



# Sources and chemical characterization of organic aerosol during the summer in the eastern Mediterranean

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**Abstract.** The concentration and chemical composition of non-refractory fine particulate matter (NR-PM<sub>1</sub>) and black carbon (BC) levels were measured during the summer of 2012 in the suburbs of two Greek cities, Patras and Athens, in an effort to better understand the chemical processing of particles in the high photochemical activity environment of the eastern Mediterranean. The composition of PM<sub>1</sub> was surprisingly similar in both areas, demonstrating the importance of regional sources for the corresponding pollution levels. The PM<sub>1</sub> average mass concentration was 9–14 μg m<sup>-3</sup>. The contribution of sulfate was around 38 %, while organic aerosol (OA) contributed approximately 45 % in both cases. PM<sub>1</sub> nitrate levels were low (2 %). The oxygen to carbon (O : C) atomic ratio was 0.50 ± 0.08 in Patras and 0.47 ± 0.11 in Athens. In both cases PM<sub>1</sub> was acidic.

Positive matrix factorization (PMF) was applied to the high-resolution organic aerosol mass spectra obtained by an Aerodyne High-Resolution Time-of-Flight Aerosol Mass Spectrometer (HR-ToF-AMS). For Patras, five OA sources could be identified: 19 % very oxygenated OA (V-OOA), 38 % moderately oxygenated OA (M-OOA), 21 % biogenic oxygenated OA (b-OOA), 7 % hydrocarbon-like OA (HOA-1) associated with traffic sources and 15 % hydrocarbon-like OA (HOA-2) related to other primary emissions (including cooking OA). For Athens, the corresponding source contributions were: V-OOA (35 %), M-OOA (30 %), HOA-1 (18 %) and HOA-2 (17 %). In both cities the major component was OOA, suggesting that under high photochemical conditions most of the OA in the eastern Mediterranean is

quite aged. The contribution of the primary sources (HOA-1 and HOA-2) was important (22 % in Patras and 35 % in Athens) but not dominant.

## 1 Introduction

Atmospheric aerosols can affect human health by causing cardiovascular and respiratory problems (Davidson et al., 2005; Pope and Dockery, 2006), they reduce visibility (Watson, 2002) and influence the energy balance of our planet (IPCC, 2013) by scattering or absorbing radiation and changing cloud reflectivity and lifetime. Submicrometer atmospheric particles mainly consist of sulfates, ammonium, organic matter, nitrates, elemental carbon and metals. Organic aerosol (OA) represents a major fraction of the submicron aerosol mass (Kanakidou et al., 2005; Zhang et al., 2007). The recent development of the Aerodyne High-Resolution Time-of-Flight Aerosol Mass Spectrometer (HR-ToF-AMS) (DeCarlo et al., 2006) allows high time resolution size-resolved measurements of the fine non-refractory inorganic and organic aerosol components. In addition, several techniques have been developed for the deconvolution of the AMS organic mass spectra (Zhang et al., 2011) including custom principal component analysis (Zhang et al., 2005), multiple component analysis (Zhang et al., 2007), and positive matrix factorization (PMF) (Paatero and Tapper, 1994; Lanz et al., 2007). The most recent algorithm, the multilinear engine, (ME-2) (Lanz et al., 2008, Canonaco et al., 2013)

is a hybrid of chemical mass balance (CMB) and bilinear models (e.g., PMF). The combination of AMS measurements with other instrumentation and the use of the corresponding source apportionment techniques can provide valuable information about the ambient aerosol sources and their chemical characterization. In this study the technique of PMF analysis on HR-ToF-AMS mass spectra is used.

Zhang et al. (2005) showed that summertime OA in a major urban area of the US (Pittsburgh) consisted of oxygenated OA (OOA) and hydrocarbon-like OA (HOA). Lanz et al. (2007) further deconvolved OOA into a more oxygenated OA (OOA-1) and a less oxygenated (OOA-2) component during a summer period in Zurich. They also reported a wood-burning and a charbroiling factor for the first time. Marine OA (MOA) was identified by Crippa et al. (2013a) in Paris during summertime, while Schmale et al. (2013) suggested the existence of an amino-acids/amine OA factor (AA-OA), a methanesulfonic acid OA factor (MSA-OA), a marine oxygenated OA factor (M-OOA) and a sea spray OA factor (SS-OA) on Bird Island in the South Atlantic. The major OA components found are usually OOA and HOA (Ng et al., 2010). In our work the OA sources are investigated, in order to characterize two urban environments in the eastern Mediterranean.

Most of the studies on air quality in the eastern Mediterranean and Greece have been based on filter measurements (Manoli et al., 2002; Grivas et al., 2004; Papaefthymiou et al., 2005; Karanasiou et al., 2007; Chrysikou and Samara, 2009) or monitoring PM mass concentrations (Chaloulakou et al., 2003; Vardoulakis and Kassomenos, 2008; Yannopoulos, 2008) in major Greek cities (Athens, Thessaloniki, Patras). During the past years a few field campaigns using continuous PM composition measurement techniques have been conducted in rural/remote areas and urban centers in Greece. At the remote site of Finokalia (Crete) factor analysis on filter samples revealed three sources of coarse particles (crustal, photochemical, and marine aerosols) and two additional factors in the fine mode (residual oil and secondary/combustion aerosols) (Koulouri et al., 2008). For the same site no HOA was detected by PMF analysis of quadrupole-AMS data either in the summer or in the winter (Hildebrandt et al., 2010, 2011). For the city of Patras, Pikridas et al. (2013) found that the transported pollution accounted for 50 % of the PM<sub>2.5</sub> during the winter and more than 70 % during the rest of the year. However, the eastern Mediterranean urban environment remains not well characterized.

In the western Mediterranean there have been more measurement campaigns (e.g., Viana et al., 2005; Pérez et al., 2008; Pey et al., 2010; Pandolfi et al., 2014). In Barcelona primary OA accounted for 59 % of the OA in the late winter (Mohr et al., 2012). El Haddad et al. (2013) reported that OOA contributed 80 % of the OA mass in Marseille during the summer, while only 5 % of the OA was of industrial origin. Nicolas (2013) found that OOA ranged from 70 to 85 % of the total OA over a year at the Cape Corsica station. For

the same site the oxidation state of the OA during the summer reached extremely high values with  $f_{44}$  (the fraction of the AMS  $m/z$  44, which is an indicator of the oxidation state) higher than 0.25. Thus the measurements in the western Mediterranean have covered the different types of environments better, compared to the eastern Mediterranean.

Despite previous efforts, there are still several knowledge gaps related to the characterization of OA sources in the Mediterranean Basin. For example, the contribution of primary sources is still uncertain. Fresh OA from diesel exhaust initially resembles HOA but after aging may resemble semi-volatile OOA (SV-OOA) (Jimenez et al., 2009; Chirico et al., 2010). Aged gas-phase emissions from diesel engines, scooters and biomass burning may also produce secondary OA (SOA) with mass spectra similar to SV-OOA (Heringa et al., 2012). In addition, volatile organic compounds (VOCs) in chamber experiments form SOA, with mass spectra close to SV-OOA (Ng et al., 2010). The conversion of SV-OOA to more oxidized OA is still quite difficult to reproduce in the laboratory. Only recently Platt et al. (2013) showed that after 12 h of aging of gasoline Euro 5 car emissions, SOA with an O : C ratio of 0.7 was produced, resembling LV-OOA. In the field, Hildebrandt et al. (2010) demonstrated that primary emissions are becoming highly oxygenated within 1–2 days of transport under intense photochemical conditions. Recently Bougiatioti et al. (2014) showed that a large fraction of biomass burning OA (BBOA) is transformed to OOA even in the dark in less than 12 h during the summer in the eastern Mediterranean. The objectives of this work are as follows:

1. to characterize the chemical composition of the PM<sub>1</sub> in two Greek cities in the eastern Mediterranean using high time resolution instrumentation
2. to determine the corresponding OA sources and evaluate the relative significance of the primary versus the oxygenated factors
3. to provide insights about the chemical processing of the primary PM
4. to compare the mass spectra profiles to the corresponding profiles extracted in previous studies and
5. to assess the overall PM<sub>1</sub> pollution in the eastern Mediterranean in comparison with other European cities.

## 2 Experimental

### 2.1 Measurement campaign

The measurements presented here were part of a larger study, which involved measurements in several areas in Greece (Patras, Athens, Thessaloniki, and Finokalia) both in summer

and winter. In this work we will focus on the summer HR-ToF-AMS measurements in Patras and Athens. More information about the summer study is provided in Tsiflikiotou et al. (2015).

## 2.2 Sampling sites in Patras

Patras has approximately 300 000 inhabitants and is located at the Gulf of Patras, at the foothills of a 2 km high mountain. The major anthropogenic activities include a small industrial zone about 16 km southwest of the city center and a harbor around 2.5 km southwest of the city. The nearest major city is Athens, around 220 km to the east. Measurements in Patras were performed simultaneously at two locations: in the center of the city (38°14'46" N, 21°44'08" E) and at the Institute of Chemical Engineering Sciences, ICE-HT (38°17'52" N, 21°48'31" E), which is 8 km (northeast) away from the city center and 1 km (south) from the Patras–Athens highway (Fig. S1 in the Supplement). The site is surrounded by olive tree fields. A few small settlements are located in a distance of 1 km (southwest and northeast). Most of the instrumentation was deployed at the ICE-HT Institute due to space limitations in the city center station. This paper focuses only on the ICE-HT measurements.

## 2.3 Instrumentation in Patras

A HR-ToF-AMS from Aerodyne Research Inc. (DeCarlo et al., 2006) measured the size-resolved chemical composition of the NR-PM<sub>1</sub> aerosol species. The tungsten filament for electron ionization was run at an accelerating voltage of 70 eV, while the vaporizer temperature was set at 600 °C. Alternative runs between V mode (single-stage reflectron) and W mode (double-stage reflectron) were performed with 3 min of measuring time for each mode. In this paper the V-mode data are presented.

A proton-transfer-reaction mass spectrometer (PTR-MS, Ionicon Analytik) was used for the characterization of the volatile organic compounds (VOCs). More details about the VOC measurements are presented in Kaltsonoudis et al. (2015). A Scanning Mobility Particle Sizer, (SMPS, classifier model 3080, DMA model 3081, CPC model 3787, TSI) was operated at a sheath flow rate of 5 L min<sup>-1</sup> and a sample flow rate of 1 L min<sup>-1</sup>. The SMPS measured the number size distribution in the 10–500 nm range. A Multiple-Angle Absorption Photometer (MAAP, Thermo Scientific Inc.) (Petzold and Schönlinner, 2004) was used for the BC measurement. NO<sub>x</sub>, SO<sub>2</sub>, O<sub>3</sub> and CO concentrations were measured by the corresponding monitors (Teledyne, models T201, 100E, 400E and 300E respectively).

A filter sampler (MetOne SAASS) was used to collect PM<sub>2.5</sub> samples for inorganic and organic chemical composition analysis. The sampling resolution was 24 h and the flow rate of each filter was 6.7 L min<sup>-1</sup>. Teflon filters (Whatman 7582 004, 0.2 μm pore size) were used for the measurement

of the inorganic anion and cation mass concentrations, using two ion chromatography systems (Metrohm 761 Compact IC). Pre-baked Quartz filters were used for the elemental carbon (EC) and organic carbon (OC) measurement using a laboratory EC / OC analyzer (Sunset Laboratory Inc). More details about the filter extraction procedure are given by Pikridas et al. (2013) and Tsiflikiotou et al. (2015).

The HR-ToF-AMS and the PTR-MS measurements covered the period from 8 to 27 June 2012, while the rest of the instrumentation provided measurements from 8 June to 26 July 2012. All the above mentioned instruments were located at the ICE-HT campus.

## 2.4 Sampling site in Athens

Athens is the most densely populated city in Greece with around 4 million inhabitants. The sampling site was at Demokritos National Center for Scientific Research, NCRS (37°59'43" N, 23°48'57" E), at the municipality of Agia Paraskevi. This is a suburban background site 10 km from the city center located at the foothills of Ymittos mountain and is surrounded by pine trees. This site is close (0.5 km) to the ring highway of Ymittos and approximately 1.5 km away from the Mesogion highway to the northwest. The closest residences are 0.5 km away. The relative position between Patras and Athens sampling site is illustrated in Fig. S2.

