Please find below the authors' response to the reviewers and all relevant changes made in the manuscript (use of Track Changes).

Response to reviewers' #1 comments

We would like to thank the reviewer for this constructive review. Please find below our response (in bold) to all comments raised and corrections suggested (included here as well).

Anonymous Referee #1

General Comments

This paper describes daily average concentrations of PM2.5 atmospheric aerosol at a suburban measuring station, in the Athens metropolitan area. For comparison and interpretation the authors also use parallel aerosol measurements of a background measuring station (Finokalia). Although the analytical measurements performed in the aerosol (mainly PM2.5 mass, organic carbon (OC), elementary carbon (EC,) water soluble organic carbon (WSOC) and water soluble ions) are not innovative the fact that these measurements were taken almost continuously during 5 years (from May 2008 to April 2013) provides multi-annual trending information that is important to the understanding of atmospheric processes involving particulate carbon. Therefore the data and paper merits to be published. I agree with most of the discussion and conclusions of the manuscript, but I have doubts about the interpretations and conclusions relating with biomass burning originated particulate carbon. The authors interpret the composition and seasonal/annual variability in aerosol/carbon concentrations as an effect of several processes namely the local impact of biomass burning for home heating during winter which they say has been of increasing importance during more recent years as result of the economic crisis that obliged the population to change to biomass fuels. As it is known biomass produces large amounts of carbonaceous particles (principally OC) when burned in less well controlled stoves and heaters. The reasoning of the authors is logical but in my opinion it is not demonstrated, being the winter /summer variability observed also alternatively explained by meteorological specific conditions such as winter more frequent atmospheric inversions and poor dispersion. The utilization of water soluble potassium tracer in Figure 5 did not confirm the predominance of biomass burning during winter periods (may be because there is interference of soil originated potassium, principally during summer). Therefore the subject should be discussed more thoroughly along the manuscript, not treating it as a clear evidence. The presentation of statistics of wood consumption for home heat burning in the Athens area, showing an increase during more recent years, would be a helpful contribution to the demonstration of the biomass burning effect.

We would like to thank the reviewer for his/her comments. We tried to take into consideration his/her remarks but unfortunately there is very limited work on the role of biomass burning on air quality in Greek cities and complete absence of inventories on wood consumption. The only available work comes from Safari et al., 2013 who reported for winter of 2012, the first year of significantly increased fuel price, a simultaneous increase in wood burning tracers followed by a decrease in fossil fuel tracers. Regarding the use of water soluble potassium, it is worth noting that during winter the interference with soil originated potassium is quite limited as also pointed out by the reviewer. In addition, a specific campaign which took place in winter 2013 revealed significant correlations between water soluble potassium and specific biomass burning tracers, such as levoglucosan and wood burning BC, indicating the accuracy of our conclusions based on the use of this tracer.

Specific comments

Page 17166,

lines 15 and 24- 0.45 μm instead of 0.45 mm

Unit "mm" was replaced by "μm".

Section 2.33 – describe better how TC and IC are analyzed to calculate WSOC.

The following text was added in line 17:

"….Carbon Analyzer. In short, the sample is injected into a combustion cell equipped with oxidation catalyst (Pt) and is heated at 680oC. TC (Total Carbon) is converted to carbon dioxide, and it is cooled, and dehumidified and is transferred through the carrier gas (synthetic air) to the NDIR (Non-Dispersive Infra-Red) gas analyzer. For the IC (Inorganic Carbon) analysis, the sample is injected to the IC reaction vessel where it is acidified, to convert IC to carbon dioxide, and it is volatilized by a sparging process. Then the sample is transferred by the carrier gas to NDIR in order to be detected."

Page 17167

- lines 14 and others (averagestandard deviation (?))

Throughout the article, all average values are provided along with the corresponding standard deviation (AVG ± StdDev)

Page 17168

line 26- (due to emissions from residential heating) – discuss. It can't be said as if it is demonstrated.

From November to March fuel combustion for residential heating constitutes a characteristic source of atmospheric aerosol in Greece. Thus, higher OC and EC values during the coldest period of the year can be mainly attributed to residential heating, in excess to meteorological factors (lower BL), since the rest of aerosol urban sources (e.g. vehicles) are present all year long.

We have smoothened the phrasing as follows:

"… higher concentrations from November to March. This is mainly attributed to emissions from residential heating and low altitude temperature inversions that trap…"

Page 17169

lines 11 and 12- the number trends for 2008 and 2012 (1.21 and 0.59) given in the text are different from those in Figure 3 (0.99 and 0.43). Should not be equal?

Yes, they should be equal. By mistake we used the median values in the text (1.21 & 0.59) instead of the average values (0.99 and 0.43), provided in Figure 3. This is now corrected.

Page 17170

lines 7-13- The discussion and conclusions here are not very clear and relevant. A R2 of 0.49 is low for taking firm conclusions.

This coefficient is based on 1365 daily samples and also it refers to the square correlation (the respective R is 0.7). The above indicate a statistically significant correlation between OC and EC as also demonstrated by the respective p-value. In all cases, we changed the sentence in line 13 as follows:

"The above suggest that a large fraction of OC and EC is emitted by common primary sources."

Page 17170

- In the text, discussion passes from figure 4 to figure 6. Figure 5 only later in the paper is discussed. Reorder the figures.

Figures were reordered, accordingly.

Page 17170

- section 3.3- there is a discussion here relating OC with WSOC. Being WSOC more than 60% of OC, of course that there is a good correlation between both. More clear information could be taken from the relation between WSOC and WIOC which are independent (?) variables.

OC was measured using a Sunset laboratory analyzer while WSOC was measured through a TOC analyzer, thus both measurements come from independent analytical techniques. As a consequence, the good correlation between the five-year daily values of these two concentrations reflects not only their expected covariance but also the success of the two techniques to capture their common variability. It has to be noted that WIOC is estimated by subtracting the calculated WSOC from OC, so it is not an independent variable.

Page 17171,

lines 20-25- The formation processes of nssSO4 are probably quite different from secondary OC; therefore the conclusion in this part of the text is not clear and relevant.

The sentence was rephrased accordingly:

"WSOC is weakly correlated to nss-SO_4^{-2} (R^2=0.15, n=1017, p<0.001, during summer R^2=0.26 vs R^2=0.03 during winter), suggesting that long-range transport and aerosol ageing could be considered as additional contributors to WSOC. Additionally…."

Page 17171,

lines 24-25- correlations between nssK+ and WSOC during winter only should probably be more clarifying than for the whole year.

The correlation between WSOC and nssK+ is low regardless the season (in summer R^2=0.09 and in winter R^2=0.03), indicating that all year round there is limited production of WSOC from biomass burning.

Page 17171,

lines 24-26- Why not use Ca2+ to remove K+ from soil origin, in order to obtain only K+ from biomass burning?

When excluding cases of high Ca2+ (mainly dust events) from the five year dataset, the correlation coefficient between nssK and WSOC or EC does not ameliorate.

Page 17172, **1773**

lines 16-18- To me this is not clear. EC is not very efficiently removed by rainfall; therefore the correlation between EC and nssK+ in winter can result also from higher regional emissions from biomass burning during this period of the year and advection / long range transport to the sampling site.

We suppose that this misunderstanding is due to the fact that in figure 5 (reordered as figure 7) the labels (winter & summer) were accidentally misplaced. The upper panel corresponds to winter and the lower to summer. As a consequence, during winter there is a clear covariance between EC and nss-K, in contradiction to summer when the two variables do not seem to be correlated.

Page 1716, **1776**

lines 9-10- , : : :or more inefficient dispersion of local emissions in Athens during winter.

The following addition was made to the text:

"Assuming that the vehicular traffic is stable throughout the year (Grivas et al., 2012) and long range transport and meteorology is similar over both sites, the increase in OC and EC during the cold season, can be attributed to an additional primary source, most probably heating. In addition…"

Page 1716, **1776**

lines 13-14- Add a reference demonstrating the maximization of wood burning activities during 2011-2013.

The following reference was added:

(Saffari et al., 2013)

Saffari, A., Daher, N., Samara, C., Voutsa, D., Kouras, A., Manoli, E., Karagkiozidou, O., Vlachokostas, C., Moussiopoulos, N., Shafer, M.M., Schauer, J.J., Sioutas, C., 2013. Increased Biomass Burning Due to the Economic Crisis in Greece and Its Adverse Impact on Wintertime Air Quality in Thessaloniki. Environmental Science & Technology 47, 13313-13320.

Response to reviewers' #2 comments

We would like to thank the reviewer for this constructive review. Please find below our response (in bold) to all comments raised and corrections suggested (included here as well).

Anonymous Referee #2

This MS presents an assessment of OC and EC concentrations in Athens (Greece) over a 5-year period, providing a comparison for a shorter period of time with a background station in Crete. The results from the assessment are interesting for the scientific community, even if the methodologies applied are not especially novel. However, the long and uninterrupted series of data is very valuable and makes up for this. I would recommend publication after a number of issues have been addressed. I am mostly concerned by the interpretation of wood burning as a source, as there seem to be some contradictions in the text (please see below).

-page 17163

*line 5: please add "road traffic" before "wintertime high energy consumption", as this is probably the more relevant source.

Done.

*line 6, please add "traffic but also" before "secondary organic aerosol"

Done.

*line 13: please clarify this sentence, what does "in excess of other significant sources" mean?

The sentence was rephrased as follows:

"Athens is located in Eastern Mediterranean, a well-known crossroad of long range transported aerosol from discrete regional sources that are superimposed on other significant local sources of pollution ..."

* line 18: "prevailing emissions" from what kind of sources? Please specify.

As prevailing emissions we mean those coming from sources such as vehicles, fuel combustion and long-range transport of aerosol, as described in the list of references provided. The text was changed accordingly:

"Studies performed in Athens basin demonstrated the prevailing emissions of carbonaceous aerosol all year round, namely vehicles, fuel combustion and long-range transport"

* line 23: the authors could stress that this is the major contribution of their work, the extremely long and uninterrupted series.

We thank the reviewer for his suggestion. We added the following sentence:

"The long measurement duration and the completeness of the data series allowed the performance of thorough and concise investigation of carbonaceous aerosol properties, sources and variability in the area, as a major contribution of this work."

* line 27: "stalked", should this maybe be "occurring"?

Done.

- page 17164

*line 6: please define ACTRIS

The following definition was added:

ACTRIS (Aerosols, Clouds, and Trace gases Research InfraStructure Network, http://www.actris.net/)

* line 20: is a website available for the station? If so, please provide

The relative website address was added:

http://finokalia.chemistry.uoc.gr/

* line23: "during most of the period", how long is this? I understand 2 different samplers were used?

The following information was added:

"…(R&P Co) during most of the period (90 % of the sampling time) and Partisol FRM Model 2000 PM2.5 & PM10 air samplers (R&P Co) (10 % of the sampling time)…"

- page 17165

* lines 10-15: please describe briefly the limitations of this sampling approach: it has been pointed out that the back-to-back filter configuration does not allow enough time for equilibration of gases on the second filter, and that therefore this approach may underestimate the positive OC artefact.

The following sentence was added in the relevant paragraph:

"Nevertheless, it has been reported that the back-to-back filter configuration does not allow enough time for equilibration of gases on the second filter, and therefore this approach could underestimate the positive OC artefact."

- page 17166

* line 2: was it a laboratory or a fiels Sunset instrument?

It is a laboratory instrument as already mentioned in line 2.

* line 18: "IC", how was the IC concentration obtained? By decarbonisation with an acid of one sample, running another sample and calculating the difference? Please describe briefly.

Following a similar comment by the first reviewer we added the following description in line 17:

"….Carbon Analyzer. In short, the sample is injected into a combustion cell equipped with oxidation catalyst (Pt) and is heated at 680oC. TC (Total Carbon) is converted to carbon dioxide and it is cooled, dehumidified and transferred through the carrier gas (synthetic air) to the NDIR (Non-Dispersive Infra-Red) gas analyzer. For the IC (Inorganic Carbon) analysis, the sample is injected to the IC reaction vessel where it is acidified, to convert IC to carbon dioxide, and it is volatilized by a sparging process. Then the sample is transferred by the carrier gas to NDIR in order to be detected."

