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High contribution of non-fossil sources to sub-micron organic aerosols in Beijing, China

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Abstract

Source apportionment of organic carbon (OC) and elemental carbon (EC) from PM1 (particulate matter with a diameter equal to or smaller than 1 µm) in Beijing, China was carried out using radiocarbon (¹⁴C) measurement. Despite a dominant fossil-fuel contribution to EC due to large emissions from traffic and coal combustion, non-fossil sources are dominant contributors of OC in Beijing throughout the year except during the winter. Primary emission was the most important contributor to fossil-fuel derived OC for all seasons. A clear seasonal trend was found for biomass-burning contribution to OC with the highest in autumn and spring, followed by winter and summer. ¹⁴C results were also integrated with those from positive matrix factorization (PMF) of organic aerosols from aerosol mass spectrometer (AMS) measurements during winter and spring. The results suggest that the fossil-derived
primary OC was dominated by coal combustion emissions whereas secondary OC was mostly from fossil-fuel emissions. Taken together with previous $^{14}$C studies in Asia, Europe and USA, a ubiquity and dominance of non-fossil contribution to OC aerosols is identified not only in rural/background/remote regions but also in urban regions, which may be explained by cooking contributions, regional transportation or local emissions of seasonal-dependent biomass burning emission. In addition, biogenic and biomass burning derived SOA may be further enhanced by un-resolved atmospheric processes.

**TOC**
1 Introduction

Carbonaceous aerosols, which can contribute 20-90% of the total fine aerosol mass concentrations $^1,^2$ are of great importance due to their significant and complex impacts on air quality, human health and climate $^3,^5$. According to different physical and chemical properties, bulk carbonaceous aerosols (total carbon, TC) are operationally divided into two sub-fractions namely organic carbon (OC) and elemental carbon (EC) or black carbon (BC) when carbonate carbon (CC) may be negligible or less than 5% of the TC mass in fine (i.e. PM2.5, particulate matter with a diameter equal to or smaller than 2.5 µm) or sub-micron particulate matter (PM1) $^6$. PM1 may be more important to human health compared to PM2.5 because smaller particles may have higher ability to penetrate into the human respiratory system $^7$. OC can scatter or reflect solar light leading to a net cooling effect on the Earth’s climate, whereas EC can significantly contribute to global warming due to its light absorbing behavior $^5$. OC and EC not only differ in their chemical and environmental effects but also differ in their origins and formation $^6,^8$. OC can be emitted as primary OC (POC) and formed as secondary OC (SOC) through gas-to-particle conversion after gas-phase oxidation of volatile organic precursors or aqueous-phase processing of low-molecular-weight water-soluble organic compounds $^6,^8,^9,^{10}$. EC almost exclusively originates from incomplete combustion either from fossil-fuel combustion or biomass burning $^{11}$. POC and its precursors can be emitted from fossil (e.g., coal combustion and vehicle exhaust) and non-fossil sources (e.g., biomass burning, vegetation emissions, cooking) $^8,^{12,14}$. Several studies have revealed that OC and EC differ in
their origins and formation processes based on bottom-up and top-down approaches.

It is therefore very challenging to quantitatively determine contributions from different sources to OC and EC separately, especially in polluted urban regions.

Beijing, the capital of China, is one of the largest megacities in the world with a population of 20 million over an area of 16,800 km² and it has faced serious air pollution problems for the last decades. Zheng et al. (2015) found that PM2.5 is associated with an average total mortality of 5100 individuals per year for the period 2001–2012 in Beijing, and their results underscored the urgent need for air pollution abatement in Beijing or similar polluted megacities and city clusters. Extensive studies have been conducted in recent years to characterize severe haze pollution. However, most of them were focused on pollution episodes, an individual season or specific seasons for comparisons (e.g., summer vs. winter; heating vs. non-heating season).

Recent studies have shown that radiocarbon measurements can unambiguously determine fossil and non-fossil sources of carbonaceous particles, because ¹⁴C is completely depleted in fossil-fuel emissions due to its age (half-life 5730 years), whereas non-fossil carbon sources (e.g., biomass burning, cooking or biogenic emissions) show a contemporary ¹⁴C content. Moreover, a better ¹⁴C-based source apportionment can be obtained when ¹⁴C determinations are performed on OC, EC and water-soluble OC. Biomass burning, coal combustion, vehicle emission, cooking, and the secondary formation from anthropogenic and biogenic precursors have been identified as important sources of
fine particle in Beijing. Recent applications of the positive matrix factorization (PMF) algorithm with aerosol mass spectrometer measurement (AMS-PMF) from field campaigns have revealed a predominance of oxygenated organic aerosol (OOA) over hydrocarbon-like OA (HOA) in various atmospheric environments, although their fossil/non-fossil sources still remain relatively unknown.

