 2006

Table 2. BC/CO (ngC m^{-3} ppbv^{-1}) ratios derived from emission factors found in the literature and from ambient measurements in Athens using the multiple regression model.

	Transport	Domestic heating (biofuel)	Reference
Derived from Emission factors			
	3.1-11.5 (gasoline)	8.7-26.6	Verma et al., 2010
	1.3-55 (diesel)		
Derived from ambient measurements (multiple regression model)			
DEM station	5.4	8.8	This study
NOA station	5.4 (fixed)	7.6	This study

Table 3. Statistical summary of calculated CO$_{wb}$ and CO$_{ff}$ concentrations, as well as CO$_{wb}$(%) using the multiple regression model (model 1) at DEM and NOA stations.

	DEM			NOA		
	CO$_{wb}$ (ppbv)	CO$_{ff}$ (ppbv)	CO$_{wb}$ (%)	CO$_{wb}$ (ppbv)	CO$_{ff}$ (ppbv)	CO$_{wb}$ (%)
mean (±stdv)	25.1 (25.7)	80.2 (65.5)	11 (9)	134.5 (230.6)	297.3 (366.9)	16.3 (14.3)
90th percentile	51.9	156.7	21	405.9	731.0	37.1
10th percentile	4.6	19.8	3.0	1.9	50.8	1.0

Table 4. Sensitivity test of the CO-NO$_x$ linear model for a constant emission ratio for traffic (r_t) and a variable emission ratio for wood burning and comparison of model 1 (linear) versus model 2 (multilinear).

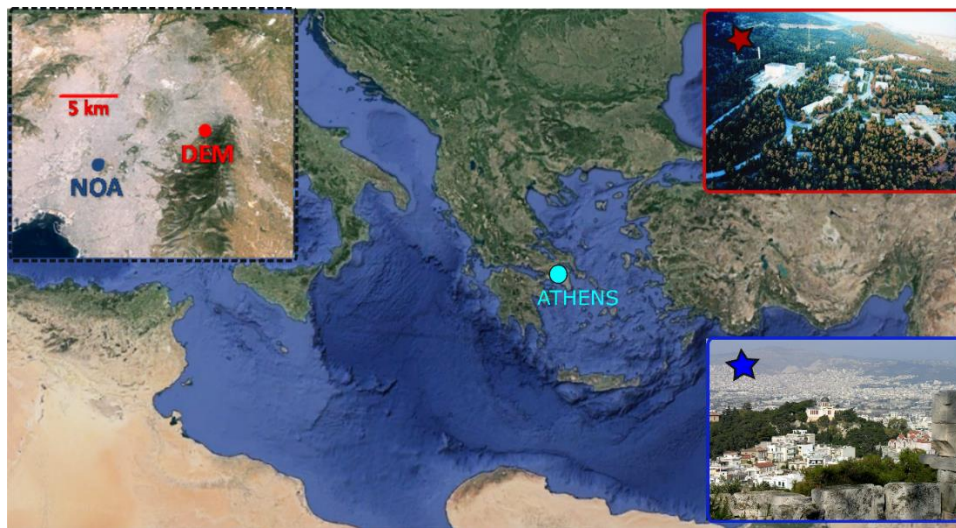|	r_t (ppbv/ppbv)	r_{wb} (ppbv/ppbv)	Mean CO$_{wb}$/CO (%)	Slope of regression between (CO$_{wb}$)$_{model1}$ and (CO$_{wb}$)$_{model2}$
DEM station				
Test 1	*7*	*50*	29%	2.4 (R^2=0.52)
Test 2	*7*	*100*	28%	2.2 (R^2=0.52)
Test 3	*7*	*150*	26%	2.1 (R^2=0.52)
NOA station				
Test 1	7	50	34%	1.6 (R^2=0.85)
Test 2	7	100	31%	1.51 (R^2=0. 85)
Test 3	7	150	30%	1.48 (R^2=0. 85)