- page 17168

* line 10: please add reference to Querol et al. (2013): Variability of carbonaceous aerosols in remote, rural, urban and industrial environments in Spain: implications for air quality policy; Atmos. Chem. Phys., 13, 6185-6206, 2013 www.atmoschem-phys.net/13/6185/2013/ doi:10.5194/acp-13-6185-2013

The suggested reference was added.

* line 27: "local sources" should be "local emissions", given that it is the emissions and not the sources that are trapped.

Replaced

* line 27: "Particulate OC" should be "particulate "OC and EC", given that this process affects both OC and EC.

Done.

- page 17169

* line 11: "reproduced by OC": why does winter OC not decrease in 2012, as is the case for EC? If the economic recession is indeed the cause for this trend (which is likely), then the behaviour of OC and EC should be more similar during this period.

In winter 2011 lower temperature values were recorded, resulting in more frequent use of residential heating (namely biomass burning). On the other hand, during winter 2012 even if ambient temperature was higher (compared to 2011), biomass burning was more widely used as a choice for residential heating.

Winter 2012 OC does not seem to follow the decreasing trend of EC because the clear daily spikes during winter 2011 & 2012 (Fig. 1), that are attributed to biomass burning, seem to be partly smoothened during the calculation of inter-annual average values for the respective winters (Fig. 3). Furthermore this is the reason for the observed increase of the standard deviations during winter 2011 and 2012.

Since the aforementioned data seem to be confusing, it was attempted to strengthen the conclusions in this work with a combination of presented figures and calculated ratios, rephrasing the text as follows:

"The summer vs. winter contrast is further shown in Fig. 3, on an annual basis. Winter refers to December–February period of the December year, while summer to June–August. The EC summer levels after 2009 appear slightly reduced compared to 2008, coinciding the economic recession period in Greece, which led to reduction of traffic emissions and industrial activities (Vrekoussis et al., 2013). In winter, there is an increase during the last two years (2011-2012), attributed to the massive turn of Athens residents in wood burning for main domestic heating. Although OC presents a significant number of spikes during the winters of 2011 and 2012 (Fig. 1), mainly attributed to wood burning, the average values of OC do not present a clear inter-annual trend. Most probably this is because, contrary to EC, OC has additionally a significant secondary origin (see section 3.5) and the influence from primary sources (wood burning) is balanced out in the average values but are shown up as increased standard deviations (episodic nature) observed during winter 2011 and 2012 (a factor 2 higher compared to previous

years). The summer to winter ratio of EC mass concentration presents a significant…"

- page 17170

* line 9: "are proportional" should be "are mostly proportional"; an R2 of 0.49 is not especially high.

Done.

* line 12: "suggest that OC and EC" should be "suggest that a large fraction of OC and EC", not all of OC and EC because the correlation is not too high.

Done.

* line 23: Figure 6 is referenced here but Figure 5 was not discussed before

Figures were reordered accordingly.

- page 17171

* line 19: please describe briefly what the SCiare and Pio methodologies are based on

The following description was added:

"The concentration of non-sea salt sulfate (nss-SO2−4) has been estimated using the equation described in Sciare et al. (2005) and Pio et al. (2007):

[sea salt]=$[Na^+]$+$[Cl^-]$+$[Mg^{2+}]$+[ss-K^+]+[ssCa^{2+}]+[ss-SO_4^{2-}]

Sea salt sulfate (ss-SO_4^{2-}) was calculated in accordance with the composition of sea water and was then subtracted from the total sulfate concentration, in order to calculate the quantity of non-sea salt sulfate (nss- SO_4^{2-})."

* line 29: "improves during summer": this would suggest that during summer one significant origin of WSOC is long-range transport and aerosol ageing, given that nss-SO42- is a tracer of this kind of processes.

Even if it slightly improves in comparison to winter, it still remains low, thus we cannot talk about a significant origin of WSOC, just that long-range and ageing could be also considered as additional contributors.

The sentence was rephrased accordingly:

"WSOC is weakly correlated to nss-SO_4^{-2} (R^2=0.15, n=1017, p<0.001, during summer R^2=0.26 vs R^2=0.03 during winter), suggesting that long-range transport and aerosol ageing could be considered as additional contributors to WSOC. Additionally, the low correlation between WSOC with nss-K^+ (R^2=0.05, n=1023, p<0.001) propounds limited production of WSOC from biomass burning. Finally …"

- page 17172

* line 2: "in winter", because in winter a significant source of WSOC is biomass burning

The text was rephrased as follows:

"The dependence of WSOC to EC is improving in winter (summer: R^2=0.29; winter: R^2=0.44), indicating production of WSOC from primary sources (e.g. biomass burning)."

* line 10: please add "water-soluble" before potassium

Done.

* line 21: "calculated" could be "obtained"

Done.

* line 22: "neither do they improve on a seasonal basis": this is unexpected: if biomass burning is a source of winter OC and EC, as described until now in the text, then nss-K+ should correlate at least partly with OC in winter. If this is not the case, how do the authors explain it?

By writing "neither do they improve on a seasonal basis" it was intended to highlight that there are low square correlation coefficients all year round. More specifically, the summer square correlation coefficient between nssK and EC is 0.02 while during winter it is 0.11. Additionally, the summer square correlation coefficient, between nssK and OC is 0.02 while during winter it is 0.04. A slight improve is observed during winter, but biomass burning seems not to be the main source of OC and EC.

On the other hand based on high resolution measurements performed in winter 2013 (Mihalopoulos et al, unpublished data) a clear correlation is observed between nss-K+, OM and EC during intense episodes of biomass burning. The absence of significant correlation between OC and nss-K using the entire data set indicates that the influence of biomass burning during intense wood burning

episodes (clearly shown in Figure 1) is masked when calculating the five year summer and winter square correlation coefficients.

The paragraph was rephrased accordingly:

"In this study, no significant correlations are calculated between nss-K^+ with OC and EC (neither do they correlate significantly on a seasonal basis; nss-K^+ vs EC: summer R^2=0.02, winter R^2=0.11; nss-K^+ vs OC: summer R^2=0.02, winter R^2=0.04), indicating that during the whole period, biomass burning does not consist the main source of organic carbon and that the dominant primary source of EC is mainly fossil fuel combustion (such as traffic). On the other hand based on high resolution measurements (30 min) performed in winter 2013 (Mihalopoulos et al, unpublished data) a clear correlation was observed between nss-K^+, OC and EC in PM_1 during intense episodes of biomass burning. The absence of significant correlation between OC and nss-K^+ using the entire data set indicates that the influence of biomass burning during intense wood burning episodes (clearly shown in Fig. 1) is masked when calculating the five year summer and winter square correlation coefficients."

* line 24: "mainly fossil fuel combustion", I agree that traffic is the main source, but some correlation should be observed if biomass burning is a (although minor) source. Please explain.

Please see the comment above.

Additionally, the covariance between winter values of nssK and EC is clearly illustrated in Figure 5. (In figure 5 the titles "summer" and "winter" were accidentally reversed and will be reordered.)

- page 17173

* line 11: "influence of wood burning during the last years": here it is suggested that wood burning is a relevant source and therefore it contradicts the results on lines 21-27 on page 17172.

Please see the two previous comments.

* line 11: I think Figure 5 should be Figure 8?

Yes, figures were reordered accordingly.

- page 17175

* line 9: ratio =1: was the OC/ECmin also calculated graphically, to verify that the local OC/ECmin is similar to the literature value proposed? What values were obtained?

The graphical calculation of OC/ECmin from April to October, results in a value of 2.3, which is not reliable for comparative reasons, since the estimation of OC/ECmin through a linear regression requires only periods during which conditions are highly unfavorable for the formation of SOC, in order to lead to secure estimation of OC/ECmin value.

Therefore, in our applied equation (page 17174, lines 6-9) OC/ECpri ratio, derived from literature under traffic conditions (tunnel studies), was used.

* line 16: what was the % of SOC with respect to OC? It would be interesting to see whether the Athens values are similar in relative terms to other Southern European cities, and not only in absolute values.

In line 12 of the same page it is mentioned that SOC constitutes 75 ± 6 % of OC in Athens.

* line 17: figure 9: an additional Figure (or an additional variable in Fig 9) would be useful, showing the variability of the % of SOC in OC throughout the year. This would allow to verify that the relative contribution of POC to OC is higher in winter

Given all available data series, SOC was calculated only from April to October, since there were no reliable data to support the estimation of SOC during winter. During the coldest period of the year, the primary emission sources such as biomass burning, fossil fuel and vehicles (with characteristically different OC/ECpri ratio values) are expected to contribute to OC/EC ratio and thus, the approximation of primary OC/EC ratio (and the subsequent estimation of SOC) in the aerosol samples would be debatable.

- page 17176

* line 5: please review the order of figures

Figures were reordered accordingly.

- page 17177

* line 10: please add "mostly" or "largely" before "proportional"

Done.

* line 11: please add "mainly" before "emitted"

Done.

* line 21: it does, according to Figure 2, with winter maxima and an additional maximum in high summer.

The text was rephrased as follows:

"….On the contrary, EC concentration during winter presents a significant increase since 2011, which can be attributed to the selection of wood as the major fuel source for domestic heating. OC concentration does not present a clear inter-annual pattern, probably because of the episodic nature of biomass burning, as depicted from the increased calculated standard deviations that may have balanced out the aforementioned trend."

Long term characterization of organic and elemental carbon in the $PM_{2.5}$ fraction: The case of Athens, Greece

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Abstract

Organic carbon (OC), elemental carbon (EC), water soluble organic carbon (WSOC) and main ions were measured in a total of 1510 $PM_{2.5}$ daily aerosol samples collected from May 2008 to April 2013, in Athens, Greece. OC and EC concentrations were 2.1±1.3 μg m^{-3} and 0.54±0.39 μg m^{-3}, accounting for 11±3% and 3±1% of $PM_{2.5}$ mass respectively, with an average OC/EC ratio of 4.7±3.1. Significant correlation was found between OC and EC during the whole period, indicating emissions by common primary sources at a regional scale. WSOC concentration ranged from 0.03 to 10.6 μg m^{-3}, with an average of 1.5±0.9 μg m^{-3}. By considering Finokalia (Crete) station as a reference, it was estimated that during the warm season in Athens 67±7% of emitted OC and 53±12% of emitted EC is regional, while during cold months, the regional contribution for OC is only 33±7% and for EC 29±8%. Furthermore, secondary organic carbon (SOC) was calculated for the warm period of the year (April to October). The estimated SOC constituted about 75±6% of $PM_{2.5}$ organic carbon in Athens, highlighting significant aging processes, at a regional scale. In the period 2011-2013 and during wintertime, an increase in OC and EC levels was observed, attributed to increase of wood burning for domestic heating due to the economic crisis.

1 Introduction

Atmospheric aerosol constitutes a crucial factor of air pollution since it presents adverse effects on health, environment and Earth radiative balance (EPA, 1996; WHO, 2003). Carbonaceous aerosol contributes to global warming, and black carbon is considered as the second most important agent of global warming after CO_2 (Probert and Tarrant, 1989; Robock and Graf, 1994; Galdos et al., 2013). Recent epidemiologic studies, have displayed the risks of exposure to increased levels of carbonaceous aerosols, revealing notable associations with cardiovascular mortality and morbidity (Ostro et al., 2010; Lipsett et al., 2011; Krall et al., 2013).

The carbonaceous content of atmospheric particles has been the objective of several studies as it represents an essential fraction of particulate matter (Alastuey et al., 2004; Na et al., 2004; Putaud et al., 2004; Querol et al., 2004; Yu et al., 2004; Yttri et al., 2007; Pey et al., 2010; Pio et al., 2011). These studies provide evidence for the relative importance of road traffic and wintertime high energy consumption, combined with unfavorable meteorological conditions, and summertime traffic but also secondary organic aerosol as major sources of carbonaceous aerosol in Europe. The formation mechanisms of organic carbon (OC) and elemental carbon (EC) have been under scrutiny during the last decade (Saylor et al., 2006; Pio et al., 2007; Schwarz et al., 2008; Pio et al., 2011; Grivas et al., 2012; Bougiatioti et al., 2013), placing emphasis on their biogenic and/or anthropogenic origin and subsequent effects.