## 2.5 Instrumentation in the Athens site

For the measurements in Athens we used our mobile laboratory as a fixed station, in which the HR-ToF-AMS and the PTR-MS (same models as described in Sect. 2.3) were placed. An aethalometer (Magee Scientific, AE31) provided the BC concentrations at 880 nm. An SMPS (classifier model 3080 TSI, custom DMA, CPC model 3022, TSI) was operated at a sheath flow rate of 3 L min<sup>-1</sup> and a sample flow rate of 0.3 L min<sup>-1</sup> and measured the number size distribution in the 10–660 nm range. PM<sub>2.5</sub> was collected on Teflon filters every 24 h for the inorganic composition characterization, while a semi-continuous OC / EC analyzer (Field Instrument, Model 4F, Sunset Laboratory Inc) equipped with a PM<sub>2.5</sub> inlet and an activated carbon denuder was used for the PM<sub>2.5</sub> EC / OC measurements with a 3 h resolution.

The sampling period was from 8 to 26 July 2012. Due to technical problems the HR-ToF-AMS started measuring on 12 July 2012.

## 2.6 Data analysis

For HR-ToF-AMS, data analysis SQUIRREL v1.51C and PIKA v1.10C (Sueper, 2014) with Igor Pro 6.22A (WaveMetrics) were used. For the HR-ToF-AMS organic mass spectra, we used the fragmentation table of Aiken et al. (2009).

PMF and ME-2 analysis (Paatero and Tapper, 1994; Lanz et al., 2007, 2008; Ulbrich et al., 2009; Canonaco et al.,

2013) were performed using the HR-ToF-AMS organic mass spectra in order to investigate the different organic aerosol sources. High-resolution PMF was performed using the  $m/z$  values 12–200 as inputs and following the procedure of Ulbrich et al. (2009).

The Patras HR-ToF-AMS data were corrected for the collection efficiency (CE) using the algorithm of Kostenidou et al. (2007) with a 2 h resolution throughout the campaign. A shape factor ( $\chi$ ) of 1 was found to be the most appropriate for this data set (Supplement Sect. S2.A, Figs. S3–S4). The average CE was  $0.91 \pm 0.10$  and it was significantly higher compared to other studies, which often use a CE of 0.5. One reason could be that the particles entering the HR-ToF-AMS were not dried. Drying the particles usually decreases the CE because the particles bounce on the vaporizer (Matthew et al., 2008). The  $R^2$  between the 2 h resolution CE and the 2 h average ambient relative humidity (RH) was very low (0.02). This low correlation and the high CE values can be explained by the fact that the particles were acidic most of the time (see Sect. 3.1) and probably contained water during all the campaign. Comparing the  $PM_{10}$  HR-ToF-AMS sulfate (after CE corrections) to the  $PM_{2.5}$  filter sulfate measurements a slope of 1.05 and a high correlation ( $R^2 = 0.98$ ) were found as shown in Fig. S5. This could indicate that most of the  $PM_{2.5}$  sulfate was in the submicrometer particles. The  $PM_{2.5}$  sodium concentration was below the detection limit, so there was practically no sodium sulfate present. The average OA density estimated from the above algorithm was  $1.34 \pm 0.21 \text{ g cm}^{-3}$ , which is very close to the organic density calculated for Finokalia during the summer of 2008 ( $1.35 \pm 0.22 \text{ g cm}^{-3}$ , Lee et al., 2010).

For Athens the aerosol was not dried before it entered the HR-ToF-AMS, but the particles entering the SMPS were dried to maintain compatibility with long-term measurements performed at the site. Thus we modified the algorithm of Kostenidou et al. (2007), converting the ambient HR-ToF-AMS mass distributions to dry mass distributions using the relative humidity (RH) inside the sampling line and calculating the inorganic aerosol water content using the Extended Aerosol Inorganic Model II (E-AIM, Carslaw et al., 1995; Clegg et al., 1998; Massucci et al., 1999). As inputs to the E-AIM model we used the inorganic concentrations of sulfate, ammonium and nitrate and the temperature and RH at the entrance of the HR-ToF-AMS line. The algorithm was run for shape factors 1–1.4 and the optimum solution was selected (i.e., the minimum of the minimum error scores) which corresponded to the optimum CE, organic density, and shape factor (Supplement Sect. S2.B, Figs. S6–S7). The average CE was  $0.63 \pm 0.13$ . After applying CE corrections the  $PM_{10}$  HR-ToF-AMS sulfate correlated well with the  $PM_{2.5}$  filter sulfate (Fig. S8) ( $R^2 = 0.91$ , slope = 0.98), once more suggesting that the sulfate in the 1–2.5  $\mu\text{m}$  range was a small fraction of the  $PM_{2.5}$  sulfate. The average organic density was  $1.15 \pm 0.36 \text{ g cm}^{-3}$ , lower than in Patras, and the aver-

age shape factor was  $1.16 \pm 0.1$ , suggesting that a lot of the particles were not spherical.

The angle theta ( $\theta$ ) between the mass spectra vectors was used as a measure of their similarity (Kostenidou et al., 2009). The mass spectra are treated as vectors and the angle  $\theta$  is calculated by using their internal product. The lower the angle  $\theta$  is, the higher the similarity between the two spectra.

### 3 Results and discussion

#### 3.1 Patras

The time series of the mass concentration of the NR- $PM_{10}$  components measured by the HR-ToF-AMS and the BC in Patras are shown in Fig. 1a. The average  $PM_{10}$  mass concentration (not including dust) was  $8.6 \mu\text{g m}^{-3}$ . On average, the organic mass concentration was  $3.8 \mu\text{g m}^{-3}$ , sulfate  $3.3 \mu\text{g m}^{-3}$ , ammonium  $0.9 \mu\text{g m}^{-3}$  and BC  $0.5 \mu\text{g m}^{-3}$ . Nitrate was very low, around  $0.1 \mu\text{g m}^{-3}$ .

The average OM:OC ratio was  $1.80 \pm 0.10$ . The average diurnal profile of O:C is depicted in Fig. 2. O:C increased in the early morning hours (02:00–07:00 LT) and during the afternoon (15:00–17:00). The OA average diurnal profile exhibited three peaks (Fig. S9a); two of them (around 08:00–10:00 and 21:00–23:00) were associated with primary sources as the BC increased the same time as well. The OA increase at 11:00–16:00 is related to the formation of secondary species as the solar intensity peaks the same time. The fragments of  $m/z$  44 and 57 represented 0.14 and 0.01 of the organic signal correspondingly (Fig. S10a).

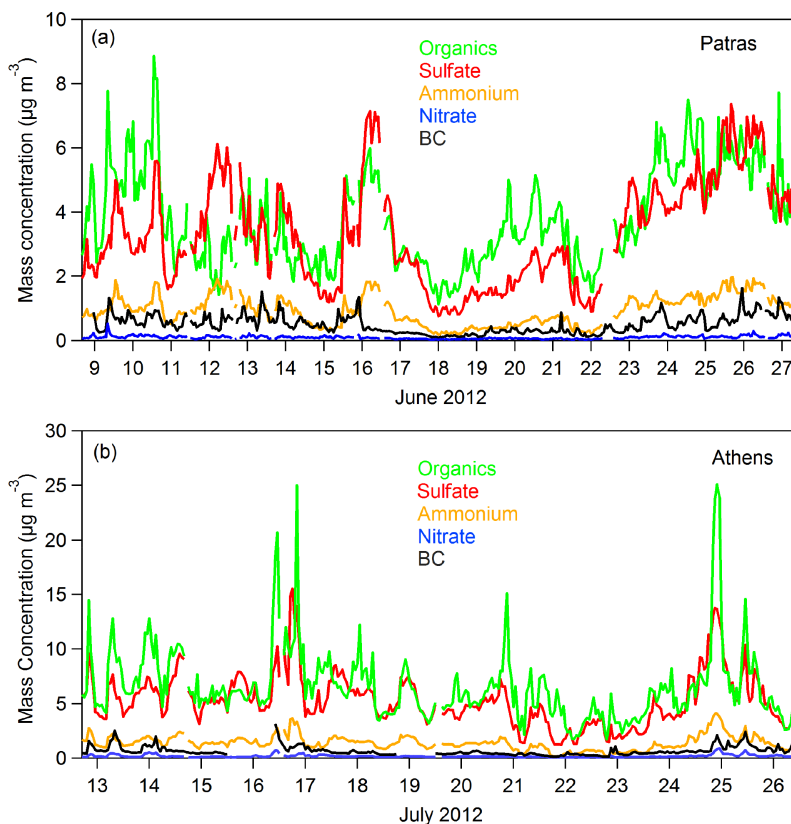
The  $PM_{2.5}$  organic carbon (OC) concentrations measured with filters was converted to organic mass (OM) using the corresponding OM:OC ratio for each filter sampling period provided by the HR-ToF-AMS and the two concentrations were compared. Figure S11a shows the correlation between the HR-ToF-AMS and the filters for organics which resulted in an  $R^2 = 0.57$ . This probably implies that the majority of the  $PM_{2.5}$  organics were in the  $PM_{10}$  range.

The  $PM_{10}$  aerosol as measured by the HR-ToF-AMS was always acidic with an average inorganic cations/anions equivalent ratio of  $0.75 \pm 0.07$ . This indicates that there was no available ammonia to fully neutralize the sulfate and thus the formation of  $PM_{10}$  ammonium nitrate (from ammonia and nitric acid) in the  $PM_{10}$  was not thermodynamically favorable.

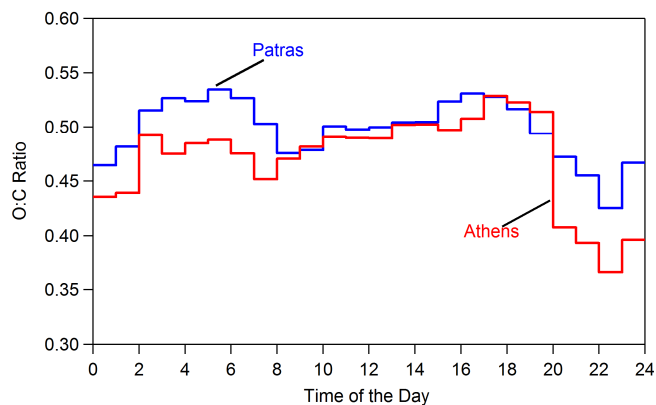
In order to estimate the organic nitrate mass (ONit) contribution to the total nitrate mass (TotNit) we followed the procedure of Farmer et al. (2010):

$$\frac{\text{ONit}}{\text{TotNit}} = \frac{(1 + R_{\text{ONit}}) \times (R_{[\text{NO}_2^+/\text{NO}^+]_{\text{meas}}} - R_{[\text{NO}_2^+/\text{NO}^+]_{\text{cal}}})}{(1 + R_{[\text{NO}_2^+/\text{NO}^+]_{\text{meas}}}) \times (R_{\text{ONit}} - R_{[\text{NO}_2^+/\text{NO}^+]_{\text{cal}}})}, \quad (1)$$

where  $R_{[\text{NO}_2^+/\text{NO}^+]_{\text{meas}}}$  is the measured ratio of  $\text{NO}_2^+/\text{NO}^+$  ions as a function of time,  $R_{[\text{NO}_2^+/\text{NO}^+]_{\text{cal}}}$  is the ratio of  $\text{NO}_2^+/\text{NO}^+$  ions obtained during  $\text{NH}_4\text{NO}_3$  calibrations (0.58



**Figure 1.** Time series of organics, sulfate, ammonium, and nitrate mass concentration measured by the HR-ToF-AMS (corrected for the CE) and BC (a) for Patras and (b) for Athens. The BC was provided by MAAP for Patras measurements and by an aethalometer for Athens.



**Figure 2.** Diurnal profile of O:C ratio for Patras (blue line) and Athens (red line) data set. The O:C was calculated using the Aiken et al. (2009) fragmentation table.

on average), and  $R_{\text{ONit}}$  is a fixed value set to 0.05, as the minimum ratio of  $\text{NO}_2^+/\text{NO}^+$  observed in this campaign was 0.05. The average organic nitrate fraction was  $0.91 \pm 0.05$ , which suggests that most of the nitrate was in the form of organic nitrate (Fig. S12a). The correlation between OA and nitrate was moderate ( $R^2 = 0.38$ ).

### 3.2 Athens (Demokritos station)

On average the  $\text{PM}_{10}$  mass concentration in Athens (not including dust) was  $14.2 \mu\text{g m}^{-3}$ . This is a different period than the one in Patras so direct comparisons could result in erroneous conclusions. A detailed description and intercomparison of the various measurements (including filter samples) performed in Athens and Patras is given in the companion paper by Tsiflikiotou et al. (2015). Briefly, these authors found that for the July period the mean concentrations of  $\text{PM}_{2.5}$  sulfate in Patras and Athens were similar, while  $\text{PM}_{2.5}$  organics were higher in Patras than in Athens. Figure 1b shows the time series of the concentration of the NR- $\text{PM}_{10}$  components measured by the HR-ToF-AMS in Athens and the BC measured by the aethalometer. The average organic concentration was  $6.6 \mu\text{g m}^{-3}$ , sulfate  $5.3 \mu\text{g m}^{-3}$ , ammonium  $1.4 \mu\text{g m}^{-3}$ , and BC  $0.7 \mu\text{g m}^{-3}$ . Similarly to Patras nitrate levels were low, approximately  $0.2 \mu\text{g m}^{-3}$  on average.