Figure 4: Regional map along with 3D satellite map of the Athens Metropolitan area (black dashed rectangle), and photos of the NCSR Demokritos (DEM) campus in Aghia Paraskevi (Athens suburban, red star), and of the National Observatory of Athens (NOA) at Thiseion (Athens centre, blue star).
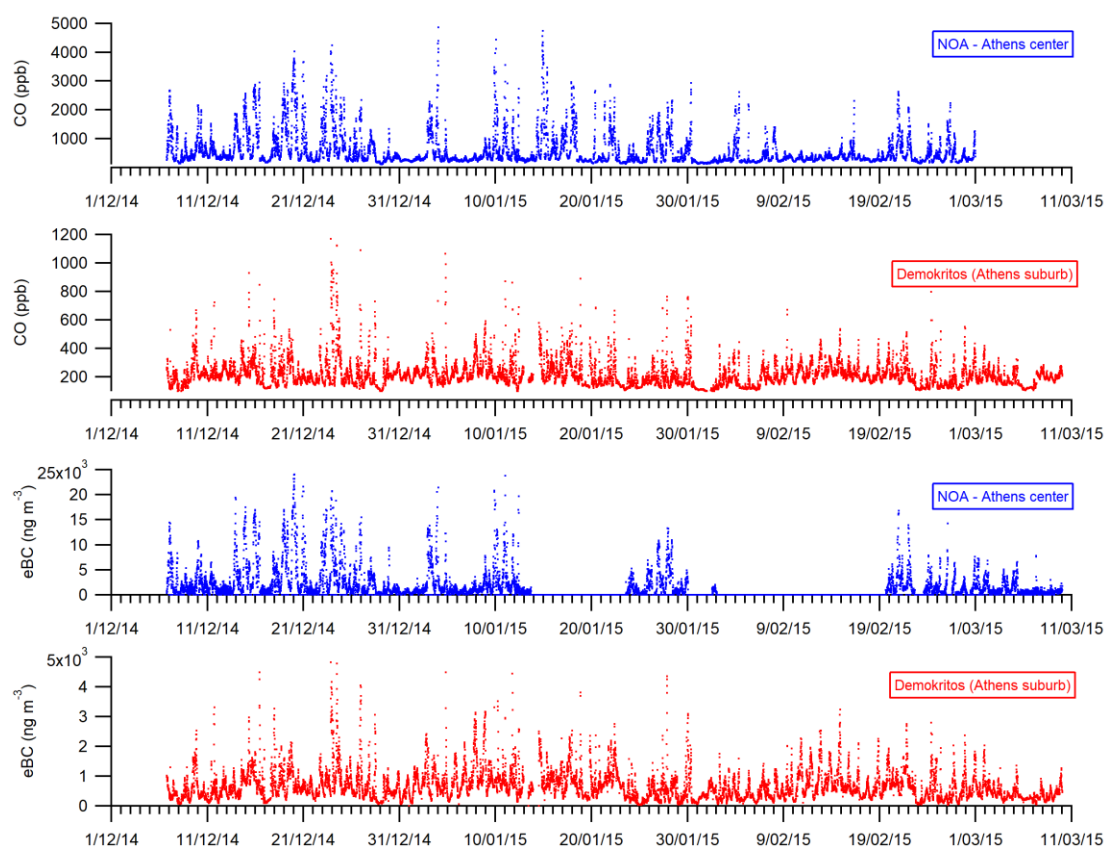

Figure 5: Time series of 10-minutes averaged CO and eBC concentrations measured at NOA and DEM monitoring stations from 6th December 2014 until 10th march 2015.
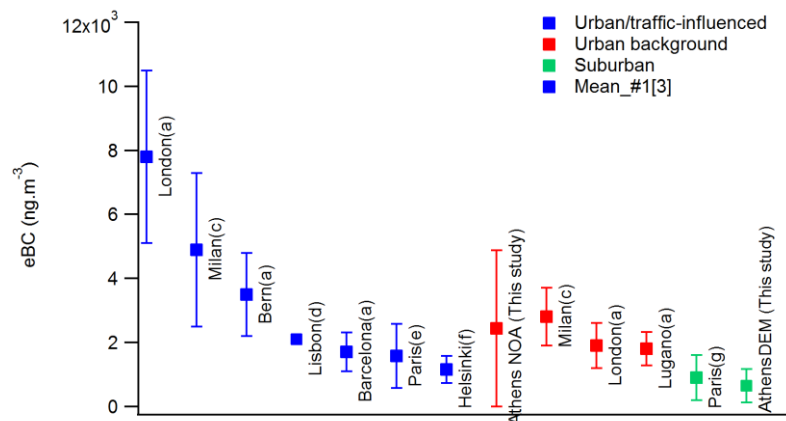
18