Athens is located in Eastern Mediterranean, a well-known ~~crossroads~~crossroad of long range ~~aerosols~~ transported aerosol from discrete ~~neighboring~~regional sources ~~in excess of~~that are superimposed on other significant local~~/regional~~ sources of ~~aerosols~~pollution (Lelieveld et al., 2002; Vrekoussis et al., 2005). A description of the Athens basin and prevailing meteorological conditions has been provided in the literature (Chaloulakou et al., 2005; Grivas et al., 2008; Kanakidou et al., 2011; Theodosi et al., 2011; Grivas et al., 2012). Studies performed in Athens basin demonstrated the prevailing emissions of carbonaceous aerosol all year ~~long~~ground, namely vehicles, fuel combustion and long-range transport (Chaloulakou et al., 2005; Sillanpaa et al., 2006; Grivas et al., 2012; Pateraki et al., 2012; Remoundaki et al., 2013). Nevertheless, it is essential to mark that there are limited studies concerning $PM_{2.5}$ fraction of aerosol in Athens and the works performed so far have been conducted for short time periods (4 – 11 months), mainly at urban locations.

This is the first to our knowledge, long-term (2008-2013) uninterrupted data record of carbonaceous aerosol in an extended area already burdened by long range transport (Eastern Mediterranean) and, in particular, an urban agglomeration with degraded Air Quality-AQ (Athens) and thus enhanced health risk. The long measurement duration and the completeness of the data series allowed the performance of thorough and concise investigation of carbonaceous aerosol properties, sources and variability in the area, as a major contribution of this work. Additionally, the study covers a five year period that includes years before and ~~after~~during the economic recession ~~stalked~~occurring in Greece, enabling additional investigation of the significant impacts of the crisis on AQ. In particular, industrial activity was decelerated, vehicles' use was limited and wood burning replaced conventional fuels for domestic heating due to the high heating oil prices. The latter, in many cases is reported to have a significant contribution to air pollution levels (Molnar et al., 2005; Sandradewi et al., 2008; Schmidl et al., 2008; Grange et al., 2013). Finally, a direct comparison between the urban background site of this study and a remote background site considered as reference for the extended Eastern Mediterranean area (Finokalia, ACTRIS supersite~~),~~ Aerosols, Clouds, and Trace gases Research InfraStructure Network, http://www.actris.net/), helped us shed light on regional patterns and processes, discriminating between regional and local emission sources.

2 Experimental

2.1 Sampling site

The measurements were conducted at the National Observatory of Athens premises in Penteli (38º 2.94'N, 23º 51.78'E, 495ma.s.l.). The site is located on top of a hill facing the city of Athens to S-SW (17 km from the city center), while to the N-NE sector it is surrounded by the Penteli Mountain. The major sources of air pollution in the close vicinity are expected to be vehicular emissions and residential heating. More details about the Greater Athens Area morphology and meteorological conditions are provided by Kanakidou et al., (2011; and references therein), while internal transport patterns in the urban complex are described by Melas et al. (1998). The station is considered as an urban background site, established and operated by the Institute of Environmental Research and Sustainable Development.

2.2 Samples collection

This study covers five years from May 2008 to April 2013, resulting in the collection of 1510 samples on a daily basis. $PM_{2.5}$ aerosol samples were collected using a Dichotomous Partisol sampler (R&P Co) during most of the period (90% of the sampling time) and a Partisol FRM Model 2000 air sampler (R&P Co) (10% of the sampling time), operating at 15.0 and 16.7 L/min, respectively. Sampling duration was 24h starting at 14:00 LT.

Samples were collected on quartz fiber filters (4.7cm, Whatman QMA). Filters were prebaked at 550^{o}C for 4h to remove any absorbed organic material and were stored and transported to and from the field into petrislides. After sampling they were stored until analysis. Filter blanks and blank field samples were also prepared and analyzed.

For the estimation and correction of the amount of adsorbed organic vapor on the sampling filter, a tandem filter collection method was applied (e.g. Turpin et al., 2000; Kirchstetter et al., 2001; Yttri et al., 2007). Two quartz fiber filters from the same lot were used in series, the front filter collects essentially 100% of the particulate matter (and some gas-phase material) and the backup filter is exposed only to gas-phase compounds. The measured carbon content of the backup filter can be subtracted from that of the front filter to give an estimate of the particulate phase OC (Turpin et al., 2000; Novakov et al., 2005; Sillanpaa et al., 2005). Nevertheless, it has been reported that the back-to-back filter configuration does not allow enough time for equilibration of gases on the second filter, and therefore this approach could underestimate the positive OC artefact. Tandem filters were collected for a selected number of samples, using the aforementioned Partisol samplers. In our analyses, the backup filters indicated a positive OC artifact which was always smaller than 5%, thus no correction was applied.

2.3 Mass and chemical analyses

2.3.1 Aerosol Mass

PM mass was determined by weighing the filters before and after sampling according to the U.S. EPA RFPS-1298-126 method, using a Mettler Toledo MX5 microbalance

(1 μg sensitivity). The filters (samples and blanks) remained for 48 h under controlled conditions (RH 40 ±5%, T 20 ±3ºC), prior to each weighing.

2.3.2 OC – EC analysis

All quartz filters (samples and blanks) were analyzed by a thermal optical transmission technique, using a Sunset Laboratory Inc. (Oregon) carbon analyzer. A punch of 1 cm^2 was removed from the filter and loaded into the analyzer as described by Bougiatioti et al. (2013) and Novakov et al. (2005). OC and EC were determined using the EUSAAR-2 protocol (Cavalli et al., 2010). Briefly, the first phase subsumes 4 stages of heating at 200, 300, 450 and 650ºC at He atmosphere, while, during the second 4-step temperature program, the sample is heated at 500, 550, 700 and 850ºC at He/O_2 atmosphere. The detection limit of the analysis was 0.26 and 0.05 μg C cm^{-2} for OC and EC, respectively. The reported results were blank-corrected.

2.3.3 WSOC analysis

For the determination of the Water Soluble Organic Carbon (WSOC) concentrations, punches of 2 cm^2 were removed from the filter and placed in an ultrasonic bath for 45 minutes using 15mL of nanopure water. The sample extract was filtered using syringe filters (PALL IC Acrodisc (PES), 0.45 ~~mm~~μm, 13 mm). The solutions obtained after the filtration were analyzed for total organic carbon (TOC) using a Shimadzu TOC-V CSH Total Organic Carbon Analyzer. In short, the sample is injected into a combustion cell equipped with oxidation catalyst (Pt) and is heated at 680ºC. TC (Total Carbon) is converted to carbon dioxide and it is cooled, dehumidified and transferred through the carrier gas (synthetic air) to the NDIR (Non-Dispersive Infra-Red) gas analyzer. For the IC (Inorganic Carbon) analysis, the sample is injected to the IC reaction vessel where it is acidified, to convert IC to carbon dioxide, and it is volatilized by a sparging process. Then the sample is transferred by the carrier gas to NDIR in order to be detected. Total water soluble organic carbon is calculated by extracting inorganic water soluble carbon from total water soluble carbon (TOC=TC–IC) and is labeled as WSOC. The analytical detection limit for WSOC was 80ppb. All data were corrected for the obtained blank levels.

2.3.4 Ion chromatography

Punches of 2 cm^2 from the quartz filters were extracted in ultrasonic bath with 10ml of nanopure water, for 45 minutes, and were then filtered using syringe filters (PALL IC Acrodisc (PES), 0.45 ~~mm~~μm, 13 mm) to remove any insoluble species. The acquired filtered solutions were analyzed by ion chromatography (IC) for the determination of the main ionic species concentrations (anions: Cl^-, Br^-, NO^{-3}, SO_4^{-2}, PO_4^{-3}, $C_2O_4^{-2}$ and cations:NH_4^+, K^+, Na^+, Mg^{+2}, Ca^{+2}). Anions were determined using a Dionex-500 ion chromatograph equipped with an Ion Pac AS4A-SC column and an AG4A-SC pre-column, with an ASRS-300 suppressor. Anions' separation was conducted with isocratic elution of $NaHCO_3$ (3.4 mM) / Na_2CO_3 (3.6 mM) as an eluent and a flow of 1.5 mL min^{-1}. For the determination of cations an Ion Pac CS12A column and a CG12A guard column was used, with a CSRS-300 suppressor, under isocratic elution of 20 mM MSA (Methanesulphonic acid) at a flow rate of 1.0 mL min^{-1}. The detection limit of the analysis was 20, 12, 40, 12 and 40 ppb for NH_4^+, K^+, Na^+, Mg^{+2} and Ca^{+2}, respectively, while the corresponding detection limit for all anions (Cl^-, Br^-, NO^{-3}, SO_4^{-2}, PO_4^{-3}, $C_2O_4^{-2}$) was 20 ppb. The reported concentrations were corrected for blanks.

3 Results and discussion

3.1 Mass concentrations of OC – EC and observed seasonal trends

The daily concentration levels of OC range from 0.1 to 8.5 μg m^{-3} (average: 2.1 ±1.3 μg m^{-3}), contributing on average about 11±3% to the total $PM_{2.5}$ mass. Accordingly, the mass concentration of EC ranges from 0.01 to 3.33 μg m^{-3} (average: 0.54±0.39 μg m^{-3}), contributing 3±1% to the total $PM_{2.5}$. OC and EC values from previous studies in Athens and other European sites are presented in Table 1. It should be noted that most of these studies refer to shorter time periods (4 – 11 months), and for different site types. Compared to OC and EC concentrations in Athens back in 2003, this study reveals levels 3-4 times lower, while later studies revealed similar levels (or slightly higher depending on the site type) in the range of 1.5-4 μg m^{-3} for OC and 0.4-1.8 μg m^{-3} for EC. OC concentrations from several studies in southern Europe cities (mainly western Mediterranean) during the period 2002-2006 are in the range 3-9 μg m^{-3} while EC values are in the range 0.7-1.7 μg m^{-3}. Concentrations in an urban site in Istanbul during the period 2008-2009 appear much higher compared to the values of this study.

Regional background concentration levels at the Finokalia site (Crete Island, 2004-2006) are on average 1.8 and 0.27 μg m^{-3}, for OC and EC, respectively.

Total carbon is calculated as the sum of OC and EC (TC=OC+EC), with OC accounting for 79±4% of the total carbon, constituting the predominant carbon contributor, in accordance with findings in other European sites (e.g. (Lonati et al., 2007; Sanchez de la Campa et al., 2009). However, the contribution of TC to PM in this study (14±3%) is lower than what is reported in the literature for other urban/urban background locations (e.g. 25-46% in Viana et al. (2006); 27-28% in Lonati et al. (2007); about 19% in Sanchez de la Campa et al. (2009); ~~27-28% in Lonati et al. (2007);~~ 29% in Perrone et al. (2011); ~~25-46% in Viana~~Querol et al. (~~2006~~2013)).

Conversion of OC to OM (Organic Matter) is recognized as one of the most critical factors of uncertainty in mass closure calculations (Yttri et al., 2007). Turpin and Lim (2001) suggest the use of different conversion factors per site type: 1.6±0.2 for urban areas, 1.9–2.3 for aged aerosols, and 2.2–2.6 for biomass burning. Taking into account that our site is an urban background station also affected by long range transport (e.g. Sciare et al., 2005; Kanakidou et al., 2011; Pateraki et al., 2012; Remoundaki et al., 2013), we used the value of 2.1 (OM=2.1·OC). On average, OM accounts for 24±6% of $PM_{2.5}$ which is consistent with the value (22%) provided by Remoundaki et al. (2013) for Athens, while lower to those reported in other European sites (e.g. Sillanpaa et al., 2005; Sanchez de la Campa et al., 2009).