The average O:C mass ratio was  $0.47 \pm 0.11$ , lower than in Patras (0.50), because of the higher contribution of primary emissions (Sect. 3.3.1 and 3.3.2). The average OM:OC ratio was  $1.76 \pm 0.14$ . The diurnal cycle of O:C is shown in Fig. 2 and is similar to the one in Patras. The O:C exhibited two peaks – one in the early morning around 03:00–

05:00 LT, and a second in the late afternoon 17:00–20:00 LT. The OA profile is characterized by three peaks (Fig. S9b). Two of them, around 07:00–12:00 and 20:00–24:00, are related to fresh emissions since the BC follows the same trend. A smaller increase around 14:00–17:00 is probably due to photochemistry. On average  $f_{44}$  and  $f_{57}$  were 0.13 and 0.02, respectively (Fig. S10b).

The OM based on the PM<sub>2.5</sub> semi-continuous OC/EC measurements was calculated using the OM:OC ratio provided by the HR-ToF-AMS. Figure S11b illustrates the correlation for the organics between the HR-ToF-AMS and the semi-continuous OC/EC samples. The measurements are in reasonable agreement ( $R^2 = 0.48$ ) with the HR-ToF-AMS, providing slightly higher concentrations. The scatter observed when comparing the corresponding measurements is due to a number of factors including the positive and negative artifacts of filter measurements, the uncertainties of the corresponding measurements, and the different size ranges. The negative artifacts of the filter measurements due to evaporation of the collected OA can explain the occurrence of some measurements in which the PM<sub>2.5</sub> filter-based OA is less than the PM<sub>1</sub> HR-ToF-AMS OA.

The equivalent ratio of PM<sub>1</sub> cations to anions (measured by the HR-ToF-AMS) was  $0.70 \pm 0.09$  on average and thus the aerosol was acidic. Again free ammonia was not enough to neutralize the sulfate and thus there was no ammonium nitrate observed in the PM<sub>1</sub> fraction.

Applying Eq. (1) to the Athens data set (with an average  $R_{[\text{NO}_2^+/\text{NO}^+]_{\text{cal}}} = 0.68$ , and  $R_{\text{ONit}} = 0.12$ ), the organic nitrate fraction was  $0.89 \pm 0.08$ , indicating that most of the nitrate was actually organic nitrate (Fig. S12b). The coefficient of determination between OA and nitrate was  $R^2 = 0.62$ .

### 3.3 OA sources

#### 3.3.1 Patras

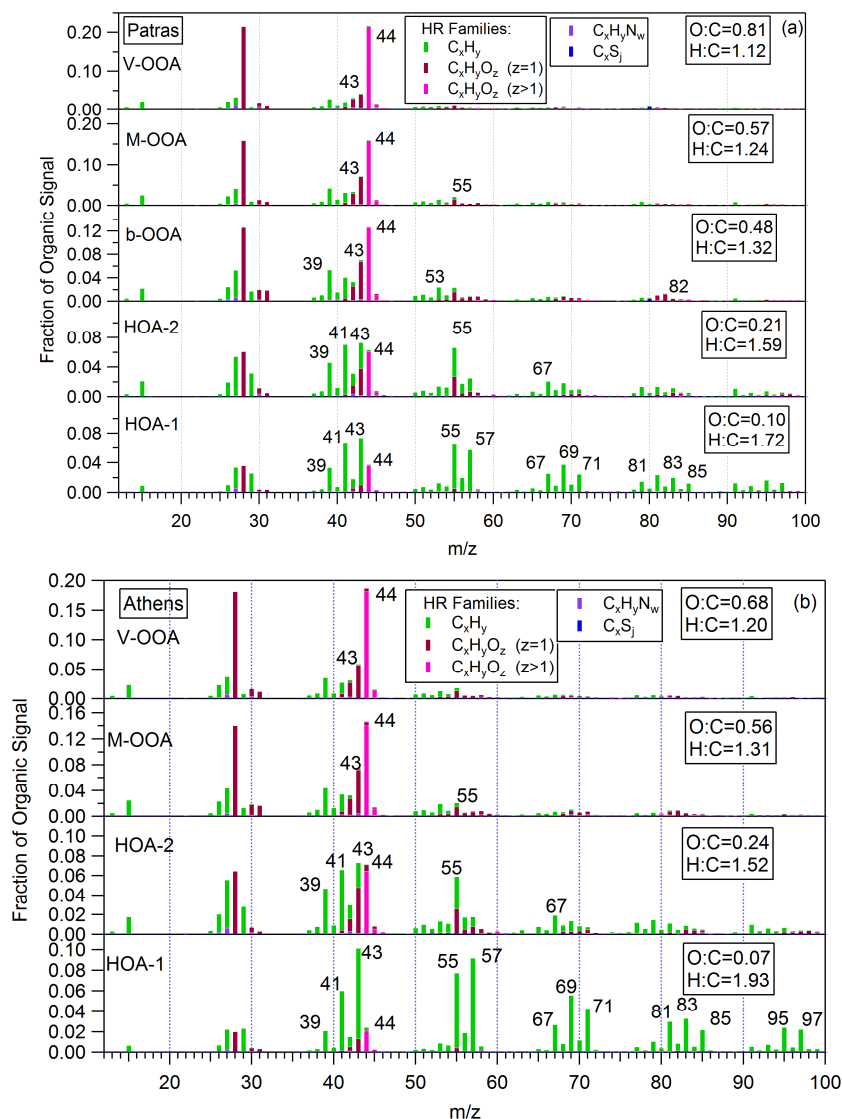
For the PMF analysis, both the PMF Evaluation Tool, PET, (Lanz et al., 2008; Ulbrich et al., 2009) and ME-2 (Lanz et al., 2008; Canonaco et al., 2013) solutions were examined and evaluated using the HR (high-resolution) organic mass spectra. A 5-factor solution was chosen as the best to describe the major sources of OA in Patras. More information about the choice of the solution is provided in the Supplement (Sect. S7.A, Figs. S13–S21). The factors corresponded to very oxygenated OA (V-OOA, 19%), moderately oxygenated OA (M-OOA, 38%), biogenic oxygenated OA (b-OOA, 21%), HOA-1 (7%) and HOA-2 (15%). The V-OOA factor corresponds to the low-volatility OOA (LV-OOA) and the M-OOA to semivolatile OOA (SV-OOA) factors reported in previous work. The lack of a direct determination of the volatility of these factors makes the assignment of names based on their oxygen content preferable. The assignment of the factors to specific sources was based on their mass spectra and diurnal profile characteristics: V-OOA had a high contri-

tribution of  $m/z$  44; M-OOA had a moderate  $m/z$  44 contribution. b-OOA was characterized by both biogenic and oxidized OA signatures; HOA-1 was similar to the literature HOA factor related to traffic emissions, and HOA-2 included primary cooking and aged traffic emissions. Overall, the oxygenated OA was the dominant component (78%) and the primary OA accounted for only 22%. The HR mass spectrum of each factor is illustrated in Fig. 3a, while their time series are shown in Fig. 4a and their average diurnal profiles in Fig. 5a.

V-OOA was characterized by a high  $m/z$  44 ( $\sim 22\%$ ) with an O:C = 0.81 and was related to aged aerosol (Fig. 3a). The V-OOA factor correlated well with sulfate ( $R^2 = 0.48$ ) and ammonium ( $R^2 = 0.51$ ), which is typical for highly oxygenated OA. Its correlation with nitrate was low ( $R^2 = 0.09$ ). The V-OOA diurnal profile was almost flat (Fig. 5a).  $R^2$  between V-OOA and individual VOCs measured by the PTR-MS were all less than 0.13.

M-OOA had a pronounced but of lower intensity  $m/z$  44 ( $\sim 16\%$ ) and an O:C = 0.54 implying aged but less oxidized particles (Fig. 3a). Nitrate has been suggested as a tracer for the less oxygenated species (e.g., Lanz et al., 2007; Mohr et al., 2012), however there was very little nitrate during our measurements and most of it was organic nitrate, resulting in a weak correlation between the M-OOA and nitrate ( $R^2 = 0.04$ ). M-OOA had a very similar pattern with the solar radiation peaking at around 14:00 (local time). M-OOA had low correlation with methyl vinyl ketone (MVK) and methacrolein (MACR) ( $m/z$  71,  $R^2 = 0.31$ ), hydroxyacetone ( $m/z$  75,  $R^2 = 0.29$ ), C<sub>5</sub> carbonyls/2-methyl-butene-2-ol (MBO)/methacrylic acid ( $m/z$  87,  $R^2 = 0.29$ ), terpene oxidation products ( $m/z$  113,  $R^2 = 0.30$ ), and nopinone ( $m/z$  139,  $R^2 = 0.28$ ), (Table 1 and Fig. S22). Comparing the M-OOA spectrum to the  $\alpha$ -pinene SOA spectrum of Heringa et al. (2012) the angle theta was quite high ( $\theta = 35^\circ$ ), while the similarity between the M-OOA and the toluene photooxidation SOA spectrum (Kostenidou et al., 2015) was greater ( $\theta = 16^\circ$ ). Thus this factor may include contributions by both anthropogenic and biogenic sources.

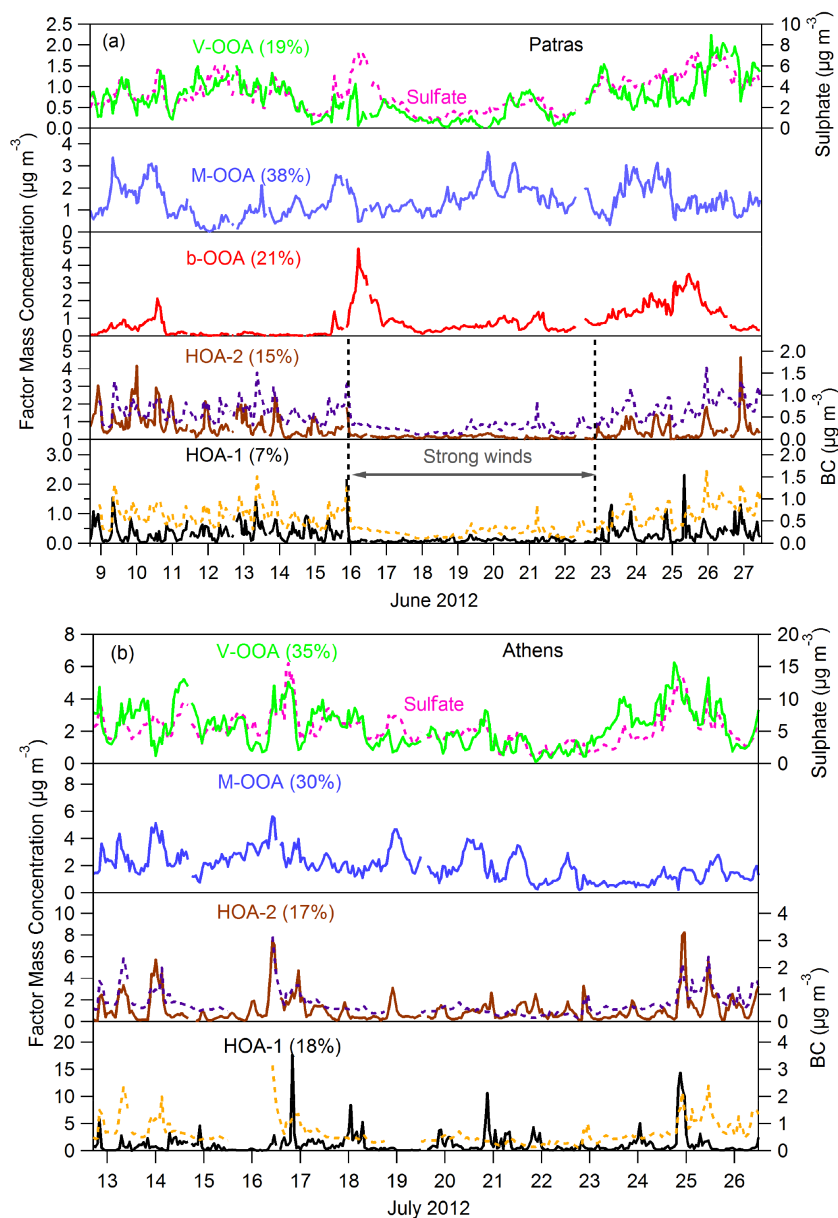
The biogenic OOA factor had an  $f_{44} = 0.13$  and O:C = 0.48 (Fig. 3a) which indicates a relatively moderate degree of oxygenation. It was characterized by a distinct  $m/z$  82 (mainly composed of C<sub>5</sub>H<sub>6</sub>O<sup>+</sup>), an elevated  $m/z$  53 (mostly C<sub>4</sub>H<sub>5</sub><sup>+</sup>) and a significant contribution at  $m/z$  39 (5%, mainly CH<sub>3</sub>O<sup>+</sup>). These characteristics were similar to those found at a rural area in Ontario, Canada (Slowik et al., 2011), downtown Atlanta, Georgia, USA (Budisulistiorini et al., 2013), in tropical rainforests in the central Amazon Basin (Chen et al., 2015) and in Borneo, Malaysia (Robinson et al., 2011), and in Centreville in rural Alabama (Xu et al., 2015), which were associated to secondary OA produced by isoprene photooxidation. Using the HYSPLIT back trajectory model (Draxler and Rolph, 2013), the mass concentration of b-OOA was almost zero when the air masses were coming from the west (e.g., Ionian Sea, 11–15 June, Fig. S23), while M-OOA and V-OOA were still high. However, the b-