Figure 6: Levels of black carbon (mean±stdv) reported for various European cities, (blue) in traffic-influenced sites, such as London (year 2009, Reche et al., 2011), Milan (Summer 2010, Lisbon (June 2000, Alves et al., 2002), Barcelona(year 2009, Reche et al., 2011), Paris (summer 2009, Zhang et al., 2013) and Helsinki (winter 2000, Hitzenberger and Tohno, 2001); (red) in urban background/residential areas such as Milan (Summer 2010, Invernizzi et al., 2011), London (year 2009, Reche et al., 2011) and Lugano (year 2009, Reche et al., 2011), (green) a suburban area of Paris (Laborde et al., 2013), along with the results from this study at NOA and DEM stations in winter 2014-2015.
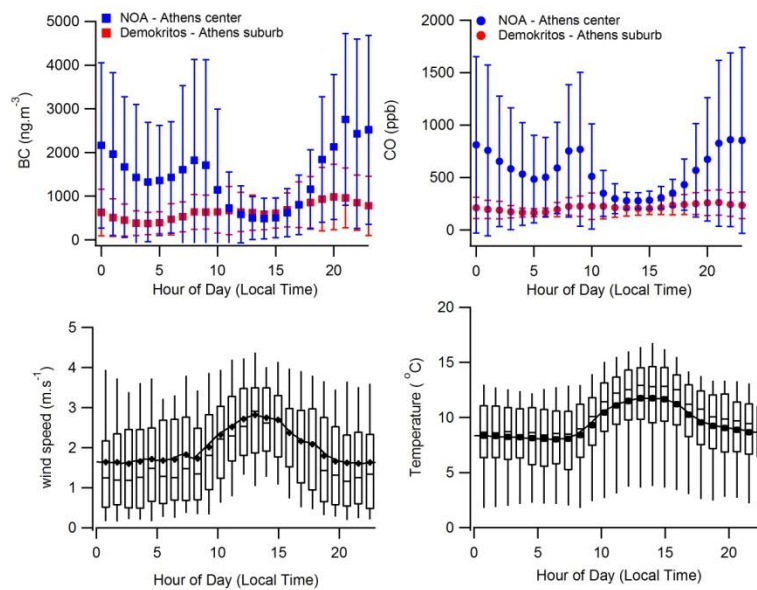
Figure 7: (Top) Diurnal trends of BC and CO concentrations at NOA and DEM monitoring stations (Local Time = UTC). Vertical bars show standard deviation to the mean value. (Bottom) Diurnal trends of wind speed and temperature measured at the meteorological station of Demokritos. Box plots indicate the 10th, 25th, 50th and 90th percentile, whereas markers represent the mean values.
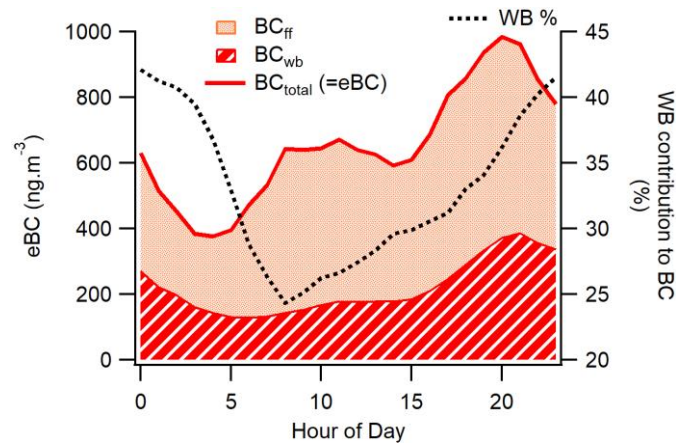
Figure 8: Diurnal cycle of BCwb, BCff, BCtotal and wood burning contribution to total BC (WB, defined as BCwb/ BCtotal*100) at DEM station.
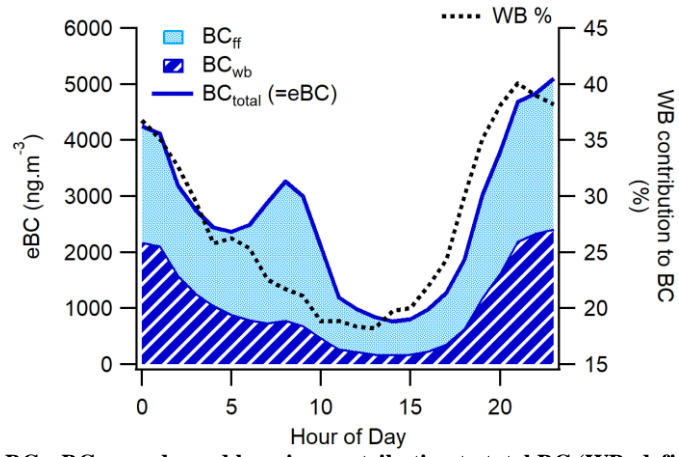
19