In Fig. 1 the daily concentrations of OC and EC are presented for the whole sampling period (May 2008-April 2013). It is observed that OC and EC present significant covariance for most of the period, with maxima mainly during the colder months. The seasonal variability in OC and EC is clearly demonstrated in Fig. 2, which reveals higher concentrations from November to March ~~(the coldest period of the year), due~~. This is mainly attributed to emissions from residential heating and low altitude temperature inversions that trap local ~~sources~~emissions of particulate OC and EC near the surface (e.g. Yttri et al., 2007). The minimum OC concentrations appears in late spring and early autumn, when there is no domestic heating and photochemistry is slowed down compared to summer. In the case of EC, minimum concentrations are found during the warmest months of the year, when there is less fuel combustion in Athens (period of summer vacations) and thus lower production of primary EC.

The summer versus winter contrast is further shown in Fig. 3, on an annual basis. Winter refers to Dec.-Feb. period of the December year, while summer to Jun-.-Aug. The EC summer levels after 20082009 appear slightly reduced compared to 2008, coinciding the economic recession period in Greece, which led to reduction of traffic emissions and industrial activities (Vrekoussis et al., 2013). In winter, there is an obvious increase induring the last two years (2011-2012), attributed to the massive turn of Athens residents in wood burning for main domestic heating. The same behaviorAlthough OC presents a significant number of spikes during the winters of 2011 and 2012 (Fig. 1), mainly attributed to wood burning, the average values of OC do not present a clear inter-annual trend. Most probably this is because, contrary to EC, OC has additionally a significant secondary origin (see section 3.5) and the influence from primary sources (wood burning) is balanced out in the average values but are shown up as increased standard deviations (episodic nature) observed during winter is reproduced also by OC.2011 and 2012 (a factor 2 higher compared to previous years). The summer to winter ratio of EC mass concentration presents a significant declining trend from 1.210.99 in 2008 to 0.5943 in 2012, illustrating the combined effect of summer and winter changes in EC emissions, as related to the economic crisis (see belowsection 3.4).

3.2 OC/EC concentration ratios

The daily OC/EC ratios range from 0.5 to 29.3, with an average of 4.7±1.3 for the 5-year period. These ratios are generally comparable with results from other Mediterranean sites (see Table 1), however, on a seasonal basis the OC/EC ratios ($[OC/EC]_{winter}$=4.6, $[OC/EC]_{summer}$=6.3) are higher than those reported for other urban background sites around the world ($[OC/EC]_{winter}$=2.4–3.5, $[OC/EC]_{summer}$=1.3–3.9) as reviewed by Lonati et al. (2008). Higher ratios are expected as a result ofcan be attributed either to secondary production from gas to particle conversion of VOCs (mainly during long-range transport of polluted air masses (; Pio et al., 2007) or to primary sources such as biomass burning, during which high OC/EC ratios are exhibited (Amiridis et al., 2012).

In more detail, the seasonal cycle of OC/EC ratio (Figure 4) presents maximum values during summer (6.3), when photo oxidation reactions lead to the production of

secondary aerosol (increase of OC concentrations) (e.g. Viana et al., 2007) and reduction of heating (decrease of EC concentration). On January (the coldest month of the year), the high OC/EC ratio could be attributed to the elevated OC concentrations, mainly due to fuel and/or biomass burning combustion for heating, that coincide with a comparatively smaller increase in the production of EC.

Overall, the high values of OC/EC ratio (>2) year round, indicate the clear impact of additional processes like the production of secondary organic carbon. To estimate the primary and secondary origins of carbonaceous aerosol, the correlation between the OC and EC mass concentrations is investigated (e.g. Turpin and Huntzicker, 1995). In the present study a statistically significant correlation is found between OC and EC for the whole period (not shown, R^2=0.49, slope=2.33, n=1365, p<0.001), revealing that OC and EC emission rates are mostly proportional to each other (e.g. Na et al., 2004). A comparable correlation coefficient was reported by Koulouri et al. (2008) for another Eastern Mediterranean, though remote coastal, location (Finokalia, Crete). The above suggest that a large fraction of OC and EC fractions ~~are~~is emitted by common primary sources ~~at a regional scale. .~~

3.3 Water Soluble Organic Carbon

Water soluble organic carbon (WSOC) is considered a major component of carbonaceous aerosol as it serves as a proxy for secondary organic aerosols due to its highly oxidized and soluble nature (Park et al., 2013).

The WSOC concentration in $PM_{2.5}$ ranged from 0.03 to 10.6 μg m^{-3}, with an average of 1.5±0.9 μg m^{-3}, and no significant differences between summer (1.7±0.8 μg m^{-3}) and winter (1.6±1.2 μg m^{-3}). These levels are similar to those reported for the remote-coastal site of Finokalia, Crete, by Bougiatioti et al. (2011), but lower than those reported for Istanbul by Theodosi et al. (2010) (PM_{10} in urban site, see Table 1). The concentration of WSOC presents a statistically significant correlation with OC (Figure ~~6~~5) (R^2=0.87, n=1000, p<0.001), indicative of their common sources. Moreover, WSOC follows the seasonal trend of OC (Figure ~~7~~6) throughout the year, showing maximum values during winter and mid-summer, when WSOC is either emitted from primary combustion sources, such as traffic, and biomass burning or is produced through atmospheric processing of volatile organic species (Park et al., 2013).

WSOC usually consists of organic compounds that derive from the atmospheric oxidation of VOCs and gas particle conversion (secondary OC), while the oxygenation of particulate OC may also occur in the particulate phase or via multiphase chemistry by reaction of strong oxidants such as ozone or hydroxy radicals. As a result, the WSOC/OC ratio decreases in urban locations and near fossil fuel sources (~20%) and increases at more remote sites due to aerosol aging (Pio et al., 2007).

In this study, the WSOC accounts, on average, for about 63±7% of the OC, which is in agreement with the value (67%) reported by Bougiatioti et al. (2011) for Finokalia, Crete, but higher than the value (42%) reported by Lonati et al. (2007) for Milan. The above indicate the dominant role of aerosol aging processes at the regional scale. Finally, the WSOC/OC ratio shows maximum values during summer (Figure ~~7~~6), when there is intense photo oxidation that leads to the production of secondary organic species.

The water insoluble organic carbon (WIOC) has been calculated through subtraction of WSOC from the total OC concentration. On an annual basis WIOC contributes about 39±7% to OC. Although WIOC shows no significant correlation with EC on a daily basis, their seasonal cycles show covariance (Figure ~~7~~6), indicating that part of the production of WIOC can be attributed to primary sources such as fossil fuel combustion.

The concentration of non-sea salt sulfate (nss-SO_4^{-2}) has been ~~also~~ estimated ~~following~~using the ~~procedure~~equation described in Sciare et al. (2005) and Pio et al. (2007~~). ~~):

$[sea\ salt]=[Na^+]+[Cl^-]+[Mg^{2+}]+[ss\text{-}K^+]+[ssCa^{2+}]+[ss\text{-}SO_4^{2-}]$

Sea salt sulfate (ss-SO_4^{2-}) was calculated in accordance with the composition of sea water and was then subtracted from the total sulfate concentration, in order to calculate the quantity of non-sea salt sulfate (nss-SO_4^{2-}).

The average value for the whole period is 3.0±2.0 μg m^{-3}, which is in agreement with the findings from other studies in Athens (Theodosi et al., 2011; Remoundaki et al., 2013). WSOC is weakly correlated to nss-SO_4^{-2} (R^2=0.15, n=1017, p<0.001, during summer R^2=0.26 vs R^2=0.03 during winter), suggesting that ~~secondary organic products, formed through formation pathways similar~~long-range transport and aerosol

ageing could be considered as additional contributors to ~~those of sulfate, are not the dominant constituents of~~ WSOC. Additionally, the low correlation ~~coefficient of~~between WSOC with nss-K^+ (R^2=0.05, n=1023, p<0.001) propounds limited production of WSOC from biomass burning. Finally, the higher correlation coefficient of WSOC with EC (R^2=0.35, n=993, p<0.001) indicates that there is some contribution to WSOC from primary anthropogenic sources rather than biogenic. ~~The correlation between WSOC and nss-SO_4^{-2} slightly improves during summer (summer: R^2=0.26; winter: R^2=0.03); while, on the contrary, the~~The dependence of WSOC to EC is improving in winter (summer: R^2=0.29; winter: R^2=0.44), indicating production of WSOC from primary sources (e.g. biomass burning).

Based on the above, the primary fossil fuel and wood combustion sources appear to contribute more to the winter WSOC concentrations, whereas during summer, sources like oxidation processes of secondary products are more efficient in generating WSOC.

3.4 Sources of carbonaceous aerosol

The independent contribution of biomass burning and fossil fuel combustion emissions to organic matter concentrations could be quantitatively estimated through the potassium-OC and potassium-EC correlations (e.g. Satsangi et al., 2012). In general, biomass burning contributes significantly to the atmospheric concentrations of water soluble potassium (K^+) and the latter is applied as an inorganic tracer for aerosol derived from this source (e.g. Currie et al., 1994; Pio et al., 2008; Schmidl et al., 2008), while fossil fuel combustion leads to minor production of potassium (e.g. Yang et al., 2005a; Yang et al., 2005b).

To utilize K^+ as a representative tracer of pure biomass burning emissions, we have applied a correction for the contribution from sea salt. Sea salt potassium (ss-K^+) was ~~calculated~~obtained in accordance with the composition of sea water (Sciare et al., 2005; Pio et al., 2007; Bougiatioti et al., 2013) and was then subtracted from the total K^+ concentration, to calculate the remaining non-sea salt potassium (nss-K^+). The nss-K^+ concentrations were ~~ranged~~ up to 1.8 μg m^{-3}, with a 5-year average of 0.17±0.~~19~~04 μg m^{-3}, comparable to the values reported by Koulouri et al. ~~(2008).~~ (2008). It is worth noting that part of the calculated nss-K^+ can be due to dust either from Sahara desert or

road-dust re-suspension. In this line, the contribution from these sources in our $PM_{2.5}$ filters cannot be totally ruled out.

In this study, no significant correlations are calculated between nss-K^+ with OC and EC (neither do they ~~improve~~correlate significantly on a seasonal basis; nss-K^+ vs EC: summer R^2=0.02, winter R^2=0.11; nss-K^+ vs OC: summer R^2=0.02, winter R^2=0.04), indicating that during the whole period, biomass burning does not consist the main source of organic carbon and that the dominant primary source of EC is mainly fossil fuel combustion (such as traffic).

~~The nss-K^+/OC ratio ranges between 0.03 and 2.4, with an average of 0.11±0.04, while nss-K^+/EC ratios vary from 0.01 to as high as 7.4, with an average of 0.45±0.14. Relatively high K^+/EC ratios for biomass burning (range: 0.21–0.46) and low ratios for fossil-fuel emissions (range: 0.025–0.09) have been reported by Andreae, (1983) along a path from Europe to South America, while Satsangi et al. (2012) reported K^+/EC and K^+/OC ratios of 0.39±0.25 and 0.08±0.02, respectively, for India. However, these ratios are not corrected for other sources of K^+, which according to Reche et al. (2012) is a crucial factor, thus direct comparison with this study is not valid. To our knowledge, such reported ratios of chemical species from biomass burning, do not exist in the Eastern Mediterranean~~On the other hand based on high resolution measurements (30 min) performed in winter 2013 (Mihalopoulos et al, unpublished data) a clear correlation was observed between nss-K^+, OC and EC in PM_1 during intense episodes of biomass burning. The absence of significant correlation between OC and nss-K^+ using the entire data set indicates that the influence of biomass burning during intense wood burning episodes (clearly shown in Fig. 1) is masked when calculating the five year summer and winter square correlation coefficients.