**Figure 3.** HR mass spectra profiles of the sources found (a) in Patras and (b) in Athens.

OOA increased in periods (e.g., 10–11 June, 16–17, and 24–26 June) when the air masses passed over the forested mountains of central Greece (Fig. S23), which is an area characterized by high terpene and isoprene emissions (Karl et al., 2009). This supports the biogenic character of this factor. The highest concentration of b-OOA was at 06:00 in the morning on 16 June ( $5.4 \mu\text{g m}^{-3}$ ). b-OOA exhibited low correlation with isoprene ( $m/z$  69,  $R^2 = 0.13$ ), isoprene peroxides ( $m/z$  101,  $R^2 = 0.28$ ), and first-generation isoprene products such as MVK and MACR ( $m/z$  71,  $R^2 = 0.21$ ) (Table 1). However, it correlated better with acetone ( $m/z$  59,  $R^2 = 0.35$ ), hydroxyl-acetone ( $m/z$  75,  $R^2 = 0.41$ ), PAN ( $m/z$  77,  $R^2 = 0.37$ ), nopinope ( $m/z$  139,  $R^2 = 0.39$ ), and pinonaldehyde ( $m/z$  151,  $R^2 = 0.30$ ) (Fig. S24), which are products of terpenes ozonolysis (Matsunaga et al., 2003; Holzinger et al., 2005; Lee et al., 2006).

HOA-1 was characterized mainly by the  $m/z$  values 39, 41, 43, 55, 57, 67, 69, and 81 (Fig. 3a) which are typical hydrocarbon fragments of fresh traffic emissions (Zhang et al., 2005; Aiken et al., 2009). Its O:C was 0.1 which is in the range found in literature (the HOA factor of Mohr et al. (2012) had an O:C of 0.03, while the HOA factor of Ulbrich et al. (2009) had an O:C of 0.18). HOA-1 had a medium correlation with BC ( $R^2 = 0.38$ ) and nitrate ( $R^2 = 0.27$ ). The HOA-1 diurnal profile was characterized by two peaks during the morning (08:00) and evening rush hours (21:00) (Fig. 5a). HOA-1 correlated moderately with benzene ( $m/z$  79,  $R^2 = 0.36$ ), toluene ( $m/z$  93,  $R^2 = 0.35$ ), xylenes ( $m/z$  107,  $R^2 = 0.37$ ), and C<sub>9</sub> aromatic compounds ( $m/z$  121,  $R^2 = 0.45$ ). The correlation with NO<sub>x</sub> was relatively low ( $R^2 = 0.26$ ).



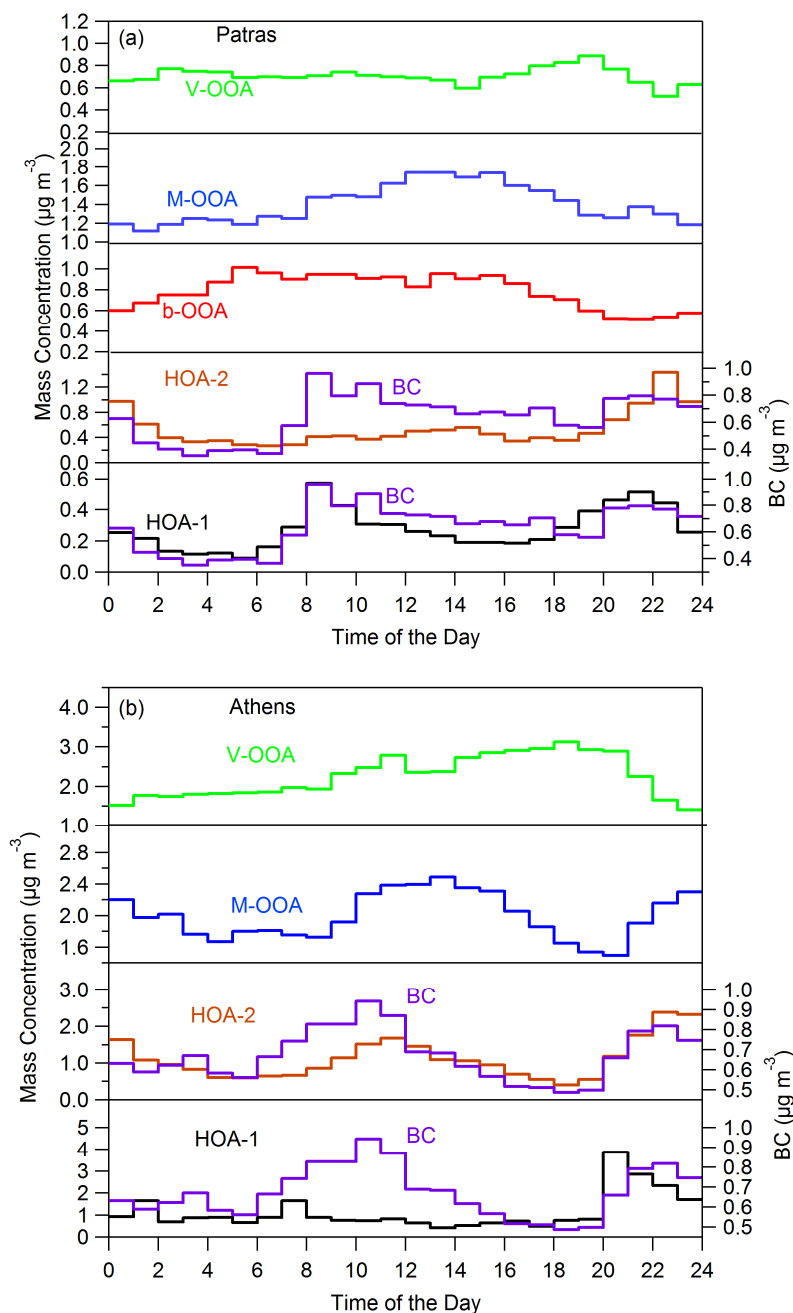
**Figure 4.** Time series (a) of the five PMF factors using HR organic mass spectra for Patras and b) of the four PMF factors found in Athens. For the Patras measurements, the HOA-1 and HOA-2 contribution was very low between the 16 and 23 June 2012 due to the high wind speed during that period.

The HOA-2 O:C was 0.21. The HOA-2 spectrum was characterized among others by the  $m/z$  values 39, 41, 43, 44, 55, 57, and 67 (Fig. 3a) which are features of cooking organic aerosol, COA (Ge et al., 2012a; Crippa et al., 2013a, b). However, the reported COA spectra (e.g., Ge et al., 2012a, b; Crippa et al., 2013a, b) have lower contributions at  $m/z$  44 (0.011–0.022), indicating less oxygenation. The  $f_{44}$  in the HOA-2 mass spectrum was 0.034 which implies that this factor may also contain species that have been oxidized to some degree. The HOA-2 diurnal profile had a small peak around 14:00 and a higher one around 22:00, which are consistent

with the Greek lunch and dinner periods (Fig. 5a). Thus, the HOA-2 in Patras is mainly due to charbroiling of meat cooking OA. The correlation between HOA-2 and BC, nitrate, benzene, toluene, xylenes, and C<sub>9</sub> aromatic compounds was moderate ( $R^2 = 0.38, 0.38, 0.33, 0.30, 0.33,$  and  $0.43$  correspondingly).

During 16–23 June the wind speed was relatively high (average  $5.3 \text{ m s}^{-1}$ ) compared to the rest of the sampling days (average  $2.5 \text{ m s}^{-1}$ ). The contribution of the local sources (HOA-1 and HOA-2) was less than 9% of the OA during





**Figure 5.** Diurnal cycles of the PMF factors (a) in Patras and (b) in Athens.

that windy period, compared to 28 % during the remaining days (Fig. 4a).

### 3.3.2 Athens

Four OA factors could be identified in the Athens HR-ToF-AMS data set: V-OOA (35 %), M-OOA (30 %), HOA-1 (18 %), and HOA-2 (17 %). A detailed description of the reasons for this selection can be found in the Supplement (Sect. S7.B, Figs. S25–S33). The corresponding mass spec-

tra are provided in Fig. 3b. The time series of the four PMF factors are shown in Fig. 4b, while their diurnal cycles are shown in Fig. 5b. Similarly to Patras, the contribution of the oxygenated OA in Athens was high (65 %), while the primary sources contributed 35 %.

The very oxidized OA (V-OOA) had an  $f_{44}$  of 0.18 and O:C of 0.68, and showed a good correlation with sulfate ( $R^2 = 0.53$ ) and ammonium ( $R^2 = 0.50$ ), consistent with the aged character of this factor. The diurnal profile of the V-OOA (Fig. 5b) was characterized by a peak around

**Table 1.** Correlations\* of the M-OOA and b-OOA factors (Patras) and the V-OOA factor (Athens) with various VOCs measured by the PTR-MS.

$R^2$	Patras M-OOA	Patras b-OOA	Athens V-OOA
$m/z$ 43	0.29	0.13	0.39
$m/z$ 47 (formic acid)	0.21	0.09	0.47
$m/z$ 59 (acetone, glyoxal)	0.21	0.35	0.32
$m/z$ 71 (MVK, MACR)	0.31	0.21	0.20
$m/z$ 73 (MEK)	0.24	0.25	0.29
$m/z$ 75 (hydroxyacetone)	0.29	0.41	0.30
$m/z$ 77 (PAN)	0.16	0.37	0.16
$m/z$ 81 (terpenes)	0.19	0.26	0.12
$m/z$ 87 (MBO, C5, methacrylic acid)	0.29	0.31	0.38
$m/z$ 95 (2 vinyl furan, phenol)	0.17	0.31	0.36
$m/z$ 99 (hexenal)	0.19	0.30	0.42
$m/z$ 101 (isoprene hydroperoxides, hexanal)	0.17	0.28	0.35
$m/z$ 103 (MPAN)	0.23	0.28	–
$m/z$ 113 (chlorobenzene, terpenes, and $O_3$ )	0.30	0.37	0.40
$m/z$ 115 (heptanal)	0.16	0.32	0.42
$m/z$ 137 (monoterpenes)	0.20	0.24	0.1
$m/z$ 139 (nopinone)	0.28	0.39	0.19
$m/z$ 151 (pinonaldehyde)	0.17	0.30	0.17

\* All correlations are significant at the  $p = 0.05$  level.

15:00–18:00, which is probably associated with production of this component in the afternoon over the region. At the same time M-OOA decreased, which indicates that V-OOA is a product of photochemical processing. V-OOA correlated with formic acid ( $m/z$  47,  $R^2 = 0.47$ ), hexenal ( $m/z$  99,  $R^2 = 0.42$ ), isoprene peroxides ( $m/z$  101,  $R^2 = 0.35$ ), terpene oxidation products ( $m/z$  113,  $R^2 = 0.40$ ), and heptanal ( $m/z$  115,  $R^2 = 0.42$ ) (Table 1 and Fig. S34).