It should be noted that most of these aerosol mass spectrometer studies have been conducted for PM1. A full yearly variation of relative fossil and non-fossil contribution of different carbonaceous aerosols in PM1 in Beijing is urgently needed. To the best of our knowledge, this study is the first time that $^{14}$C-based source apportionment of PM1 is simultaneously carried out in different carbonaceous fractions during four seasons in Beijing to attain a comprehensive picture of the source and formation information of carbonaceous aerosols. In addition, $^{14}$C results were also combined with AMS-PMF results to quantify the fossil and non-fossil contributions to oxygenated organic carbon (OOC, a surrogate for SOC) and assess contributions to POC from different sources (cooking, biomass burning, coal combustion, hydrocarbon-like OC). Finally, the dataset is also complemented by previous $^{14}$C-based source apportionment studies conducted in urban, rural and remote regions in the Northern Hemisphere to gain an overall picture of the sources of OC aerosols.

2 Experimental

2.1 Sampling

PM1 samples were collected on the rooftop of a two-floor building (8 m a.g.l.)
located at the State Key Laboratory of Atmospheric Boundary Layer Physics and Atmospheric Chemistry (LAPC), Institute of Atmospheric Physics (IAP), Chinese Academy of Sciences in Beijing, China. The samples were collected onto pre-baked quartz fibre filters (Pallflex) by a gravimetric volume sampler (Zambelli, Italy) at a flow rate of 38.7 L min$^{-1}$ for around three days for each sample from 28 July 2013 to 21 April 2014. For each season, 10-15 samples were collected. Blank was collected during each season with the pump off during the sampling. The filters were previously enveloped with aluminum foils and then baked at 450 °C for 6 hours before sampling. After sampling, each filter was packed separately stored in a refrigerator under –20°C until the analysis.

2.2 Thermal-optical carbon analysis

OC and EC mass concentrations were measured by the NIOSH thermal-optical transmission (TOT) protocol. The replicate analysis of samples (every 10 samples) showed a good analytical precision with relative standard deviations of 5.2%, 9.5%, and 5.2% for OC, EC and TC, respectively. The average field blank of OC was 1.9±1.0 µg/cm$^2$ (n=4, equivalent to ~0.3±0.15 µg/m$^3$), which was subtracted from the measured OC concentrations. A corresponding EC blank was not detectable.

2.3 $^{14}$C analysis of the carbonaceous fractions

One to three sequent filter samples were pooled together for $^{14}$C measurement. The method of $^{14}$C measurement of carbonaceous aerosols was described elsewhere. In short, $^{14}$C of TC was analyzed by coupling of an elemental analyzer (EA)
with a Mini CARbon Dating System (MICADAS) at the University of Bern, Switzerland. \(^{41, 42}\) \(^{14}\)C analysis of EC was carried out by online coupling the MICADAS with a Sunset Lab OC/EC analyzer \(^{43}\) where CO\(_2\) evolved from the EC peak is separated after OC was combusted from the filter sample (1.5 cm\(^2\)) by TOT Swiss_4S protocol \(^{39}\). Two samples with relatively high concentrations for each season were selected for \(^{14}\)C measurements of water-soluble OC (WSOC). The mass and \(f_M\) values of WSOC were deduced from subtraction of OC and water-insoluble OC (WIOC) based on mass and isotope-mass balancing. \(^{14}\)C measurement of WIOC was measured under the same conditions as OC after water extraction of the filter \(^{26}\).

\(^{14}\)C results were expressed as fractions of modern (\(f_M\)), i.e., the fraction of the \(^{14}\)C/\(^{12}\)C ratio of the sample related to that of the reference year 1950 \(^{44}\). \(f_M\) (EC) for each sample was further corrected by EC loss (20±8% on average) during the OC removal steps and possibly positive EC artifact from OC charring (10±6% of EC on average) similar to previous analyses \(^{39, 45}\). \(f_M\) (TC) was corrected for field blanks. The mean uncertainties of \(f_M\) (EC) and \(f_M\) (TC) were 5% and 2%, respectively. \(^{14}\)C results in OC (\(f_M\) (OC)) were then calculated indirectly according to an isotope mass balance \(^{40}\):

\[
f_M(OC) = \frac{TC \times f_M(TC) - EC \times f_M(EC)}{TC - EC}
\]

The uncertainty of \(f_M\) (OC) estimated by this approach is on average 8% obtained from an error propagation and includes all the individual uncertainties of \(f_M\) (TC) (2%), \(f_M\) (EC) (5%), TC (8%) and EC (25%).