The annual means of nss-K^+/OC and nss-K^+/EC ratios (not shown) exhibit an increasing trend through the studied period which, in the case of nss-K^+/EC, can be mostly attributed to the notable increase of nss-K^+ concentration compared to that of EC, supporting the influence of wood burning during the last years~~..~~. In Fig. ~~5~~7, EC and nss-K^+ concentrations are presented on a seasonal basis from 2008 to 2013, showing an anti-correlation in summers indicating limited role of biomass burning during that season. This behavior of EC during summers is indicative of accumulative EC from regional sources (such as fossil fuel combustion from traffic), combined with limited

atmospheric washout due to precipitation. During winter, frequent rainfalls remove the regional EC, and thus, the covariance between EC and nss-K^+ reflects mainly local sources like domestic heating.

3.5 Estimation of Secondary Organic Carbon

Greece is significantly affected by long-range transport of African dust and other aerosol types from distant anthropogenic pollution sources (e.g. Gerasopoulos et al., 2011; Kanakidou et al., 2011). Thus, the comparison between an urban background site and a remote site within the same geographical region would be a useful tool for exploring long range transport vs local sources in conjunction with aerosol ageing processes. In this line, OC and EC data from Finokalia (35°32'N, 25°67'N; http://finokalia.chemistry.uoc.gr) were used to represent remote conditions where the aged nature of aerosol has been previously established (Bougiatioti et al., 2009; Bougiatioti et al., 2011; Bougiatioti et al., 2013). Simultaneous measurements of OC and EC at the two sites were conducted for the period from May 2008 to March 2013, and the comparison of the measured levels and their covariance over the different seasons was used to infer the origins and processes responsible for the carbonaceous aerosol loading.

In order to estimate the secondary organic carbon (SOC), we applied the EC tracer method (Turpin and Huntzicker, 1995; Cabada et al., 2002), using the equations:

$$(OC)_{tot} = (OC)_{pri} + (OC)_{sec} \quad (1)$$ or

$$(OC)_{tot} = \left(\frac{OC}{EC}\right)_{pri} \cdot (EC)_{pri} + (OC)_{sec} \quad (2)$$

where $(OC/EC)_{pri}$ is the ratio for the local primary sources affecting the measured concentrations. A qualitative estimation of SOC using OC/EC ratios is valid only after careful inspection of local sources of OC and EC on a seasonal basis (e.g. Na et al., 2004). ~~Taking into account the seasonal variation in the primary emissions and also the effect of meteorology on the primary emissions ratio, different primary OC/EC ratios for the cold and the warm period were applied for this study (Gelencsér et al., 2007; Grivas et al., 2012).~~

In Fig. 8 the seasonal cycles of OC and EC at Penteli-Athens and Finokalia-Crete are shown. The levels of OC and EC in Athens are constantly higher than those at Finokalia, by 55% in the warm season up to 200% in the cold season. By considering Finokalia station as a reference, it is estimated that in Athens during the warm season 67±7% of ~~emitted~~measured OC and 53±12% of ~~emitted~~ EC is regional, while during cold months, the regional contribution for OC is only 33±7% and for EC 29±8%. It is observed that from April to October there is an almost a constant difference between the two sites that increases notably during the coldest period of the year, from November to March.

During the warm period, due to the limited rain in the area which favors the aging of polluted air masses (e.g. Perrone et al., 2011), a standard background is formed at the regional context. The increased values in Athens compared to Finokalia, can be attributed to an additional EC fraction due to traffic and a constant fractional input of OC added to the fossil fuel road transport emitted aerosol, in agreement with Theodosi et al. (2011). According to Pio et al. (2007) and Theodosi et al. (2011) the simple use of the same primary OC/EC factor to estimate secondary carbon aerosol in rural and remote European areas in the warm season, is adequate. Thus, from April to October in Athens, we estimated the contribution of primary and secondary organic aerosols in the organic carbon concentrations using Eq. (2) and applying an OC/EC_{pri} ratio equal to 1, since traffic is the main active source during this time period (e.g. Lonati et al.; 2008).

During this period, SOC ranges from 0.06 to 5.2 μg m^{-3}, with an average of 1.5±0.9 μg m^{-3}, constituting about 75±6% of organic carbon in Athens. It is shown that SOC is a major contributor to OC during the warm season in the area, as also indicated by Bougiatioti et al. (2013) and Lonati et al. (2007), underlying the secondary nature of fine particles (Pateraki et al., 2012). In absolute values, the average in Athens is lower than the one (2.7 μg m^{-3}) reported by Sanchez de la Campa et al. (2009) in an urban background station in Spain. The monthly means of SOC (Figure 9) in the warm period ~~presents a~~present maximum in summer (Jul-Aug), when there is intense photochemical activity that leads to the production of secondary organic carbon. WSOC, which is considered to be predominantly a secondary atmospheric product, also follows the seasonal variability of SOC (Figure 9), a conclusion strengthened by the significant correlation between daily SOC and WSOC values (R^2=0.53, slope=0.69, n=591, p<0.001). Contrary, the correlation between SOC and nss-SO_4^{-2} was much weaker (R^2=0.22, slope=1.00, n=785, p<0.001), indicating less common sources between SOC

and nss-SO_4^{-2}. Finally, it is worth noting the decreasing trend of SOC during the five year period of this study~~,~~ (not shown), accompanied by a decrease in WSOC (22% reduction from 2008 to 2013) and nss-SO_4^{-2}~~.~~ (58% reduction from 2008 to 2013). This downward tendency of the aforementioned concentrations can be attributed to the decrease in fuel consumption ~~and the concurrent reduction of private car use~~, as a result of the economic crisis in Greece.

In the cold season, for the estimation of SOC and the relevant primary OC/EC ratio, fossil fuel and wood burning combustion from domestic heating should be also taken into account (Gelencsér et al., 2007; Lonati et al., 2007; Lonati et al., 2008). Since this ratio can vary largely depending on the site and the different sources, it was not feasible to estimate SOC during the cold period. In Fig. 8, the difference between OC and EC levels at Finokalia (Crete) and Penteli (Athens), increases during the cold season compared to warm, reflecting the contribution of additional local sources in Athens. Assuming that the vehicular traffic is stable throughout the year (Grivas et al., 2012) and long range transport and meteorology is similar over both sites, the increase in OC and EC during the cold season, can be attributed to an additional primary source, most probably heating. In addition by examining the difference ~~between~~of OC and EC levels between Athens and Finokalia during the winter months for the whole studied period a notable increase during the 2011-2013 period compared to 2008-2010 is also observed (30% in ΔOC and 80% in ΔEC), mainly driven by wood burning activities maximized during the last two winters (2011-2013) in most Greek cities (Saffari et al., 2013).

Unfortunately, statistical information or inventories for the use of wood in domestic heating in Athens are totally missing. Moreover, the only study addressing the increasing role of biomass burning on air quality in Greek cities is from Safari et al., (2013), who reported an increase in wood burning tracers at the same time with a decrease in fossil fuel tracers, at Thessaloniki (the second most important Greek city) and during the first winter with a significant increase in fuel price.

4 Conclusions

Continuous sampling of the $PM_{2.5}$ aerosol fraction on a daily basis was conducted in Athens (Penteli station, urban background) during a five year period (2008-2013). Subsequent chemical analyses allowed the determination of organic carbon (OC), elemental carbon (EC) and water soluble organic carbon (WSOC) concentrations and

the estimation of secondary organic carbon (SOC). A comparison with parallel measurements from a remote site on Crete Island (reference ACTRIS site for Eastern Mediterranean) enabled the identification and quantification of urban sources contribution on regional background. The results of this study, coinciding with the beginning of the economic crisis in Greece, reflect the combinational effect of limited vehicular circulation and increased wood combustion for domestic heating. This first long term measurement of OC, EC, WSOC and the estimation of SOC provide a unique opportunity to qualify and quantify the rapidly changing air pollution characteristics in the studied area, which is a mandate for future air quality policies.

The main conclusions arising from this study are summarized below:

- OC and EC concentrations in Athens back in 2003, were 3-4 times higher compared to this study, while later studies revealed similar ~~(~~or slightly higher values depending on the site type~~).~~. Average OC and EC concentration is 2.1±1.3 μg m^{-3} and 0.54±0.39 μg m^{-3}, respectively. OC and EC present covariance for most of the sampling period while maximum values are observed during the coldest months of the year, when there is increased fuel combustion. The aforementioned outputs reveal that OC and EC emission rates are mostly proportional to each other, suggesting hence that OC and EC fractions are mainly emitted by common primary sources at a regional scale.
- On a seasonal basis, summer EC is formed by predominant regional sources (53±12% of EC), such as fossil fuel combustion (traffic), whereas during winter, the prevailing result of local sources such as fuel combustion is highlighted (71±8% of EC). EC during summertime is decreasing through the years, since there is a simultaneous reduction in traffic and industrial activity, due to the economic crisis in Greece. On the contrary, EC concentration during winter presents a significant increase since 2011, which can be attributed to the selection of wood as the major fuel source for domestic heating. OC concentration does not present a clear ~~seasonal~~inter-annual pattern, probably because of the episodic nature of biomass burning, as depicted from the increased calculated standard deviations that may have balanced out the aforementioned trend.

- Total carbon for the whole sampling period (sum of OC and EC) constitutes a significant part of $PM_{2.5}$ aerosol fraction (TC/PM= ~14%), while OC accounts for 79±4% of total carbon, constituting the predominant carbon contributor. Additionally, the estimated POM accounts for 24±6% of the collected fine aerosol.
- The total of five-year samples provides an average OC/EC ratio of 4.7±1.3, while on a seasonal basis the OC/EC ratios are higher than those reported for other urban background sites around the world~~, which is expected for long-range transport polluted sites.~~. The elevated measured values of OC/EC ratio highlight the secondary nature of secondary organic carbon in the area~~.~~ especially during summertime. Additionally, the calculated correlation between OC and EC suggests that OC and EC fractions are emitted by common primary sources while, simultaneously there is impact of additional sources like production of secondary organic carbon. More specifically, in regards to primary emissions, it appears that the dominant primary source of EC is mainly fossil fuel combustion (such as traffic) while, biomass emission sources contributes mainly during the cold period.
- The calculated WSOC average concentration is 1.5±0.9 μg m^{-3}, and it presents significant dependence on OC concentration, revealing their common sources and subsequently the predominant secondary nature of OC in the studied area. Furthermore, the estimated WSOC/OC ratio is 63±7%, illustrating the presence of aged aerosol in the site. In addition, this work indicates that emissions, from primary non-biomass burning sources of water-soluble organic carbon and from secondary organic products, can contribute to some extent to the variability of organic carbon observed in the studied location.
- SOC presents maximum values during summer, when there is intense photochemical activity, while the intra-annual variability of SOC is similar to that of WSOC, highlighting significant aging processes as characteristic at the regional scale. SOC estimation was not feasible in the cold period (November to March).
- The comparison of OC and EC levels between the urban background and the remote-coastal sites indicated ~~the increasing contribution~~an 80% increase of EC, due to local sources in Athens, during the cold season of the last two years

(wintertime 2011-2012 and 2012-2013), when economic hardship massively led residents to wood burning for heating purposes.

Acknowledgments

This research has been co-financed by the European Union (European Social Fund – ESF) and Greek national funds through the Operational Program "Education and Lifelong Learning" of the National Strategic Reference Framework (NSRF) - Research Funding Program: Heracleitus II. Investing in knowledge society through the European Social Fund.

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List of figures

Figure 1. Daily OC and EC concentrations at Penteli station, Athens, for the period May 2008 - April 2013.

Figure 2. Average seasonal cycle of OC and EC concentrations calculated from daily values, for the period May 2008 - April 2013.

Figure 3. Average winter and summer OC and EC concentrations calculated from daily values and; EC_{summer} to EC_{winter} median ratios, for the period May 2008 - April 2013.

Figure 4. Average seasonal cycle of the OC/EC ratio calculated from daily values, for the period May 2008 - April 2013.

Figure 5. ~~Average summer and winter nss-K^+ and EC concentrations calculated from daily values, for the period May 2008 - April 2013.~~

~~Figure 6.~~ Scatter plot of the daily OC and WSOC concentrations, for the period May 2008 - April 2013.