The moderately oxidized OA (M-OOA) was characterized by an  $f_{44}$  of 0.14 and O : C of 0.56 and exhibited a weak correlation with sulfate, ammonium, and nitrate ( $R^2 = 0.17$ , 0.17 and 0.13, respectively). M-OOA increased during the day with a maximum at 12:00–14:00, following the diurnal profile of solar radiation, which implies relatively fast photochemical reactions. M-OOA had a second peak during the night around midnight, which could be an indication of nighttime production or condensation due to the change in temperature between day and night (the average temperature at noon was 32 °C, while during the night it decreased to around 21 °C). M-OOA did not show any correlation ( $R^2$  less than 0.07) with the measured VOCs.

The HOA-1 O : C was 0.07. Surprisingly it had a rather weak correlation with BC ( $R^2 = 0.05$ ) and it also showed a low correlation with nitrate ( $R^2 = 0.13$ ). The HOA-1 diurnal profile had two peaks, a small increase during the morning (07:00) and a larger peak in the evening hours (20:00), consistent with the contribution of traffic emissions. HOA-1 did not correlate with VOCs characteristic of traffic such as benzene, toluene and xylenes (the  $R^2$  values were correspondingly 0.15, 0.13, and 0.16) and inorganic gases as  $NO_x$  ( $R^2 = 0.06$ ). The HOA-1 mass spectrum and time series were very stable for 2 to 5 factorial solutions and for

$f_{\text{peaks}}$  values from  $-1$  to  $1$ . The  $R^2$  between the HOA-1 of the selected solution and the HOA-1 of the solutions of 2, 3, and 5 factors was always greater than 0.973 (both for the time series and the mass spectra). This weak correlation between the HOA-1 factor and other primary organic pollutants indicates that their concentrations were not dominated by the same sources. For example HOA-1 possibly originated mostly from passenger cars and scooters. In Greece the car-to-scooter ratio is around 3 to 1 and using the Platt et al. (2014) primary OA emissions from two-stroke engines, the scooter emissions are expected to be a significant OA source. BC mainly originated from diesel vehicles. Another potential BC source could be shipping emissions from Piraeus (15 km southwest of the sampling site) and Rafina (17 km east) ports. However, during high BC concentration periods (around 10:00 LT) the wind was from the north (Fig. S35). Thus, the main source of BC was probably diesel vehicles.

The location of the sampling site and the inhomogeneity of the surrounding areas, in combination with the wind direction changes have confounded these effects. The rose plots of HOA-1, BC,  $NO_x$ , and benzene for wind speeds greater than  $1 \text{ m s}^{-1}$  indicated that BC,  $NO_x$ , and benzene had the same origin, while HOA-1 did not. For example at 08:00 LT the HOA-1 was coming on average from the southwest (Figs. S35–S38), likely from the ring highway of Ymittos, while BC,  $NO_x$ , and benzene were coming from the north and were probably influenced by the Mesogion highway.

HOA-2 had an O : C of 0.24 and exhibited a good correlation with BC ( $R^2 = 0.57$ ). HOA-2 also correlated well with nitrate ( $R^2 = 0.75$ ), implying that organic nitrate compounds were possibly emitted or produced along with this OA type. The HOA-2 profile had two peaks at around 11:00 and 22:00. The second peak is characteristic of Greek dinner period, thus part of HOA-2 could be attributed to meat cooking OA. However, the first peak can not be explained by the Greek lunch period. Although it could contain cooking emissions from canteens or other catering outlets which start cooking earlier than the typical Greek lunchtime, it still does not explain the good correlation with BC. Greek cooking emissions have a low BC / OA ratio (unpublished measurements). Thus HOA-2 may include sources other than cooking. The correlation with the BC implies that HOA-2 and BC had the same origin. Comparing the HOA-2 mass spectrum with aged POA or SOA emissions from other sources such as  $\alpha$ -pinene, wood burning, scooters and diesel (Heringa et al., 2012) the angles  $\theta$  were 19, 19, 28, and 17°, respectively. This indicates that HOA-2 could include aged diesel emissions since  $\alpha$ -pinene is not associated with BC and there were no observed biomass burning events during the sampling period. The HOA-2 factor correlated with the  $m/z$  43 ( $R^2 = 0.43$ ), acetone ( $m/z$  59,  $R^2 = 0.44$ ), methyl ethyl ketone (MEK,  $m/z$  73,  $R^2 = 0.49$ ), benzene ( $m/z$  79,  $R^2 = 0.62$ ), toluene ( $m/z$  93,  $R^2 = 0.54$ ), xylenes ( $m/z$  107,  $R^2 = 0.56$ ),  $C_9$  aro-

matic compounds ( $m/z$  121,  $R^2 = 0.58$ ) and  $C_{10}$  aromatic compounds ( $m/z$  135,  $R^2 = 0.55$ ). It also had a good correlation with  $NO_x$  ( $R^2 = 0.58$ ).

Trying rotations in the  $f_{\text{peak}}$  range  $-1$  to  $1$ , the correlations between the factors HOA-1 and HOA-2 and traffic markers such as BC and toluene practically did not change. In addition, using a fixed HOA spectrum (the HOA mass spectrum of Aiken et al. (2009) and the HOA mass spectrum found in Athens during winter, unpublished results) with  $a = 0.1$ , the correlation between HOA-1 and BC did not improve. All these suggest that our conclusions are robust to the details of the PMF process. Our explanation is that the correlations are also affected by the locations of the various sources around the receptor site and the corresponding wind directions. The fact that these area sources (gasoline cars, diesel cars, cooking activities) did not have a homogeneous spatial distribution can lead to these rather unexpected results.

### 3.3.3 Comparison of the PMF factors in the two cities

The mass spectra of the V-OOA factors in the two cities were almost the same ( $\theta = 6.7^\circ$ ). However, Athens V-OOA exhibited a lower  $f_{44}$  and O:C ratio (0.18 and 0.68 correspondingly), compared to Patras V-OOA (0.22 and 0.81, respectively). This difference could be partially due to the different periods of the two measurements.

The two M-OOA mass spectra were even more similar to each other ( $\theta = 5.4^\circ$ ). A high correlation was also observed between the two HOA-2 mass spectra ( $\theta = 5.9^\circ$ ). The Athens HOA-2 was slightly more oxygenated (O:C = 0.24), as the oxygenated part of  $m/z$  43 was more elevated (65%), compared to 51% observed in Patras HOA-2, and the  $f_{44}$  was just slightly higher (0.07), while in Patras HOA-2 was 0.06.

The two HOA-1 factors exhibited a lower correlation with each other ( $\theta = 22.8^\circ$ ). The main differences were at  $m/z$  41, 43, 55, 57, 69, 71, 81, 83, and 85 which were more abundant in the Athens HOA-1 spectrum, while in the Patras spectrum, the  $f_{44}$  was higher (0.04) compared to Athens (0.02). In Patras, HOA-1 spectrum  $m/z$  57 was lower in comparison with  $m/z$  55. The O:C in Athens HOA-1 was a little lower (0.07) than in Patras HOA-1 (0.10).

### 3.3.4 Comparing the PMF factors with other studies

Table 2 shows comparisons of the mass spectra of the factors found in the two cities with selected PMF factors from the literature (Aiken et al., 2009; Docherty et al., 2011; Sun et al., 2011; Robinson et al., 2011; Heringa et al., 2012; Mohr et al., 2012; Ge et al., 2012a, b; Crippa et al., 2013a, b; Budisulistiorini et al., 2013; Xu et al., 2015) that have all been extracted using the fragmentation table of Aiken et al. (2009).

The two V-OOA factors were quite similar with LV-OOA at Riverside (Docherty et al., 2011),  $\theta = 8$ – $10^\circ$ , and with LV-OOA at New York City (Sun et al., 2011),  $\theta = 11$ – $14^\circ$ . They also showed good correlation with LV-OOA measured

in Barcelona (Mohr et al., 2012) and Paris (Crippa et al., 2013a, b),  $\theta = 13$ – $19^\circ$ .

M-OOA had moderate to low agreement with the majority of the literature profiles. The lowest angle  $\theta$  (around  $22$ – $24^\circ$ ) corresponded to the comparison with the SV-OOA found in Mexico City (Aiken et al., 2009). It did however resemble ( $\theta = 13$ – $16^\circ$ ) the toluene SOA spectrum (Kostenidou et al., unpublished data).

The b-OOA factor in Patras correlated moderately with  $\alpha$ -pinene SOA,  $\theta = 29^\circ$ , (Heringa et al., 2012) and the isoprene factor found in Alabama,  $\theta = 28^\circ$ , (Xu et al., 2015). However, it had low correlation with the Factor 82,  $\theta = 47^\circ$ , found in Malaysia (Robinson et al., 2011), and the IEPOX-OA factor extracted in Atlanta,  $\theta = 76^\circ$ , (Budisulistiorini et al., 2013).

The HOA-1 factors correlated well with most of the literature HOA profiles,  $\theta = 10$ – $25^\circ$ . The highest angles ( $24$  and  $25^\circ$ ) corresponded to the comparison with Paris during the winter (Crippa et al., 2013b). The major differences were in the  $m/z$  values 44 and 28 which were higher than in Paris,  $m/z$  values 29 and 43 which were lower compared to Paris, and  $m/z$  39 which was absent in Paris probably due to the unit mass resolution spectra used as input for the Crippa et al. (2013b) PMF analysis.

The HOA-2 mass spectra resembled the COA factor extracted in New York City,  $\theta = 11$ – $14^\circ$ , (Sun et al., 2011), and the SOA from diesel VOCs emissions,  $\theta = 17^\circ$  (Heringa et al., 2012).

Figure S39 summarizes Patras and Athens OA measurements and PMF factors in the Ng triangle (Ng et al., 2010). All the data fall within the triangle.

## 3.4 Discussion

In both cities the composition of NR-PM<sub>1</sub> was surprisingly similar. Organic contributions in Patras and Athens were around 45%, which is similar to other areas in Europe: London (UK) 46%, mountain Taunus (Germany) 59%, Melpitz (Germany) 59%, Mace Head (Ireland) 39%, Po Valley (Italy) 33%, and Paris (France) 50% (Cubison et al., 2006; Hings et al., 2007; Poulain et al., 2011; Dall'Osto et al., 2010; Saarikoski et al., 2012; Crippa et al., 2013a). With 38%, sulfate made a larger contribution compared to other studies in Europe during the summer: London 31%, mountain Taunus 24%, Mace Head 32%, Melpitz 22%, Po Valley 9%, and Paris 25% (Cubison et al., 2006; Hings et al., 2007; Dall'Osto et al., 2010; Poulain et al., 2011; Saarikoski et al., 2012; Crippa et al., 2013a). Nitrate contributed very little (less than 2%) and was mostly attributed to organonitrate compounds, in contrast with other European studies where nitrate ranged from 6% (Melpitz) to 39% (Po Valley) (Poulain et al., 2011; Saarikoski et al., 2012) and was mainly ammonium nitrate. The absence of particulate nitrate in PM<sub>1</sub> was also observed at Finokalia (Hildebrandt et al., 2010) and is characteristic of the eastern Mediterranean. Ammonia lev-

**Table 2.** Correlations between PMF factors from Patras and Athens and PMF factors from selected studies using both the angle theta and  $R^2$  (in parentheses).