Figure 9: Diurnal cycle of BC$_{wb}$, BC$_{ff}$, BC$_{total}$ and wood burning contribution to total BC (WB, defined as BC$_{wb}$/ BC$_{total}$*100) at NOA station.
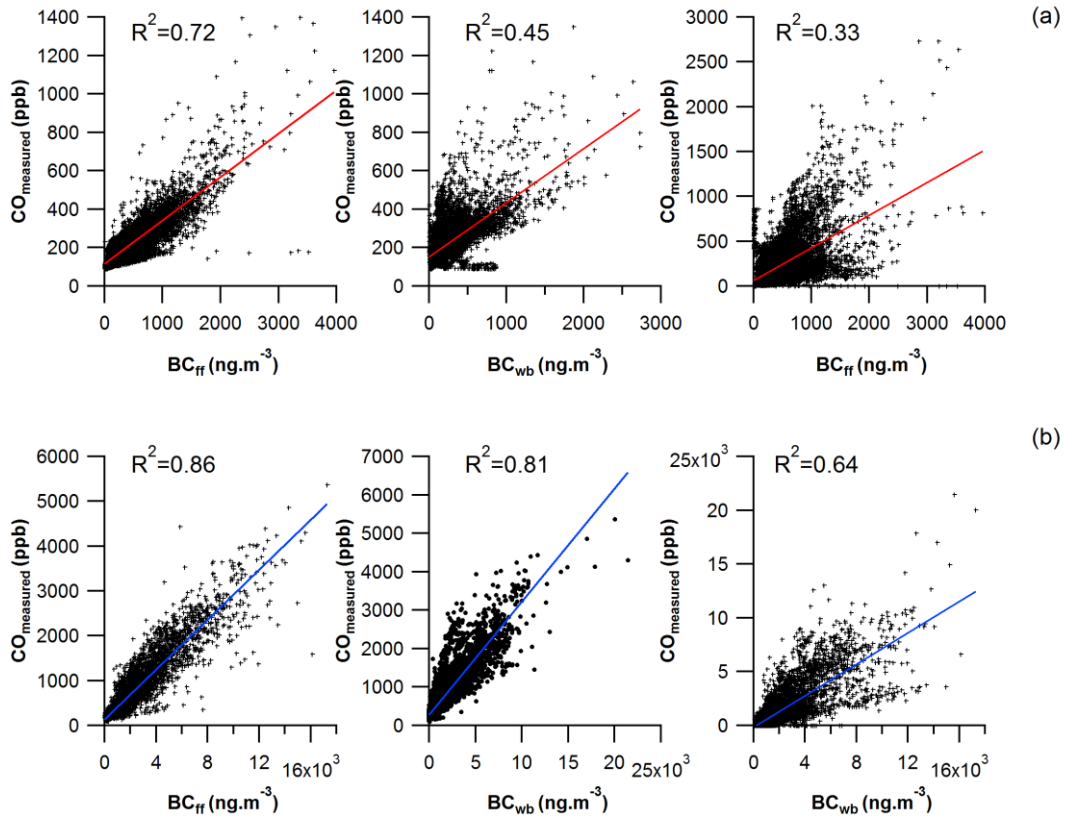