Figure ~~7~~6. Average seasonal cycle of OC, EC, WSOC, WIOC concentrations and the WSOC/OC ratio calculated from daily values, for the period May 2008 - April 2013

Figure 7. Average summer and winter nss-K^+ and EC concentrations calculated from daily values, for the period May 2008 - April 2013. nss-K^+ concentrations were multiplied by 2 for visualization purposes.

Figure 8. Average seasonal cycles of OC and EC concentrations at Penteli, Athens and Finokalia, Crete Island, calculated from daily values, for the period May 2008 - April 2013.

Figure 9. Average monthly variability (from April to October) of WSOC and estimated SOC concentrations, calculated from daily values, for the period May 2008 - April 2013.

Table 1: $PM_{2.5}$ mass, OC, EC, WSOC concentrations and OC/EC ratios reported in bibliography compared to this study.

Location Site*	Sampling Period	$PM_{2.5}$ mass ($\mu g\ m^{-3}$)	OC ($\mu g\ m^{-3}$)	EC ($\mu g\ m^{-3}$)	WSOC ($\mu g\ m^{-3}$)	OC/EC
Athens, Urb-BG, Current study	May 2008-April 2013	20±11	2.±1.3	0.54±0.39	-	4.7±1.3
El Arenosillo (Spain), Urb-BG [1]	02/06/2005-30/06/2006	21	2.9	1.1	-	2.9
Barcelona, Urb-BG [2]	27/07-01/09/2004	16.4	3.7	0.8	1.6	4.6
Barcelona, Urb-BG [2]	16/11-16/12/2004	25.8	6.7	1.2	2.1	5.6
Duisburg, Urb-BG [3]	Oct-Nov/2002	14.7	-	1.32	-	-
Prague, Urb-BG [3]	Nov/2002-Jan/2003	29.6	-	1.69	-	-
Amsterdam, Urb-BG [3]	Jan-Mar/2003	25.4	-	1.37	-	-
Helsinki, Urb-BG [3]	Mar-May/2003	8.3	-	0.7	-	-
Barcelona, Urb-BG [3]	Mar-May/2003	20	-	1.52	-	-
Athens, Urb-BG [3]	Jun-Jul/2003	25.3	-	1.67	-	-
Salento's pen. (Lecce), Urb-BG [4]	Mar-Dec/2007	19±9	5.6±2.8	1.5±12	-	-
Milan, Urb-BG [5] [6]	Aug/2002-Dec/2003, spor	24.5	9.2±7.2	1.4±0.4	-	-
Madrid, Urb-BG [7]	June/2009	-	2.71	0.94	-	-
Madrid, Urb-BG [7]	Jan-Feb/2010	-	1.2	1.53	-	-
Athens, Urban** [8]	Jan-Aug/2003	-	6.8	2.2	-	-
Istanbul, Urban [9]	Jul/2008-Jun/2009	-	6.65	2.92	-	-
Athens, Urban [10]	Feb-Dec/2010, spor	20	2.43	0.99	-	2.92±0.6
Athens, Suburb [11]	29/02-02/05 & 04/06-05/08/2008	23.8	4.1	0.48	-	-
Athens, Traf-Ind [11]	29/02-02/05 & 04/06-05/08/2008	24.7	1.46	1.8	-	-
Athens, Coa-BG [11]	29/02-02/05 & 04/06-05/08/2008	19.2	2.39	0.44	-	-
Thessaloniki, Urb-Ind**[12]	Jun-Sep/2007	-	6.4	2.91	-	2.2
Thessaloniki, Urb-Ind**[12]	Dec/2006-Mar/2007	-	8.73	2.93	-	2.98
Thessaloniki, Urb-Traf**[12]	Jun-Sep/2007	-	7.66	2.64	-	2.9
Thessaloniki, Urb-Traf**[12]	Dec/2006-Mar/2007	-	8.07	1.82	-	4.43
Finokalia (Crete), Remote [13]	Jul/2004-Feb/2007, spor	-	-	-	-	5.1
Finokalia (Crete), Remote [14]	Jul/2004-Jul/2006, spor	-	1.8±1.4	0.27±0.18	-	-
Finokalia (Crete), Remote [15]	10/7-23/7/2007	-	2.58±1.12	0.36±0.25	1.74±0.86	-
Finokalia (Crete), Remote [15]	24/7-6/8/2007	-	3.04±1.55	0.32±0.17	1.93±0.84	-
Akrotiri (Chania,Crete), Suburban [16]	Oct/2009	-	2.3±1.2	0.8±0.2	-	2.8±1.0
El Campus (Spain), Rural [1]	02/06/2005-30/06/2006	21	3	0.6	-	4.7
French Riviera, Coastal [17]	5-29/5/2007	-	2.07-5.37	0.13-0.33	0.02-0.08	-
Montseny, Reg-BG [18]	2002-2007	-	2	0.2	-	-
C. de Belver, Mallorca, Sub-BG [19]	8/1/2004-29/2/2005, spor	20	2.9	0.5	-	-

* spor: Sporadically, Urb-BG: Urban Background, Urb-Ind: Urban Industrial, Urb-Traf: Urban Traffic, Traf-Ind: Traffic Industrial, Sub-BG: Suburban Background, Coa-BG: Coastal Background.

**PM_{10} sampling

[1.](Sanchez de la Campa et al., 2009) [2.](Viana et al., 2007) [3.](Sillanpaa et al., 2006) [4.](Perrone et al., 2011) [5.](Lonati et al., 2008) [6.](Lonati et al., 2007) [7.](Mirante et al., 2014) [8.](Grivas et al., 2012) [9.](Theodosi et al., 2010) [10.](Remoundaki et al., 2013) [11.](Pateraki et al., 2012) [12.](Terzi et al., 2010) [13.](Bougiatioti et al., 2013) [14.](Koulouri et al., 2008) [15.](Bougiatioti et al., 2011) [16.](Kopanakis et al., 2012) [17.](Piazzola et al., 2012) [18.](Pey et al., 2009a) [19.](Pey et al., 2009b)

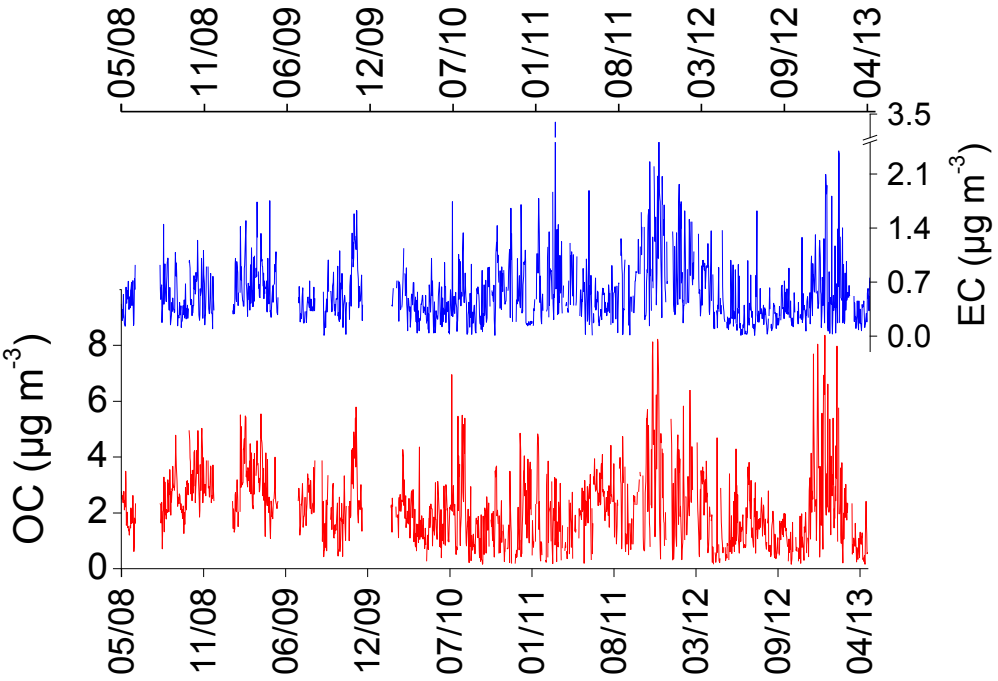


Figure 1. Daily OC and EC concentrations at Penteli station, Athens, for the period May 2008 - April 2013.

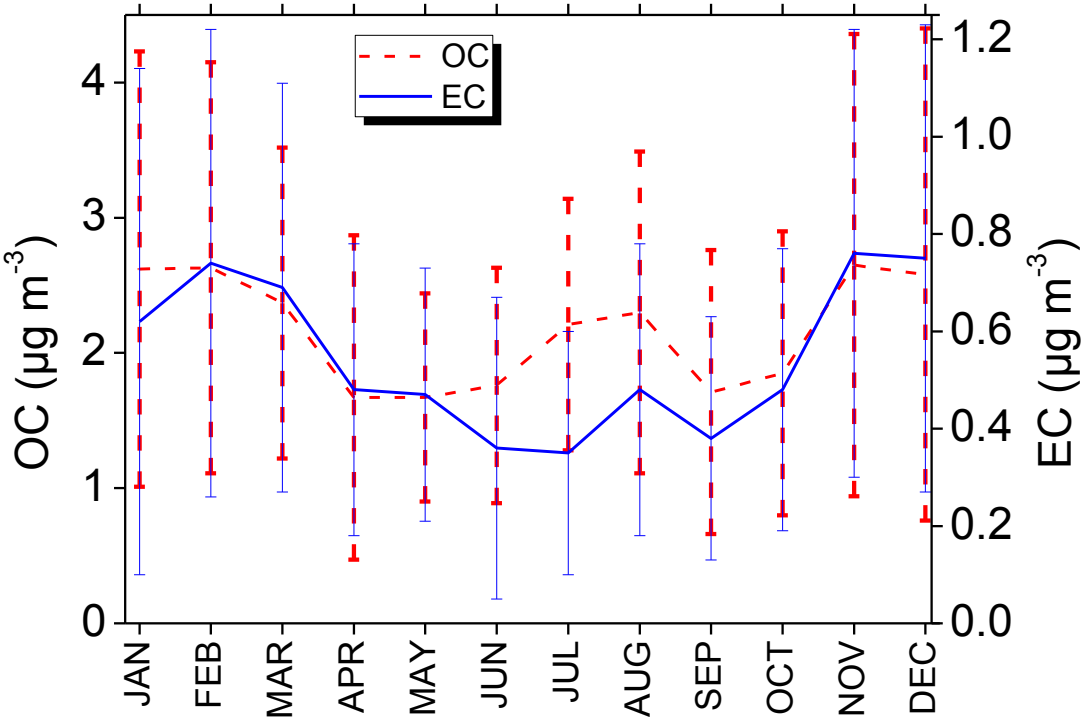


Figure 2. Average seasonal cycle of OC and EC concentrations calculated from daily values, for the period May 2008 - April 2013.

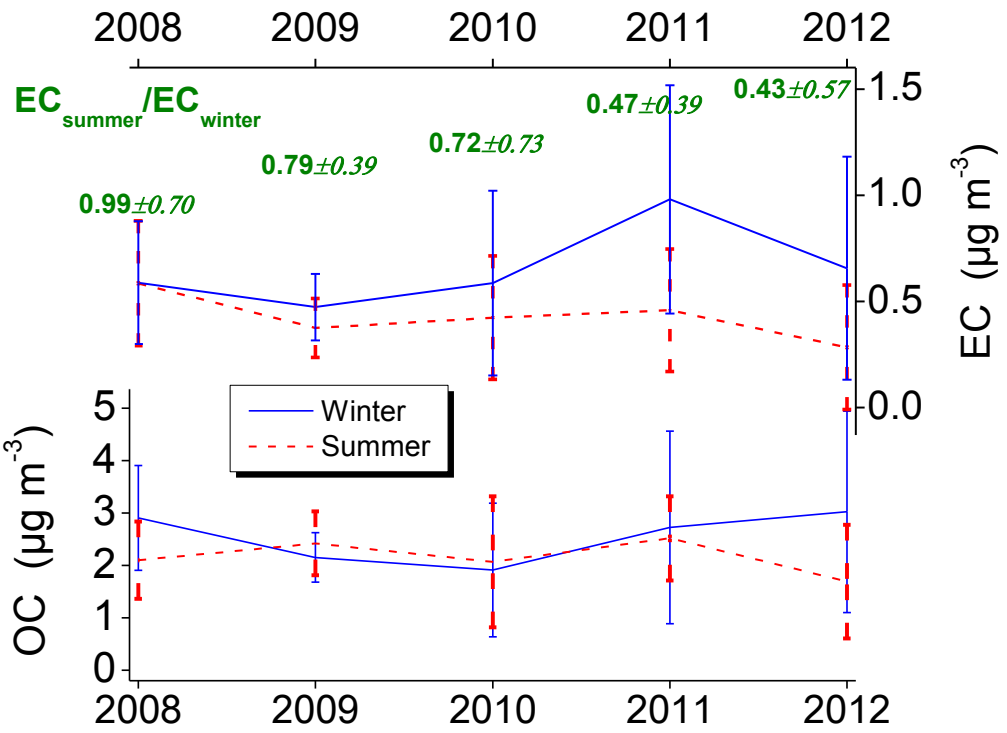


Figure 3. Average winter and summer OC and EC concentrations calculated from daily values and; EC_{summer} to EC_{winter} median ratios, for the period May 2008 - April 2013.