Non-fossil fractions of OC and EC (i.e., \(f_{NF}\) (OC) and \(f_{NF}\) (EC), respectively) were determined from the \(f_M\) values and reference values for pure non-fossil sources:
f_{NF}=f_{M}(\text{sample})/f_{M}(\text{REF}). The estimation of reference values (f_{M}(\text{REF})) have been previously reported in details \textsuperscript{26, 39, 46}. f_{M}(\text{REF}) values amount to 1.07±0.04 and 1.10±0.05 for OC and EC, respectively by a tree-growth model with a long term \textsuperscript{14}CO\textsubscript{2} measurement \textsuperscript{47} and by assuming that biomass burning contribution to non-fossil OC and EC is 50±25% and 100%, respectively. It should be noted that the uncertainties of references values of f_{NF}(\text{ref}) were relatively small compared to uncertainties from overall source-apportionment calculation. Uncertainties were determined by error propagation of all individual uncertainties including OC and EC mass concentrations, \textsuperscript{14}C results of OC and EC, f_{M}(\text{REF}) as well as corrections for field blanks, EC recovery and charring. The overall average uncertainties of f_{NF} were estimated as 5\% (i.e., ranging from 3\% to 7\%) for OC and 8\% (4\% to 12\%) for EC.

Indeed, blank corrections and EC yield corrections are the most important contributors to the total uncertainties of OC and EC, respectively.

### 2.4 HR-ToF-AMS operation and PMF

An Aerodyne High-resolution Time-of-Flight Aerosol Mass Spectrometer (HR-ToF-AMS) was deployed at the same location for real-time measurements of non-refractory submicron species, including organic aerosols, sulfate, nitrate, ammonium, and chloride in spring (8–28 March, 2014) and winter (17 December 2013 to 17 January, 2014). The detailed setup and operations of the HR-ToF-AMS is given elsewhere \textsuperscript{22}. The high-resolution mass spectra were then analyzed to determine the elemental ratios of OA, e.g., organic-mass to organic-carbon (OM/OC) and oxygen-to-carbon (O/C), using the Improved-Ambient method \textsuperscript{48}, and OC mass was
calculated as [OA]/[OM/OC]. Positive matrix factorization (PMF) was performed to
high-resolution OA spectra to resolve potential source factors in spring and winter.
After careful evaluations of the mass spectral profiles and times series following the
procedures described elsewhere 49, six factor solution was chosen for both spring and
winter studies, which included a hydrocarbon-like OA (HOA), cooking OA (COA),
biomass burning OA (BBOA), coal combustion OA (CCOA), and two oxygenated OA
factors, i.e., less oxidized OOA (LO-OOA) and more oxidized OOA (MO-OOA). The
OC mass for each factor such as hydrocarbon-like OC (HOC), cooking OC (COC),
biomass burning OC (BBOC), coal combustion OC (CCOC), and oxidized OOA
(OOC) was calculated by dividing the corresponding OM/OC ratio. A more detailed
PMF analysis and data interpretation has been given 22.

2.5 14C-based source apportionment model
An advanced 14C-based source apportionment model was used to quantify OC
and EC from each source, which was achieved by the Latin-Hypercube Sampling
(LHS) simulations using the dataset from mass concentrations of OC and EC,
estimated primary emission ratios for fossil fuel and biomass burning as well as 14C
results (termed as the 14C-LHS method) 40. In total, four major sources were resolved
including EC from fossil and non-fossil sources (EC\textsubscript{FF} and EC\textsubscript{NF}, receptively), OC
from fossil and non-fossil sources (OC\textsubscript{FF} and OC\textsubscript{NF}, receptively). OC\textsubscript{FF} and OC\textsubscript{NF}
were further apportioned into sub-fractions of fossil-fuel OC from primary (POC\textsubscript{FF})
and secondary organic carbon (SOC\textsubscript{FF}) and non-fossil OC from primary
biomass-burning sources (POC\textsubscript{BB}) and other non-fossil (ONF) sources (e.g. cooking
and primary/secondary non-fossil OC, OC\textsubscript{ONF}). The equations for the detailed source apportionment are shown in Table 1. Central (median) values with low and high limits were used as input parameters, and all solutions were included in frequency distributions of possible solutions except those producing negative values.