	Angle in degrees (and $R^2$ ) with V-OOA Patras	Angle in degrees (and $R^2$ ) with V-OOA Athens
LV-OOA Mexico City <sup>1</sup>	21 (0.86)	20 (0.87)
LV-OOA Riverside <sup>2</sup>	10 (0.97)	8 (0.98)
LV-OOA Barcelona <sup>3</sup>	18 (0.90)	16 (0.92)
LV-OOA Paris (SIRTA), summer <sup>4</sup>	19 (0.89)	15 (0.93)
OOA Paris (SIRTA), winter <sup>5</sup>	13 (0.95)	15 (0.93)
LV-OOA New York City <sup>6</sup>	14 (0.94)	11 (0.96)
LV-OOA Fresno <sup>7,8</sup>	36 (0.64)	30 (0.73)
	Angle in degrees (and $R^2$ ) with M-OOA Patras	Angle in degrees (and $R^2$ ) with M-OOA Athens
SV-OOA Mexico City <sup>1</sup>	24 (0.81)	22 (0.84)
SV-OOA Riverside <sup>2</sup>	42 (0.48)	39 (0.53)
SV-OOA Barcelona <sup>3</sup>	33 (0.66)	31 (0.69)
SV-OOA Paris (SIRTA), summer <sup>4</sup>	42 (0.48)	39 (0.53)
SV-OOA New York City <sup>6</sup>	30 (0.73)	27 (0.77)
$\alpha$ -pinene ozonolysis SOA, aged <sup>9</sup>	35 (0.62)	32 (0.67)
Toluene photooxidation (HONO) SOA <sup>10</sup>	16 (0.93)	13 (0.95)
	Angle in degrees (and $R^2$ ) with HOA-1 Patras	Angle in degrees (and $R^2$ ) with HOA-1 Athens
HOA Mexico City <sup>1</sup>	13 (0.94)	14 (0.93)
HOA Riverside <sup>2</sup>	20 (0.86)	10 (0.96)
HOA Barcelona <sup>3</sup>	22 (0.84)	11 (0.96)
HOA Paris (SIRTA), summer <sup>4</sup>	16 (0.92)	18 (0.90)
HOA Paris (SIRTA), winter <sup>5</sup>	25 (0.79)	24 (0.81)
HOA New York City <sup>6</sup>	12 (0.95)	10 (0.97)
HOA Fresno <sup>7,8</sup>	11 (0.96)	11 (0.96)
	Angle in degrees (and $R^2$ ) with HOA-2 Patras	Angle in degrees (and $R^2$ ) with HOA-2 Athens
COA Barcelona <sup>3</sup>	77 (0.01)	77 (0.01)
COA Paris (SIRTA), summer <sup>4</sup>	30 (0.68)	34 (0.6)
COA Paris (SIRTA), winter <sup>5</sup>	30 (0.74)	28 (0.70)
COA Paris (LHVP), winter <sup>5</sup>	27 (0.76)	31 (0.70)
COA New York City <sup>6</sup>	11 (0.96)	14 (0.93)
COA Fresno <sup>7,8</sup>	28 (0.72)	33 (0.64)
Aged VOCs diesel emissions <sup>9</sup>	17 (0.90)	17 (0.90)
$\alpha$ -pinene ozonolysis SOA, aged <sup>9</sup>	20 (0.86)	19 (0.87)
Toluene photooxidation (HONO) SOA <sup>10</sup>	26 (0.79)	23 (0.84)
	Angle in degrees (and $R^2$ ) with b-OOA Patras	
$\alpha$ -pinene ozonolysis SOA, aged <sup>9</sup>	29 (0.73)	
Factor 82 <sup>11</sup>	47 (0.40)	
IEPOX OA <sup>12</sup>	76 (0.01)	
Isoprene-OA <sup>13</sup>	28 (0.75)	

<sup>1</sup> Aiken et al. (2009), <sup>2</sup> Docherty et al. (2011), <sup>3</sup> Mohr et al. (2012), <sup>4</sup> Crippa et al. (2013a), <sup>5</sup> Crippa et al. (2013b), <sup>6</sup> Sun et al. (2011), <sup>7,8</sup> Kostanidou et al. (2012a, b), <sup>9</sup> Heringa et al. (2012), <sup>10</sup> Kostenidou et al. (unpublished data), <sup>11</sup> Robinson et al. (2011), <sup>12</sup> Budisulistiorini et al. (2013), <sup>13</sup> Xu et al. (2015).

els in this region are quite low (Wichink Kruit et al., 2012) to be able to fully neutralize the existing relatively high sulfate.

The O : C ratios (0.50 for Patras and 0.47 for Athens) were moderately high. The O : C ratio at Finokalia was 0.8 (Hildebrandt et al., 2010), at Cape Corsica 0.9 (Nicolas, 2013), while in Paris it was 0.38 (Crippa et al., 2013a).

In both cities the OOA was the dominant OA component (78 % in Patras and 65 % in Athens). This fraction is within the range that has been measured in previous summer studies in the Mediterranean. For example, the OOA at Finokalia was 100 % of the OA (Hildebrandt et al., 2010), in Marseille accounted for 80 % (El Haddad et al., 2013), at Cape Corsica 80–85 % (Nicolas, 2013), while in Po Valley 61 % (Saarikoski et al., 2012).

In Athens 35 % of the OA was V-OOA, while in Patras only 19 % of the OA was attributed to V-OOA. In addition the V-OOA in Athens was increasing in the afternoon, suggesting its production either locally or regionally. In Patras V-OOA had an almost flat diurnal profile. This difference could be attributed to the different air masses that arrive at each site. According to back trajectory analysis, based on FLEXPART (Stohl et al., 2005) (Fig. S40) and HYSPLIT (Draxler and Rolph 2013), during most of the sampling days in Athens the air masses had spent considerable time over the source-poor Aegean Sea, while the majority of the air masses that arrived in Patras were continental and passed over the mountains of central Greece.

Given the location of the two sites, one would expect to find a marine OA (MOA) factor. The S : C ratio estimated by the AMS is often underestimated in the presence of organosulfates (Farmer et al., 2010; Docherty et al., 2011). To avoid such artifacts, we investigated the contribution of MOA, applying a constrained solution in the ME-2 using the MOA mass spectrum of Crippa et al. (2013) with  $a = 0.1$ . For Patras the average MOA concentration for 4, 5, and 6 factors was around  $0.04 \mu\text{g m}^{-3}$  corresponding to 1 percent of the OA mass. For Athens the MOA concentration for the 3-, 4- and 5-factor solutions was approximately  $0.25 \mu\text{g m}^{-3}$  (3.7 % of the OA mass). So if MOA was indeed present, its contribution to OA was quite low.

#### 4 Conclusions

During the summer of 2012 the air pollution in Patras (June) and Athens (July) was monitored continuously. The sum of the NR-PM<sub>1</sub> and BC concentration was on average  $8.6 \mu\text{g m}^{-3}$  in Patras and  $14.2 \mu\text{g m}^{-3}$  in Athens. However, the aerosol composition was quite similar in both areas: 45 % OA, 38 % sulfate, 11 % ammonium, 1 % nitrate (mostly organic), and 5 % BC, indicating the importance of regional sources. In both cities the fine aerosol was acidic, which is consistent with the low ammonia levels in the eastern Mediterranean.

For Patras the average O : C ratio was  $0.50 \pm 0.08$ , while in Athens it was  $0.47 \pm 0.11$ . In both cities oxygenated OA was the major component of organic aerosol (78 % in Patras and 65 % in Athens), indicating the impact of regional pollution in Mediterranean. OOA included a moderately oxygenated OA and a very oxygenated OA component. In Patras a biogenic oxidized OA factor could be identified, which was related to air masses passing over the forests of central Greece. A primary OA factor (HOA-2) was found in both cities, attributed to primary emissions such as meat cooking. This factor may also contain oxygenated primary emissions (e.g., aged diesel emissions). Hydrocarbon-like OA mainly from traffic emissions was also identified, accounting only for 7–18 % of the OA and indicating that new emission control technologies applied to vehicles during the last decade have dramatically reduced the levels of the corresponding primary OA.

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#### References

- Aiken, A. C., Salcedo, D., Cubison, M. J., Huffman, J. A., DeCarlo, P. F., Ulbrich, I. M., Docherty, K. S., Sueper, D., Kimmel, J. R., Worsnop, D. R., Trimborn, A., Northway, M., Stone, E. A., Schauer, J. J., Volkamer, R. M., Fortner, E., de Foy, B., Wang, J., Laskin, A., Shutthanandan, V., Zheng, J., Zhang, R., Gaffney, J., Marley, N. A., Paredes-Miranda, G., Arnott, W. P., Molina, L. T., Sosa, G., and Jimenez, J. L.: Mexico City aerosol analysis during MILAGRO using high resolution aerosol mass spectrometry at the urban supersite (T0) – Part 1: Fine particle composition and organic source apportionment, *Atmos. Chem. Phys.*, 9, 6633–6653, doi:10.5194/acp-9-6633-2009, 2009.
- Bougiatioti, A., Stavroulas, I., Kostenidou, E., Zarnmpas, P., Theodosi, C., Kouvarakis, G., Canonaco, F., Prévôt, A. S. H., Nenes, A., Pandis, S. N., and Mihalopoulos, N.: Processing of biomass-burning aerosol in the eastern Mediterranean during summertime, *Atmos. Chem. Phys.*, 14, 4793–4807, doi:10.5194/acp-14-4793-2014, 2014.

- Budisulistiorini, S. H., Canagaratna, M. R., Croteau, P. L., Marth, W. J., Baumann, K., Edgerton, E. S., Shaw, S. L., Knipping, E. M., Worsnop, D. R., Jayne, J. T., Gold, A., and Surratt, J. D.: Real-time continuous characterization of secondary organic aerosol derived from isoprene epoxydiols in downtown Atlanta, Georgia, using the Aerodyne Aerosol Chemical Speciation Monitor, *Environ. Sci. Technol.*, 47, 5686–5694, doi:10.1021/es400023n, 2013.
- Canonaco, F., Crippa, M., Slowik, J. G., Baltensperger, U., and Prévôt, A. S. H.: SoFi, an IGOR-based interface for the efficient use of the generalized multilinear engine (ME-2) for the source apportionment: ME-2 application to aerosol mass spectrometer data, *Atmos. Meas. Tech.*, 6, 3649–3661, doi:10.5194/amt-6-3649-2013, 2013.
- Carslaw, K. S., Clegg, S. L., and Brimblecombe, P.: A thermodynamic model of the system HCl-HNO<sub>3</sub>-H<sub>2</sub>SO<sub>4</sub>-H<sub>2</sub>O, including solubilities of HBr, from < 200 K to 328 K, *J. Phys. Chem.*, 99, 11557–11574, 1995.
- Chaloulakou A., Kassomenos, P., Spyrellis, N., Demokritou, P., and Koutrakis, P.: Measurements of PM<sub>10</sub> and PM<sub>2.5</sub> particle concentrations in Athens, Greece, *Atmos. Environ.*, 37, 649–660, 2003.
- Chen, Q., Farmer, D. K., Rizzo, L. V., Pauliquevis, T., Kuwata, M., Karl, T. G., Guenther, A., Allan, J. D., Coe, H., Andreae, M. O., Pöschl, U., Jimenez, J. L., Artaxo, P., and Martin, S. T.: Submicron particle mass concentrations and sources in the Amazonian wet season (AMAZE-08), *Atmos. Chem. Phys.*, 15, 3687–3701, doi:10.5194/acp-15-3687-2015, 2015.
- Chirico, R., DeCarlo, P. F., Heringa, M. F., Tritscher, T., Richter, R., Prévôt, A. S. H., Dommen, J., Weingartner, E., Wehrle, G., Gysel, M., Laborde, M., and Baltensperger, U.: Impact of aftertreatment devices on primary emissions and secondary organic aerosol formation potential from in-use diesel vehicles: results from smog chamber experiments, *Atmos. Chem. Phys.*, 10, 11545–11563, doi:10.5194/acp-10-11545-2010, 2010.
- Chrysikou, L. P. and Samara, C.: Seasonal variation of the size distribution of urban particulate matter and associated organic pollutants in the ambient air, *Atmos. Environ.*, 43, 4557–4569, 2009.
- Clegg, S., Brimblecombe, L. P., and Wexler, A. S.: A thermodynamic model of the system H<sup>+</sup>-NH<sub>4</sub><sup>+</sup>-SO<sub>4</sub><sup>2-</sup>-NO<sub>3</sub><sup>-</sup>-H<sub>2</sub>O at tropospheric temperatures, *J. Phys. Chem. A*, 102, 2137–2154, doi:10.1021/jp973043j, 1998.
- Crippa M., El Haddad I., Slowik J., G., DeCarlo P. F., Mohr, C., Heringa, M., F, Chirico, R., Marchand, N., Sciare, J., Urs, B., and Prévôt, A. S. H.: Identification of marine and continental aerosol sources in Paris using high resolution aerosol mass spectrometry, *J. Geophys. Res.*, 118, 1950-1963, doi:10.1002/jgrd.50151, 2013a.
- Crippa, M., DeCarlo, P. F., Slowik, J. G., Mohr, C., Heringa, M. F., Chirico, R., Poulain, L., Freutel, F., Sciare, J., Cozic, J., Di Marco, C. F., Elsasser, M., Nicolas, J. B., Marchand, N., Abidi, E., Wiedensohler, A., Drewnick, F., Schneider, J., Borrmann, S., Nemitz, E., Zimmermann, R., Jaffrezo, J.-L., Prévôt, A. S. H., and Baltensperger, U.: Wintertime aerosol chemical composition and source apportionment of the organic fraction in the metropolitan area of Paris, *Atmos. Chem. Phys.*, 13, 961–981, doi:10.5194/acp-13-961-2013, 2013b.
- Cubison, M. J., Alfarra, M. R., Allan, J., Bower, K. N., Coe, H., McFiggans, G. B., Whitehead, J. D., Williams, P. I., Zhang, Q., Jimenez, J. L., Hopkins, J., and Lee, J.: The characterisation of pollution aerosol in a changing photochemical environment, *Atmos. Chem. Phys.*, 6, 5573–5588, doi:10.5194/acp-6-5573-2006, 2006.
- Dall'Osto, M., Ceburnis, D., Martucci, G., Bialek, J., Dupuy, R., Jennings, S. G., Berresheim, H., Wenger, J., Healy, R., Facchini, M. C., Rinaldi, M., Giulianelli, L., Finessi, E., Worsnop, D., Ehn, M., Mikkilä, J., Kulmala, M., and O'Dowd, C. D.: Aerosol properties associated with air masses arriving into the North East Atlantic during the 2008 Mace Head EUCAARI intensive observing period: an overview, *Atmos. Chem. Phys.*, 10, 8413–8435, doi:10.5194/acp-10-8413-2010, 2010.
- Davidson, C. I., Phalen, R. F., and Solomon, P. A.: Airborne particulate matter and human health: A review, *Aerosol Sci. Technol.*, 39, 737–749, 2005.
- DeCarlo, P.F., Kimmel, J. R., Trimborn, A., Northway, M. J., Jayne, J. T., Aiken, A. C., Gonin, M., Fuhrer, K., Horvath, T., Docherty, K., Worsnop, D. R., and Jimenez, J. L.: Field-Deployable, High-Resolution, Time-of-Flight Aerosol Mass Spectrometer, *Anal. Chem.*, 78, 8281–8289, 2006.
- Docherty, K. S., Aiken, A. C., Huffman, J. A., Ulbrich, I. M., DeCarlo, P. F., Sueper, D., Worsnop, D. R., Snyder, D. C., Peltier, R. E., Weber, R. J., Grover, B. D., Eatough, D. J., Williams, B. J., Goldstein, A. H., Ziemann, P. J., and Jimenez, J. L.: The 2005 Study of Organic Aerosols at Riverside (SOAR-1): instrumental intercomparisons and fine particle composition, *Atmos. Chem. Phys.*, 11, 12387–12420, doi:10.5194/acp-11-12387-2011, 2011.
- Draxler, R. R. and Rolph, G. D.: HYSPLIT (HYbrid Single-Particle Lagrangian Integrated Trajectory) Model access via NOAA ARL READY Website, <http://ready.arl.noaa.gov/HYSPLIT.php> (last access: 16 September 2014), NOAA Air Resources Laboratory, Silver Spring, MD, 2013.
- El Haddad, I., D'Anna, B., Temime-Roussel, B., Nicolas, M., Boreave, A., Favez, O., Voisin, D., Sciare, J., George, C., Jaffrezo, J.-L., Wortham, H., and Marchand, N.: Towards a better understanding of the origins, chemical composition and aging of oxygenated organic aerosols: case study of a Mediterranean industrialized environment, Marseille, *Atmos. Chem. Phys.*, 13, 7875–7894, doi:10.5194/acp-13-7875-2013, 2013.
- Farmer, D. K., Matsunaga, A., Docherty, K. S., Surratt, J. D., Seinfeld, J. H., Ziemann P. J., and Jimenez, J. L.: Response of an aerosol mass spectrometer to organonitrates and organosulfates and implications for atmospheric chemistry, *P. Natl. Acad. Sci. USA*, 107, 6670–6675, doi:10.1073/pnas.0912340107, 2010.
- Ge, X., Setyan, A., Sun, Y., and Zhang, Q.: Primary and secondary organic aerosols in Fresno, California during wintertime: Results from high resolution aerosol mass spectrometry, *J. Geophys. Res.*, 117, D19301, doi:10.1029/2012JD018026, 2012a.
- Ge, X., Zhang, Q., Sun, Y., Ruehl, C. R., and Setyan, A.: Effect of aqueous-phase processing on aerosol chemistry and size distribution in Fresno, California, during wintertime, *Environ. Chem.*, 9, 221–235, doi:10.1071/EN11168, 2012b.
- Grivas, G., Chaloulakou, A., Samara, C., and Spyrellis, N.: Spatial and temporal variation of PM<sub>10</sub> mass concentrations within the greater area of Athens, Greece, *Water Air Soil Pollut.*, 158, 357–371, 2004.
- Heringa, M. F., DeCarlo, P. F., Chirico, R., Tritscher, T., Clairotte, M., Mohr, C., Crippa, M., Slowik, J. G., Pfaffenberger, L., Dommen, J., Weingartner, E., Prévôt, A. S. H., and Baltensperger,