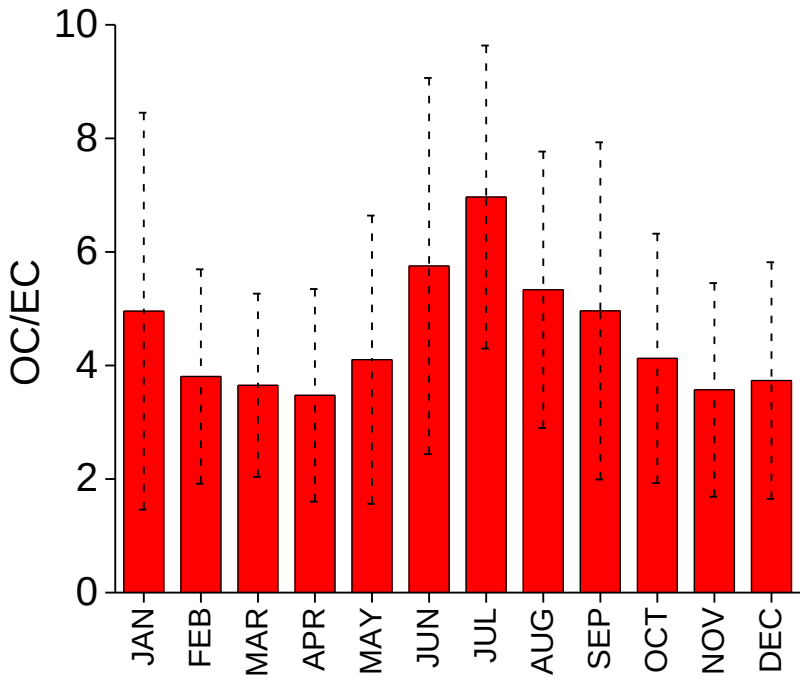


Figure 4. Average seasonal cycle of the OC/EC ratio calculated from daily values, for the period May 2008 - April 2013.

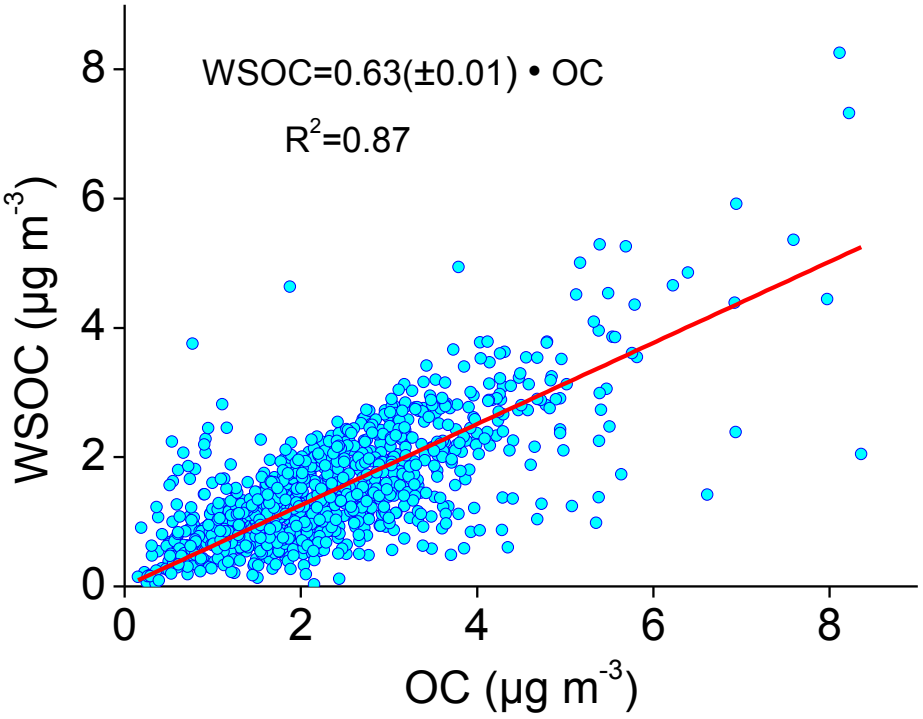
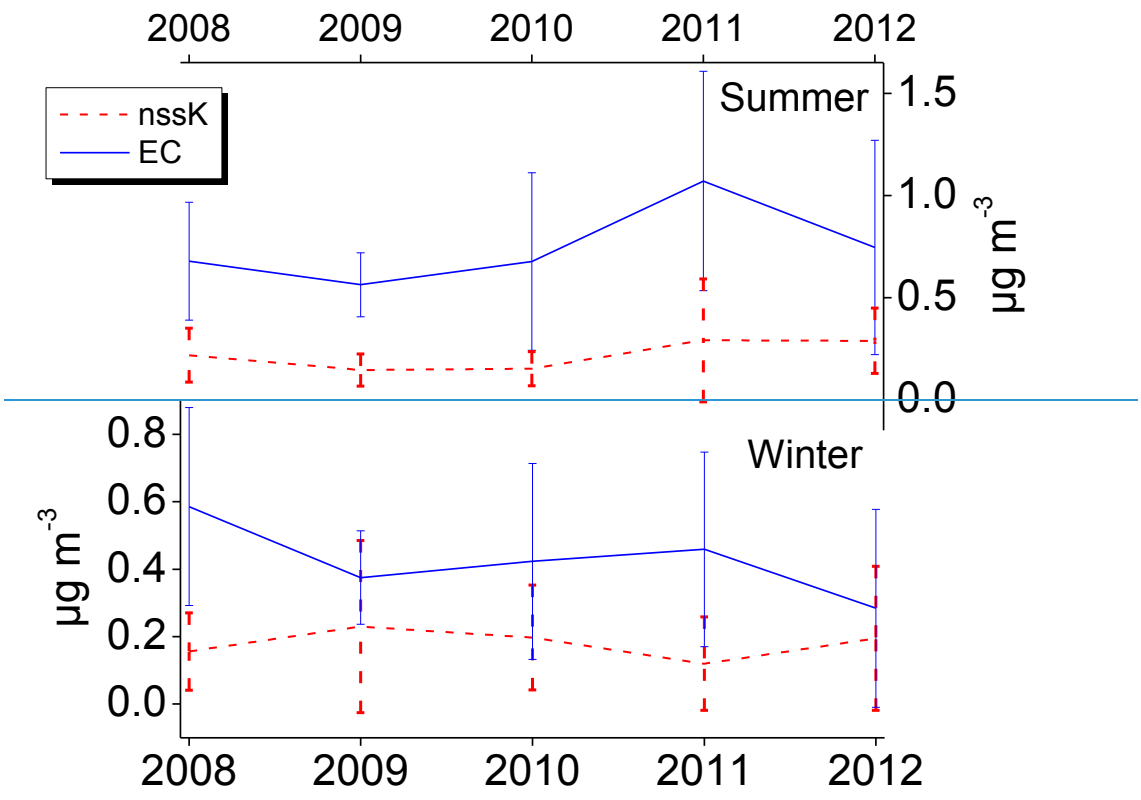
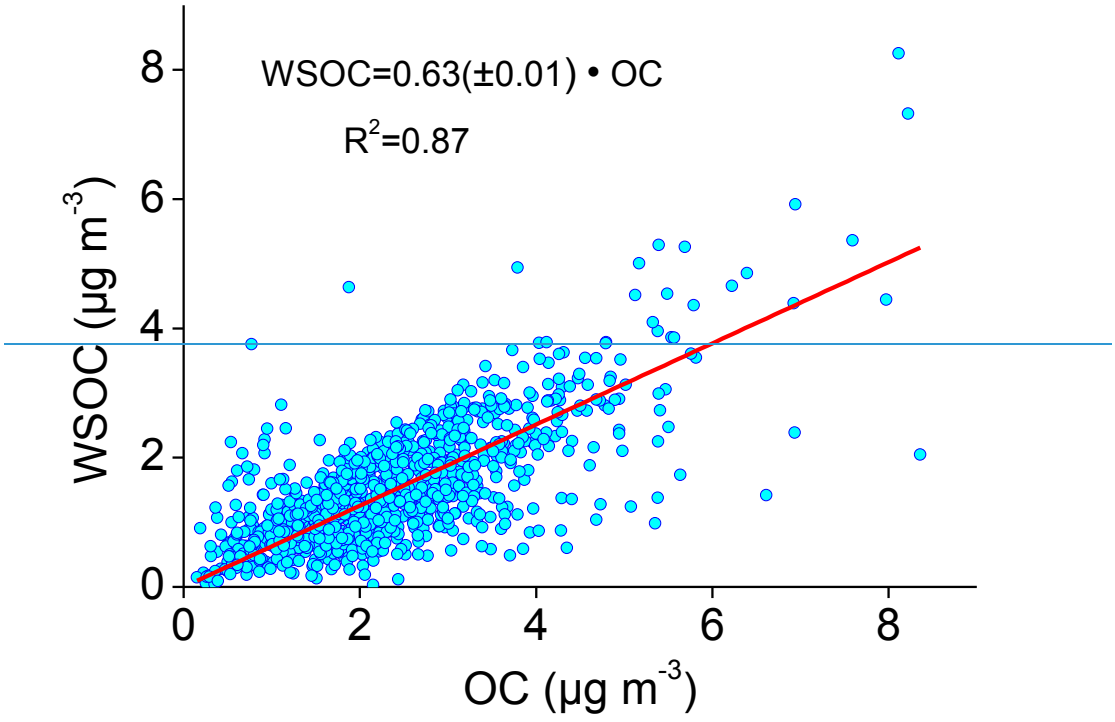


Figure 5. Scatter plot of the daily OC and WSOC concentrations, for the period May 2008 - April 2013.