The median values of (EC/POC)\textsubscript{BB} amounted to 0.3 with a range from 0.1 (low limit) to 0.5 (high limit), according to composed emission ratios in previous literatures\textsuperscript{1,40,50}. The (EC/POC)\textsubscript{FF} values were calculated as (EC/POC)\textsubscript{FF} = EC\textsubscript{FF}/(HOC+CCOC). Individual HOC and CCOC values were obtained from the AMS-PMF method (see Sec. 2.4). For the samples without AMS-PMF data, a seasonal mean of (EC/POC)\textsubscript{FF} associated with an uncertainty of 30% was used, which amounted to 0.69 (0.48-0.89) and 1.25 (0.87-1.62) for wintertime and springtime samples, respectively. For samples collected during the autumn, (EC/POC)\textsubscript{FF} was assumed to be equal to that in spring.

In summer, due to decreased contribution from coal combustion to fossil-fuel emissions as previously reported in Beijing\textsuperscript{51}, a higher (EC/POC)\textsubscript{FF} of 1.9 (1.3-2.5) was used. This was slightly smaller than EC/OC emission ratios (2.1) from vehicle emission used in our previous study, which were taken from the tunnel experiments in Europe (Gelencsér et al., 2007) and China\textsuperscript{52,53}. The uncertainties and sensitivity test of source apportionment results were carried out by the LHS methodology by generating 10000 sets of inputs used in calculations (see Table 1)\textsuperscript{40}. Simulations with negative solutions were not included in final results and the 50\textsuperscript{th} percentiles (or median) of the solution were considered as the best estimate, and the uncertainties were the 10\textsuperscript{th} and 90\textsuperscript{th} percentiles of the solutions.
3 Results and discussion

3.1 OC and EC mass concentrations

As shown in Figure 1, the annual average mass concentrations of OC and EC were 10.1 µg m\(^{-3}\) (ranging from 1.9 to 33.8 µg m\(^{-3}\)) and 3.8 µg m\(^{-3}\) (1.3 to 9.4 µg m\(^{-3}\)), respectively. OC mass concentrations were less than those for PM\(_{2.5}\) samples in Beijing during 2000 (i.e., 21 µg m\(^{-3}\)) and 2013/2014 (i.e., 14.0 ± 11.7 µg/m\(^{3}\)) \(^{33, 54}\), whereas EC values were comparable to those reported previously (i.e., 3 µg m\(^{-3}\)) \(^{33, 54}\). The relatively lower OC mass concentrations in PM1 than PM2.5 is likely due to substantial contribution to PM2.5 from larger particles such as dust and primary biogenic emissions \(^{55}\). The annual concentrations of OC and EC in PM1 have been only reported in a few studies, and the concentrations in Beijing were significantly higher than those in Elche, Spain (i.e., OC: 3.7±1.3 µg m\(^{-3}\); EC: 1.5±0.6 µg m\(^{-3}\)) \(^{56}\), Brno, the Czech Republic (i.e., OC: 5.8 µg m\(^{-3}\); EC: 1.6 µg m\(^{-3}\)) \(^{57}\) and Taipei (i.e., OC:1.7 µg m\(^{-3}\); EC: 0.8µg m\(^{-3}\)) \(^{58}\) but lower than those in Xi’an (i.e., OC: 21.0 µg m\(^{-3}\); EC: 5.1 µg m\(^{-3}\)), China \(^{59}\). The seasonal variations of OC and EC were characterized by the lowest mass concentrations in summer with a small standard derivation and the relatively higher values in other three seasons with much larger variations. As illustrated in Figure 1, both relatively high and low values in OC and EC concentrations could be occasionally observed in autumn, winter and spring although their average values were in the following order: winter=spring>autumn. It is very interesting to note that both OC and EC concentrations were very low during a long holiday season (30\(^{th}\) Jan to 11\(^{th}\) Feb 2014) for the Chinese Spring Festival, which was due to a large decrease in anthropogenic source emissions, e.g., traffic and cooking emissions. Such a “holiday effect” has been also reported in Beijing for 2013 \(^{60}\). Similar lower organic aerosols and/or EC concentrations in summer than in the other seasons were also observed previously in Beijing, which was associated with relatively high wet scavenging effects and convection due to abundant precipitation and high temperature, respectively \(^{34, 51}\). The overall higher concentrations of carbonaceous aerosols in other seasons were mainly due to combined and complex
effects such as increasing emissions from local and regional-transported coal and biomass/bio-fuel combustion and associated secondary formation as well as unfavorable metrological conditions for pollution dispersions. The relative fossil and non-fossil contributions to OC and EC will be discussed in the following sections.