- U.: A new method to discriminate secondary organic aerosols from different sources using high-resolution aerosol mass spectra, *Atmos. Chem. Phys.*, 12, 2189–2203, doi:10.5194/acp-12-2189-2012, 2012.
- Hildebrandt, L., Engelhart, G. J., Mohr, C., Kostenidou, E., Lanz, V. A., Bougiatioti, A., DeCarlo, P. F., Prevot, A. S. H., Baltensperger, U., Mihalopoulos, N., Donahue, N. M., and Pandis, S. N.: Aged organic aerosol in the Eastern Mediterranean: the Finokalia Aerosol Measurement Experiment – 2008, *Atmos. Chem. Phys.*, 10, 4167–4186, doi:10.5194/acp-10-4167-2010, 2010.
- Hildebrandt, L., Kostenidou, E., Lanz, V. A., Prevot, A. S. H., Baltensperger, U., Mihalopoulos, N., Laaksonen, A., Donahue, N. M., and Pandis, S. N.: Sources and atmospheric processing of organic aerosol in the Mediterranean: insights from aerosol mass spectrometer factor analysis, *Atmos. Chem. Phys.*, 11, 12499–12515, doi:10.5194/acp-11-12499-2011, 2011.
- Hings, S. S., Walter, S., Schneider, J., Borrmann, S., and Drewnick, F.: Comparison of a Quadrupole and a Time-of-Flight Aerosol Mass Spectrometer during the Feldberg Aerosol Characterization Experiment 2004, *Aerosol Sci. Technol.*, 41, 679–691, 2007.
- Holzinger, R., Lee, A., Paw, K. T., and Goldstein, U. A. H.: Observations of oxidation products above a forest imply biogenic emissions of very reactive compounds, *Atmos. Chem. Phys.*, 5, 67–75, doi:10.5194/acp-5-67-2005, 2005.
- IPCC: Climate Change 2013 – The Physical Science Basis, Contribution of Working Group I to the Fourth Assessment Report of the IPCC, Cambridge University Press, Cambridge, 2013.
- Jimenez, J. L., Canagaratna, M. R., Donahue, N. M., Prévôt, A. S. H., Zhang, Q., Kroll, J. H., DeCarlo, P. F., Allan, J. D., Coe, H., Ng, N. L., Aiken, A. C., Docherty, K. S., Ulbrich, I. M., Grieshop, A. P., Robinson, A. L., Duplissy, J., Smith, J. D., Wilson, K. R., Lanz, V. A., Hueglin, C., Sun, Y. L., Tian, J., Laaksonen, A., Raatikainen, T., Rautiainen, J., Vaattovaara, P., Ehn, M., Kulmala, M., Tomlinson, J. M., Collins, D. R., Cubison, M. J., Dunlea, E. J., Huffman, J. A., Onasch, T. B., Alfarra, M. R., Williams, P. I., Bower, K., Kondo, Y., Schneider, J., Drewnick, F., Borrmann, S., Weimer, S., Demerjian, K., Salcedo, D., Cottrell, L., Griffin, R., Takami, A., Miyoshi, T., Hatakeyama, S., Shimojo, A., Sun, J. Y., Zhang, Y. M., Dzepina, K., Kimmel, J. R., Sueper, D., Jayne, J. T., Herndon, S. C., Trimborn, A. M., Williams, L. R., Wood, E. C., Middlebrook, A. M., Kolb, C. E., Baltensperger, U., and Worsnop, D. R.: Evolution of organic aerosols in the atmosphere, *Science*, 326, 1525–1529, 2009.
- Kaltsonoudis, C., Kostenidou, E., Florou, K., Psychoudaki, M., and Pandis, S. N.: Temporal variability of VOCs in the Eastern Mediterranean, in preparation, 2015.
- Kanakidou, M., Seinfeld, J. H., Pandis, S. N., Barnes, I., Dentener, F. J., Facchini, M. C., Van Dingenen, R., Ervens, B., Nenes, A., Nielsen, C. J., Swietlicki, E., Putaud, J. P., Balkanski, Y., Fuzzi, S., Horth, J., Moortgat, G. K., Winterhalter, R., Myhre, C. E. L., Tsigaridis, K., Vignati, E., Stephanou, E. G., and Wilson, J.: Organic aerosol and global climate modelling: a review, *Atmos. Chem. Phys.*, 5, 1053–1123, doi:10.5194/acp-5-1053-2005, 2005.
- Karanasiou, A. A., Sitaras, I. E., Siskos, P. A., and Eleftheriadis, K.: Size distribution and sources of trace metals and n-alkanes in the Athens urban aerosol during summer, *Atmos. Environ.*, 41, 2368–2381, 2007.
- Karl, M., Guenther, A., Köble, R., Leip, A., and Seufert, G.: A new European plant-specific emission inventory of biogenic volatile organic compounds for use in atmospheric transport models, *Biogeosciences*, 6, 1059–1087, doi:10.5194/bg-6-1059-2009, 2009.
- Kostenidou, E., Pathak, R. K., and Pandis, S. N.: An algorithm for the calculation of secondary organic aerosol density combining AMS and SMPS data, *Aerosol Sci. Technol.*, 41, 1002–1010, 2007.
- Kostenidou, E., Lee, B. H., Engelhart, G. J., Pierce, J. R., and Pandis, S. N.: Mass spectra deconvolution of low, medium and high volatility biogenic secondary organic aerosol, *Environ. Sci. Technol.*, 43, 4884–4889, 2009.
- Koulouri, E., Saarikoski, S., Theodosi, C., Markaki, Z., Gerasopoulos, E., Kouvarakis, G., Makela, T., Hillamo, R., and Mihalopoulos, N.: Chemical composition and sources of fine and coarse aerosol particles in the Eastern Mediterranean, *Atmos. Environ.*, 42, 6542–6550, 2008.
- Lanz, V. A., Alfarra, M. R., Baltensperger, U., Buchmann, B., Hueglin, C., and Prévôt, A. S. H.: Source apportionment of submicron organic aerosols at an urban site by factor analytical modelling of aerosol mass spectra, *Atmos. Chem. Phys.*, 7, 1503–1522, doi:10.5194/acp-7-1503-2007, 2007.
- Lanz, V. A., Alfarra, M. R., Baltensperger, U., Buchmann, B., Hueglin, C., Szidat, S., Wehrl, M. N., Wacker, L., Weimer, S., Caseiro, A., Puxbaum, J., and Prévôt, A. S. H.: Source attribution of submicron organic aerosols during wintertime inversions by advanced factor analysis of aerosol mass spectra, *Environ. Sci. Technol.*, 42, 214–220, 2008.
- Lee, A., Goldstein, A. H., Keywood, M. D., Gao, S., Varutbangkul, V., Bahreini, R., Ng, N. L., Flagan, R. C., and Seinfeld, J. H.: Gas-phase products and secondary aerosol yields from the ozonolysis of ten different terpenes, *J. Geophys. Res.*, 111, D07302, doi:10.1029/2005JD006437, 2006.
- Lee, B. H., Kostenidou, E., Hildebrandt, L., Riipinen, I., Engelhart, G. J., Mohr, C., DeCarlo, P. F., Mihalopoulos, N., Prevot, A. S. H., Baltensperger, U., and Pandis, S. N.: Measurement of the ambient organic aerosol volatility distribution: application during the Finokalia Aerosol Measurement Experiment (FAME-2008), *Atmos. Chem. Phys.*, 10, 12149–12160, doi:10.5194/acp-10-12149-2010, 2010.
- Manoli, E., Voutsas, D., and Samara, C.: Chemical characterization and source identification/apportionment of fine and coarse air particles in Thessaloniki, Greece, *Atmos. Environ.*, 36, 949–961, 2002.
- Massucci, M., Clegg, S. L., and Brimblecombe, P.: Equilibrium partial pressures, thermodynamic properties of aqueous and solid phases, and Cl<sub>2</sub> production from aqueous HCl and HNO<sub>3</sub> and their mixtures, *J. Phys. Chem. A*, 103, 4209–4226, doi:10.1021/jp9847179, 1999.
- Matsunaga, S., Mochida, M., and Kawamura, K.: Growth of organic aerosols by biogenic semi-volatile carbonyls in the forest atmosphere, *Atmos. Environ.*, 37, 2045–2050, 2003.
- Mathew, B. M., Middlebrook, A. M., and Onasch, T. B.: Collection efficiencies in an Aerodyne Aerosol Mass Spectrometer as a function of particle phase for laboratory generated aerosols, *Aerosol Sci. Technol.*, 42, 884–898, 2008.
- Mohr, C., DeCarlo, P. F., Heringa, M. F., Chirico, R., Slowik, J. G., Richter, R., Reche, C., Alastuey, A., Querol, X., Seco, R., Peñuelas, J., Jiménez, J. L., Crippa, M., Zimmermann, R., Bal-