Figure 7: Correlation plots between (left) CO and BC$_{ff}$, (middle) CO and BC$_{wb}$, (right) BC$_{wb}$ and BC$_{ff}$ for DEM (a) and NOA (b) stations.
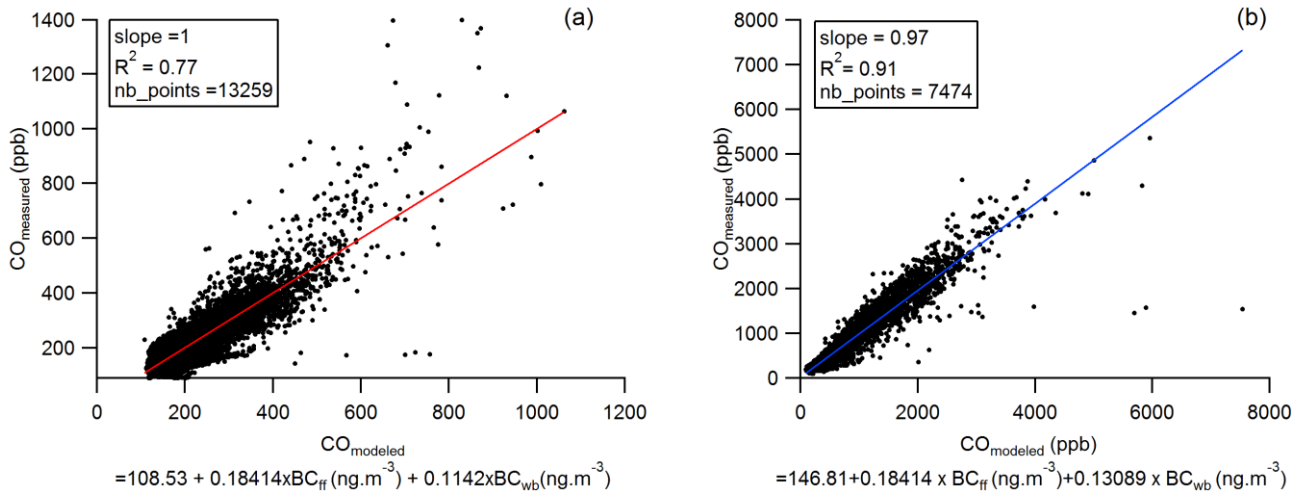

Figure 8: Best-fit linear correlations between CO and a combination of BC$_{ff}$ and BC$_{wb}$ for DEM (a) and NOA station (b).
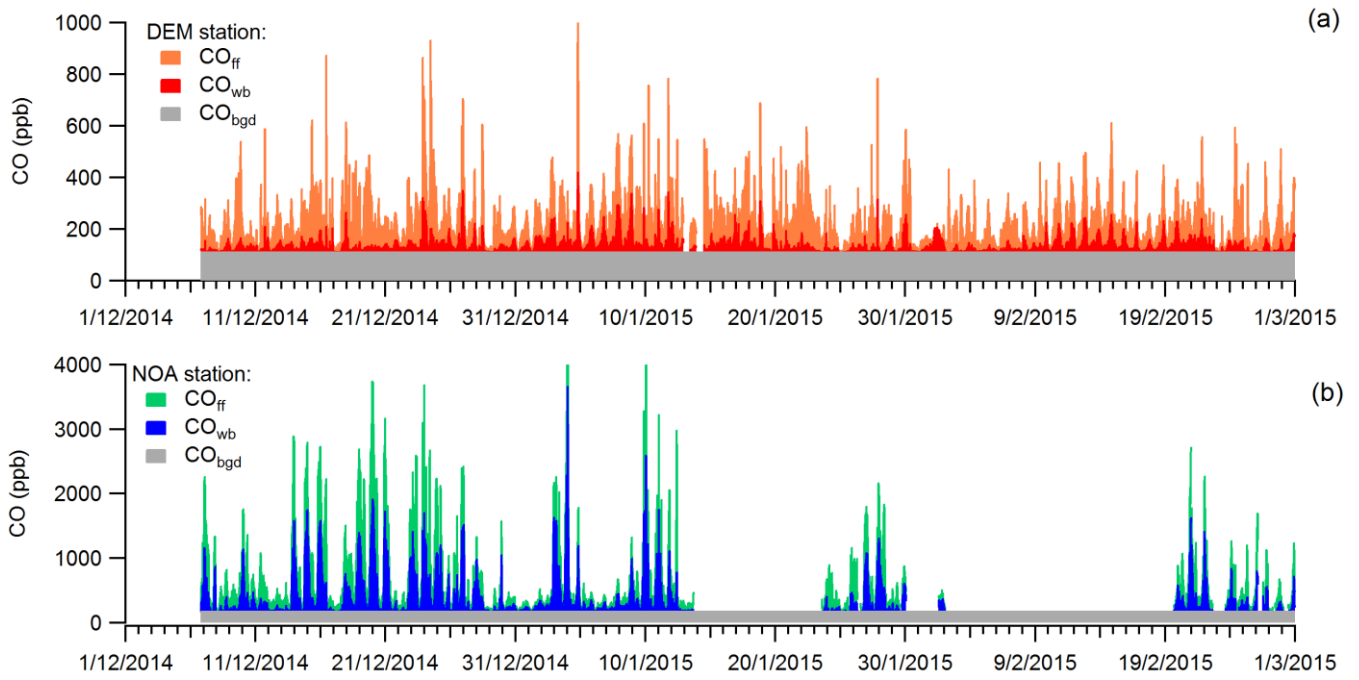
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Figure 9: Time series of the calculated CO_{ff}, CO_{wb} and CO_{bgd} concentration at (a) DEM and (b) NOA stations.
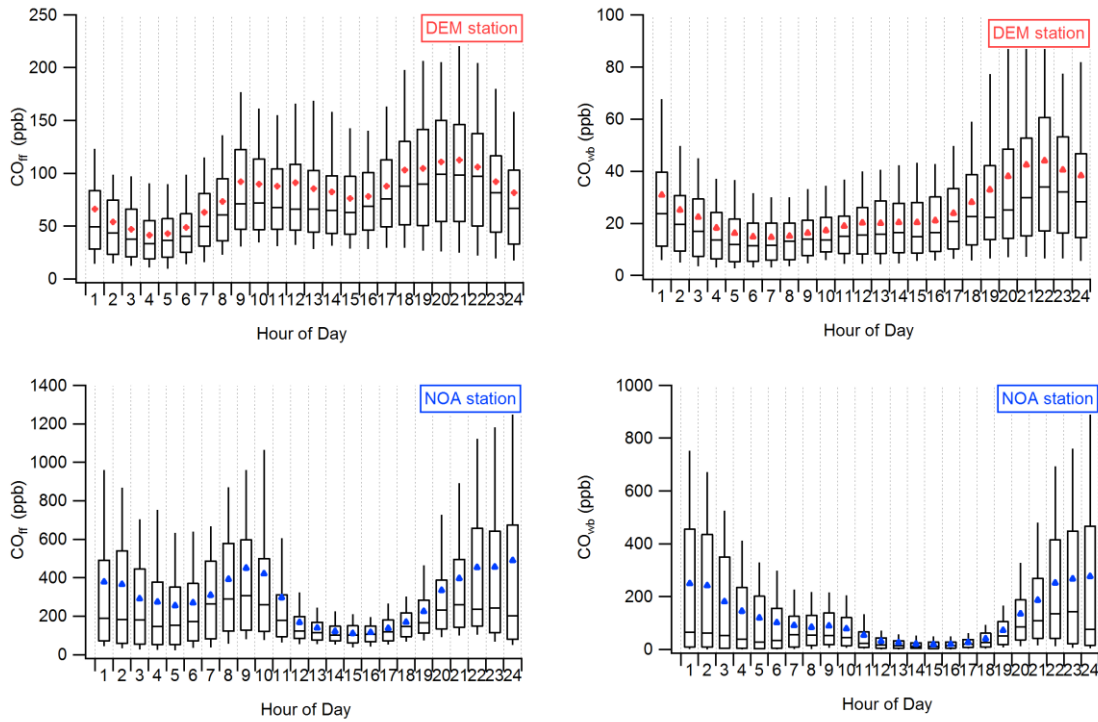