~~Figure 5. Average summer and winter nss-K^+ and EC concentrations calculated from daily values, for the period May 2008 – April 2013.~~



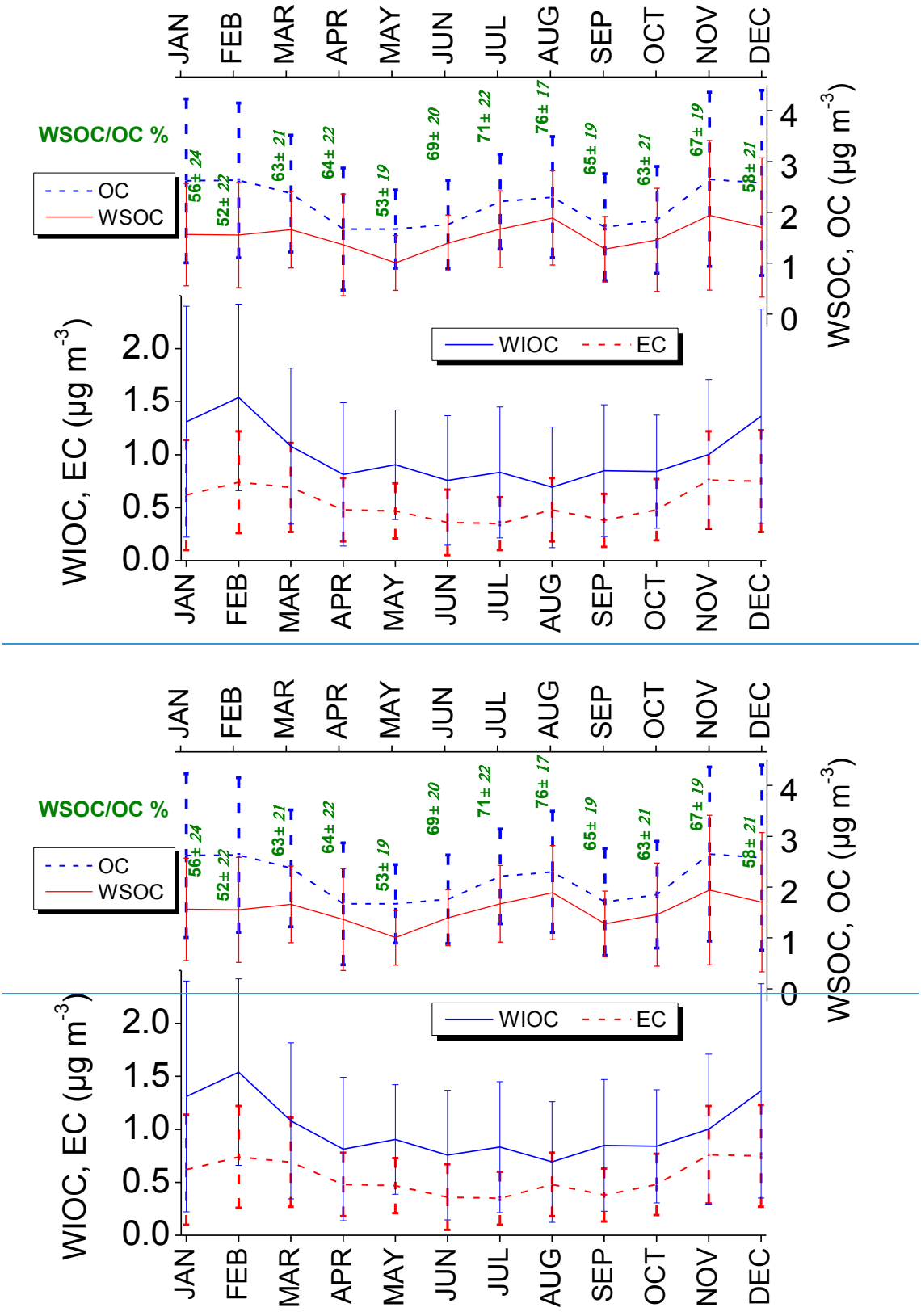


Figure 6. ~~Scatter plot of the daily OC and WSOC concentrations, for the period May 2008 – April 2013.~~

~~Figure 7.~~ Average seasonal cycle of OC, EC, WSOC, WIOC concentrations and the WSOC/OC ratio calculated from daily values, for the period May 2008 - April 2013.

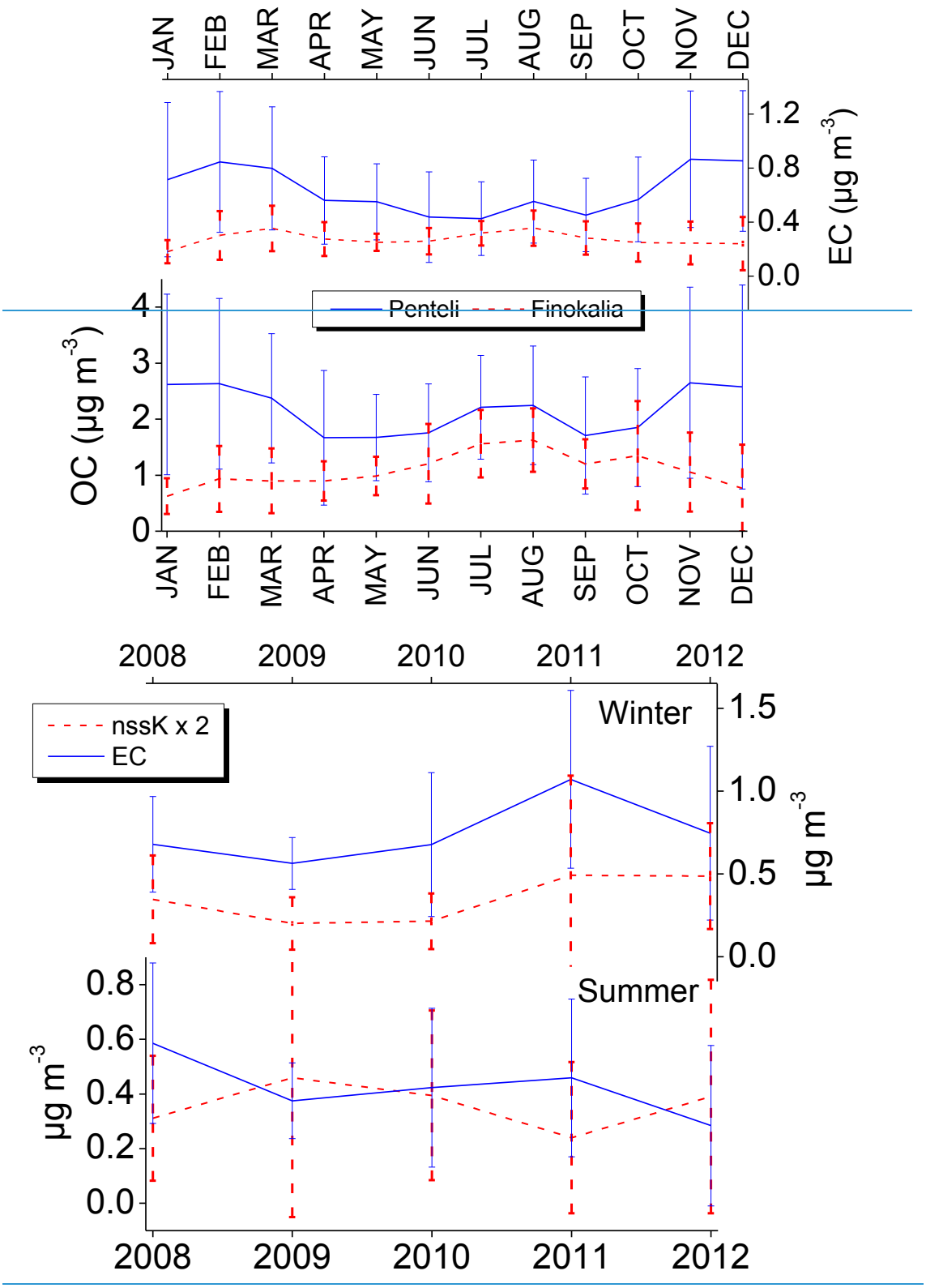


Figure 7. Average summer and winter nss-K^+ and EC concentrations calculated from daily values, for the period May 2008 - April 2013. nss-K^+ concentrations were multiplied by 2 for visualization purposes.

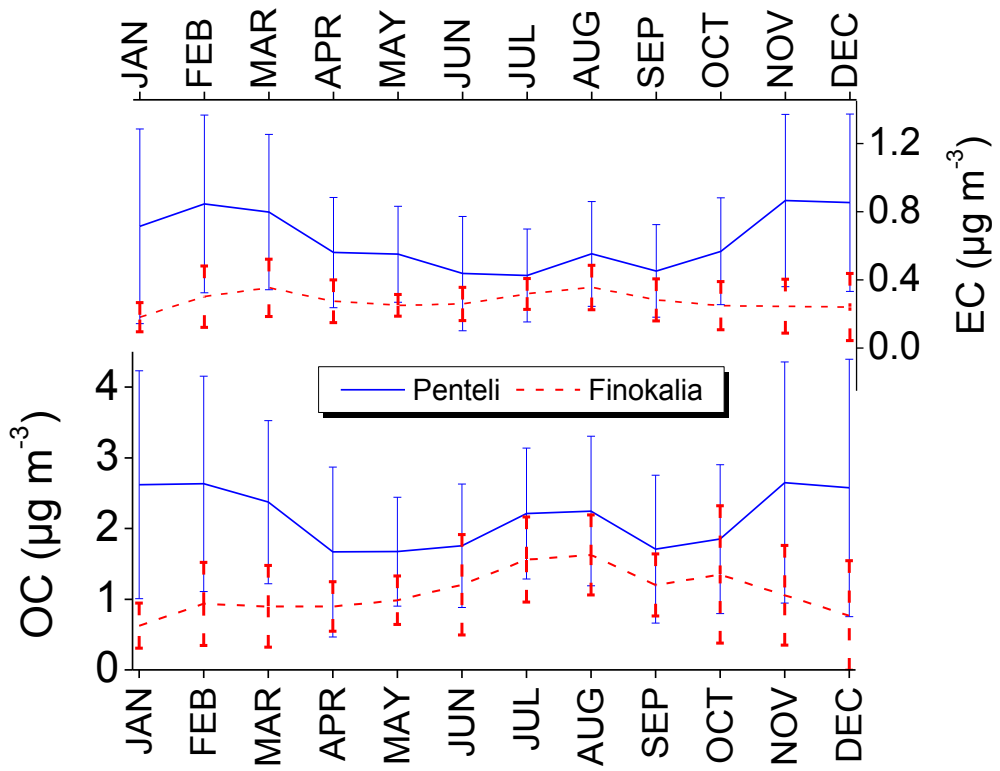


Figure 8. Average seasonal cycles of OC and EC concentrations at Penteli, Athens and Finokalia, Crete Island, calculated from daily values, for the period May 2008 - April 2013.

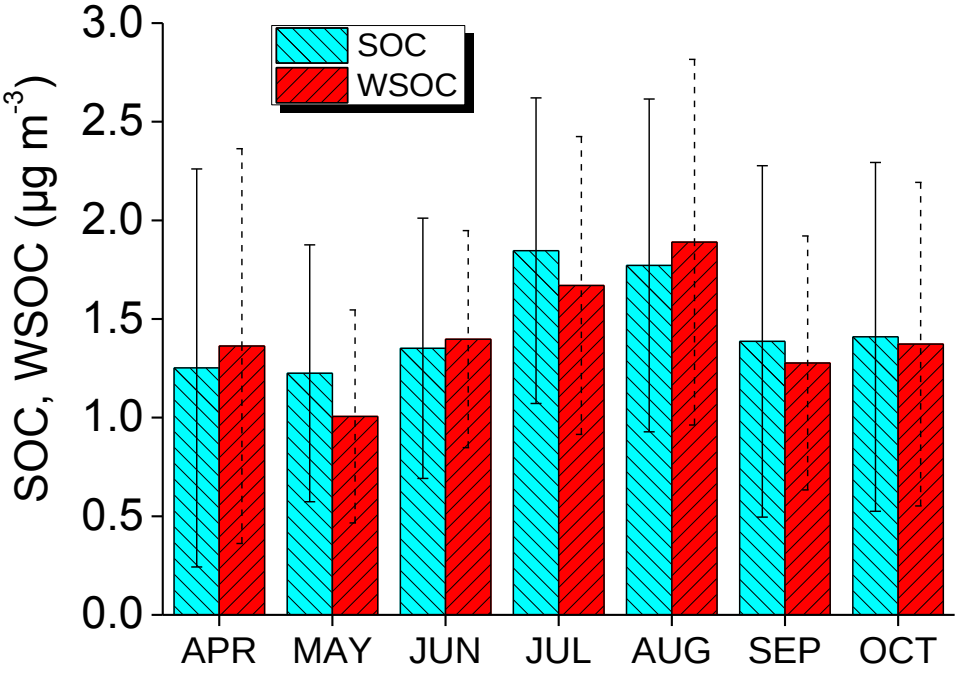


Figure 9. Average monthly variability (from April to October) of WSOC and estimated SOC concentrations, calculated from daily values, for the period May 2008 - April 2013.