- tensperger, U., and Prévôt, A. S. H.: Identification and quantification of organic aerosol from cooking and other sources in Barcelona using aerosol mass spectrometer data, *Atmos. Chem. Phys.*, 12, 1649–1665, doi:10.5194/acp-12-1649-2012, 2012.
- Ng, N. L., Canagaratna, M. R., Zhang, Q., Jimenez, J. L., Tian, J., Ulbrich, I. M., Kroll, J. H., Docherty, K. S., Chhabra, P. S., Bahreini, R., Murphy, S. M., Seinfeld, J. H., Hildebrandt, L., Donahue, N. M., DeCarlo, P. F., Lanz, V. A., Prévôt, A. S. H., Dinar, E., Rudich, Y., and Worsnop, D. R.: Organic aerosol components observed in Northern Hemispheric datasets from Aerosol Mass Spectrometry, *Atmos. Chem. Phys.*, 10, 4625–4641, doi:10.5194/acp-10-4625-2010, 2010.
- Nicolas, J.: Caractérisation physico-chimique de l'aérosol troposphérique en Méditerranée, Sources et Devenir, PhD thesis, Université de Versailles Saint-Quentin-en-Yvelines, Ecole Doctorale des Sciences de l'Environnement d'Ile-de-France, Paris, France, 2013.
- Paatero, P. and Tapper, U.: Positive matrix factorization – a nonnegative factor model with optimal utilization of error-estimates of data values, *Environmetrics*, 5, 111–126, 1994.
- Pandolfi, M., Querol, X., Alastuey, A., Jimenez, J. L., Jorba, O., Day, D., Ortega, A., Cubison, M. J., Comerón, A., Sicard, M., Mohr, C., Prévôt, A. S. H., Mingüillón, M. C., Pey, J., Baldasano, J. M., Burkhardt, J. F., Seco, R., Peñuelas, J., van Drooge, B. L., Artiñano, B., Di Marco, C., Nemitz, E., Schallhart, S., Metzger, A., Hansel, A., Llorente, J., Ng, S., Jayne, J., and Szidat, S.: Effects of sources and meteorology on particulate matter in the Western Mediterranean Basin: An overview of the DAURE campaign, *Geophys. Res. Atmos.*, 119, 4978–5010, doi:10.1002/2013JD021079, 2014.
- Papaefthymiou, H., Kritidis, P., Anousis, J., and Sarafidou, J.: Comparative assessment of natural radioactivity in fallout samples from Patras and Megalopolis, Greece, *J. Environ. Radioact.*, 78, 249–265, 2005.
- Pérez, N., Pey, J., Castillo, S., Viana, M., Alastuey, A., and Querol, X.: Interpretation of the variability of levels of regional background aerosols in the Western Mediterranean, *Sci. Total Environ.*, 407, 527–540, 2008.
- Petzold, A. and Schönlinner, M.: Multi-angle absorption photometry – a new method for the measurement of aerosol light absorption and atmospheric black carbon, *J. Aerosol Sci.*, 35, 421–441, 2004.
- Pey, J., Pérez, N., Querol, X., Alastuey, A., Cusack, M., and Reche, C.: Intense winter atmospheric pollution episodes affecting the Western Mediterranean, *Sci. Total Environ.*, 408, 1951–1959, 2010.
- Pikridas, M., Tasoglou, A., Florou, K., and Pandis, S. N.: Characterization of the origin of fine particulate matter in a medium size urban area in the Mediterranean, *Atmos. Environ.*, 80, 264–274, 2013.
- Platt, S. M., El Haddad, I., Zardini, A. A., Clairotte, M., Astorga, C., Wolf, R., Slowik, J. G., Temime-Roussel, B., Marchand, N., Ježek, I., Drinovec, L., Mocnik, G., Möhler, O., Richter, R., Barmet, P., Bianchi, F., Baltensperger, U., and Prévôt, A. S. H.: Secondary organic aerosol formation from gasoline vehicle emissions in a new mobile environmental reaction chamber, *Atmos. Chem. Phys.*, 13, 9141–9158, doi:10.5194/acp-13-9141-2013, 2013.
- Platt, S. M., El Haddad, I., Pieber, S. M., Huang, R.-J., Zardini, A. A., Clairotte, M., Suarez-Bertoa, R., Barmet, P., Pfaffenberger, L., Wolf, R., Slowik, J. G., Fuller, S. J., Kalberer, M., Chirico, R., Domme, J., Astorga, C., Zimmermann, R., Marchand, N., Hellebust, S., Temime-Roussel, B., Baltensperger, U., and Prévôt, A. S. H.: Two-stroke scooters are a dominant source of air pollution in many cities, *Nat. Communications*, 5, 3749, doi:10.1038/ncomms4749, 2014.
- Pope, C. A. and Dockery, D. W.: Health effects of fine particulate air pollution: Lines that connect, *J. Air Waste Manage.*, 56, 709–742, 2006.
- Poulain, L., Spindler, G., Birmili, W., Plass-Dülmer, C., Wiedensohler, A., and Herrmann, H.: Seasonal and diurnal variations of particulate nitrate and organic matter at the IfT research station Melpitz, *Atmos. Chem. Phys.*, 11, 12579–12599, doi:10.5194/acp-11-12579-2011, 2011.
- Robinson, N. H., Hamilton, J. F., Allan, J. D., Langford, B., Oram, D. E., Chen, Q., Docherty, K., Farmer, D. K., Jimenez, J. L., Ward, M. W., Hewitt, C. N., Barley, M. H., Jenkin, M. E., Rickard, A. R., Martin, S. T., McFiggans, G., and Coe, H.: Evidence for a significant proportion of Secondary Organic Aerosol from isoprene above a maritime tropical forest, *Atmos. Chem. Phys.*, 11, 1039–1050, doi:10.5194/acp-11-1039-2011, 2011.
- Saarikoski, S., Carbone, S., Decesari, S., Giulianelli, L., Angelini, F., Canagaratna, M., Ng, N. L., Trimborn, A., Facchini, M. C., Fuzzi, S., Hillamo, R., and Worsnop, D.: Chemical characterization of springtime submicrometer aerosol in Po Valley, Italy, *Atmos. Chem. Phys.*, 12, 8401–8421, doi:10.5194/acp-12-8401-2012, 2012.
- Schmale, J., Schneider, J., Nemitz, E., Tang, Y. S., Dragosits, U., Blackall, T. D., Trathan, P. N., Phillips, G. J., Sutton, M., and Braban, C. F.: Sub-Antarctic marine aerosol: dominant contributions from biogenic sources, *Atmos. Chem. Phys.*, 13, 8669–8694, doi:10.5194/acp-13-8669-2013, 2013.
- Slowik, J. G., Brook, J., Chang, R. Y.-W., Evans, G. J., Hayden, K., Jeong, C.-H., Li, S.-M., Liggio, J., Liu, P. S. K., McGuire, M., Mihele, C., Sjostedt, S., Vlasenko, A., and Abbatt, J. P. D.: Photochemical processing of organic aerosol at nearby continental sites: contrast between urban plumes and regional aerosol, *Atmos. Chem. Phys.*, 11, 2991–3006, doi:10.5194/acp-11-2991-2011, 2011.
- Stohl, A., Forster, C., Frank, A., Seibert, P., and Wotawa, G.: Technical note: The Lagrangian particle dispersion model FLEXPART version 6.2, *Atmos. Chem. Phys.*, 5, 2461–2474, doi:10.5194/acp-5-2461-2005, 2005.
- Sueper, D.: ToF-AMS High Resolution Analysis Software – Pika, available at: <http://cires.colorado.edu/jimenez-group/ToFAMSResources/ToFSoftware>, last access: 1 December 2014.
- Sun, Y.-L., Zhang, Q., Schwab, J. J., Demerjian, K. L., Chen, W.-N., Bae, M.-S., Hung, H.-M., Hogrefe, O., Frank, B., Rattigan, O. V., and Lin, Y.-C.: Characterization of the sources and processes of organic and inorganic aerosols in New York city with a high-resolution time-of-flight aerosol mass spectrometer, *Atmos. Chem. Phys.*, 11, 1581–1602, doi:10.5194/acp-11-1581-2011, 2011.
- Tsifikiotiou, T., Papanastasiou, D., Zarpas, P., Paraskevopoulou, D., Diapouli, E., Kostenidou, E., Kaltsonoudis, C., Bougiatioti, A., Theodosi, C., Kouvarakis, G., Liakakou, E., Vassilatou, V., Siakavaras, D., Biskos, G., Eleftheriadis, K., Gerasopoulos, E.,



- Mihalopoulos, N., and Pandis, S. N.: Spatial distribution of summertime particulate matter and its composition in Greece, in preparation, 2015.
- Ulbrich, I. M., Canagaratna, M. R., Zhang, Q., Worsnop, D. R., and Jimenez, J. L.: Interpretation of organic components from Positive Matrix Factorization of aerosol mass spectrometric data, *Atmos. Chem. Phys.*, 9, 2891–2918, doi:10.5194/acp-9-2891-2009, 2009.
- Vardoulakis, S. and Kassomenos, P.: Sources and factors affecting PM10 levels in two European cities: Implications for local air quality management, *Atmos. Environ.*, 4142, 3949–3963, 2008.
- Viana, M., Pérez, C., Querol, X., Alastuey, A., Nickovic, S., and Baldasano J. M.: Spatial and temporal variability of PM levels and composition in a complex summer atmospheric scenario in Barcelona (NE Spain), *Atmos. Environ.*, 39, 5343–5361, 2005.
- Watson, J. G.: Visibility: Science and regulation, *J. Air Waste Manage.*, 52, 628–713, 2002.
- Wichink Kruit, R. J., Schaap, M., Sauter, F. J., van Zanten, M. C., and van Paul, W. A. J.: Modeling the distribution of ammonia across Europe including bi-directional surface-atmosphere exchange, *Biosciences*, 9, 5261–5277, 2012.
- Yannopoulos, P. C.: Long-term assessment of airborne particulate concentrations in Patras, Greece, *Fresenius Environ. Bull.*, 17, 608–616, 2008.
- Xu, L., Guo, H., Boyd, C. M., Klein, M., Bougiatioti, A., Cerully, K., M., Hite, J. R., Isaacman-VanWertz, G., Kreisberg, N. M., Knote, C., Olson, K., Koss, A., Goldstein, A. H., Hering, S. V., de Gouw, J., Baumann, K., Lee, S-H., Nenes, A., Weber, R. J., and Ng, N. L.: Effects of anthropogenic emissions on aerosol formation from isoprene and monoterpenes in the Southeastern United States, *P. Natl. Acad. Sci.*, 112, 37–42, doi:10.1073/pnas.1417609112, 2015.
- Zhang, Q., Alfarra, M. R., Worsnop, D. R., Allan, J. D., Coe, H., Canagaratna, M., and Jimenez, J. L.: Deconvolution and quantification of hydrocarbon-like and oxygenated organic aerosols based on aerosol mass spectrometry, *Environ. Sci. Technol.*, 39, 4938–4952, 2005.
- Zhang, Q., Jimenez, J. L., Canagaratna, M. R., Allan, J. D., Coe, H., Ulbrich, I., Alfarra, M. R., Takami, A., Middlebrook, A. M., Sun, Y. L., Dzepina, K., Dunlea, E., Docherty, K., Decarlo, P. F., Salcedo, D., Onasch, T., Jayne, J. T., Miyoshi, T., Shimono, A., Hatakeyama, S., Takegawa, N., Kondo, Y., Schneider, J., Drewnick, F., Borrmann, S., Weimer, S., Demerjian, K., Williams, P., Bower, K., Bahreini, R., Cottrell, L., Griffin, R. J., Rautiainen, J., Sun, J. Y., Zhang, Y. M., and Worsnop, D. R.: Ubiquity and dominance of oxygenated species in organic aerosols in anthropogenically-influenced Northern Hemisphere midlatitudes, *Geophys. Res. Lett.*, 34, L13801, doi:10.1029/2007gl029979, 2007.
- Zhang, Q., Jimenez, J., Canagaratna, M., Ulbrich, I., Ng, N., Worsnop, D., and Sun, Y.: Understanding atmospheric organic aerosols via factor analysis of aerosol mass spectrometry: a review, *Anal. Bioanal. Chem.*, 401, 3045–3067, 2011.