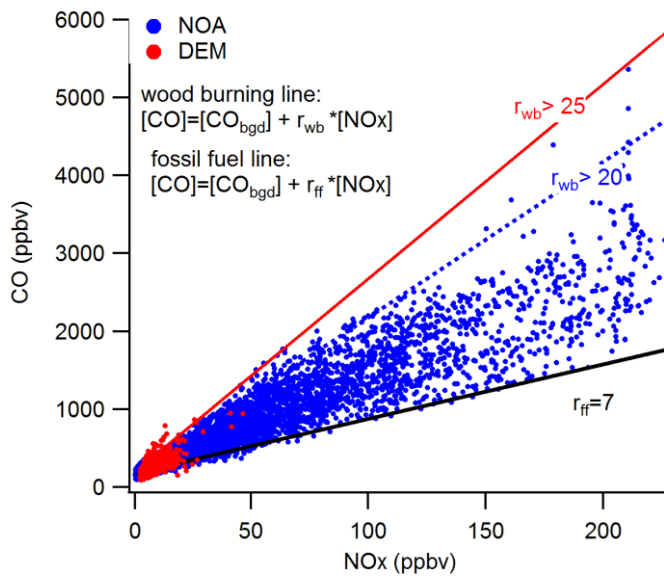**Figure 10: Diurnal variations of CO_{ff} and CO_{wb} at DEM and NOA stations.**

Figure 11: Scatter plot for CO and NOₓ data from NOA (blue) and DEM (red) along with theoretical lines based on pure traffic and pure wood combustion CO/NOₓ emission ratios.

5