3.2 Fossil and non-fossil sources of OC and EC

Carbonaceous aerosol was divided into the following four categories: OC from fossil and non-fossil sources, i.e., $OC_{\text{FF}}$ and $OC_{\text{NF}}$, and EC from fossil and non-fossil (or biomass-burning) sources, i.e., $EC_{\text{FF}}$ and $EC_{\text{NF}}$ (i.e., $EC_{\text{NF}} = EC_{\text{BB}}$) (see Section 2.5). Annual-average biomass-burning contribution to EC was 18±7% with a range of 4% to 33%, suggesting a dominant contribution of fossil-fuel combustion to EC in Beijing rather than non-fossil sources. Fossil fraction in EC reported here was larger than those estimated by bottom-up inventories (i.e., 61±7%) in China. Such a high annual-average fossil fraction in EC is consistent with the results reported in Beijing (i.e., 79±6%), China, Jeju Island, Korea (i.e., 76 ± 11%) as well as a background site in South China (62±11%) where local/regional biomass burning contribution was found to be more important than fossil fuel combustion. The biomass-burning fraction in EC was the lowest in summer (7%) and increased to around 20% during the rest of the year due to increased residential and/or open biomass-burning emissions, which was in line with a previous study for larger particles (e.g., PM4.3) in Beijing during 2010/2011. As shown Figure 2b, fossil-derived EC was a substantial contribution of TC in summer with a mean
contribution of 39±3%, significantly higher than those in autumn (23±5%), winter (19±2%) and spring (19±2%).

Non-fossil contribution to OC ranged from 28% to 75% with a mean of 52%±12%, which is exclusively larger than the corresponding contribution to EC (Figure 2a). This is due to relatively high contribution to OC from primary and secondary formation from non-fossil emissions such as biogenic, cooking and biomass-burning sources compared to EC. OC was dominated by non-fossil sources throughout the year except winter when a higher fossil-derived contribution for both absolute mass concentration (i.e., 8.0±5.2 µg m$^{-3}$) and relative fraction (i.e., 59±6%) was observed. The highest fossil-derived OC in winter was associated with enhanced coal combustions for heating during the cold periods in North China.$^{51,55}$ Interestingly, fossil fraction in EC was not higher in winter than in autumn and spring, suggesting that source pattern was not changed significantly during these three seasons.

However, the secondary formation from fossil-derived precursors may become more important and this would actually increase the fossil fraction in OC (see the next section). Indeed, the importance of SOC formation from fossil-fuel source has been previously identified in winter of Beijing and a downwind site of North China.$^{13,21,40}$ In contrast to fossil-derived OC, mass concentrations and relative contributions of non-fossil OC were higher during autumn and spring, which was very likely due to enhanced biomass-burning. The lowest non-fossil OC was observed in summer, although secondary production from biogenic emissions should be higher in this
season with relatively high temperature and strong solar radiation\textsuperscript{13}, and the overall low mass concentration was likely due to strong atmospheric convection and dispersion as explained above. The seasonal trend of the TC sources was very similar to that of OC but with a relatively lower non-fossil contribution, suggesting that total carbonaceous aerosols are largely controlled by OC emissions and formation processes.

3.3 Primary and secondary organic carbon

OC contributions from POC\textsubscript{BB}, OC\textsubscript{ONF}, POC\textsubscript{FF}, SOC\textsubscript{FF} sources are displayed in Figure 3. In order to present data variability, the best estimates (the median values) as well as 10\textsuperscript{th}, 25\textsuperscript{th}, 75\textsuperscript{th} and 90\textsuperscript{th} percentiles from the LHS simulations are also shown. On a yearly basis, the most important contributor of OC was OC\textsubscript{ONF}, i.e., all other non-fossil sources (i.e., 33\%±11\% for OC\textsubscript{ONF}) excluding primary biomass-burning OC (POC\textsubscript{BB}), mainly comprising primary and secondary biogenic OC as well as cooking OC. The highest OC\textsubscript{ONF} contribution in summer was due to the increasing contributions from primary biogenic emissions and associated SOC formation with favorable atmospheric conditions (i.e., high temperature and solar radiation) as well as reduced emission for heating. OC\textsubscript{ONF} contribution became lowest in winter because biogenic OC in sub-micron aerosols should be negligible or very small in the cold periods in North China. The mean OC\textsubscript{ONF} contribution (22±9\%) in winter may be used as a upper limit of cooking OC, which was comparable to results resolved from AMS-PMF (~20\% for COC/OC in winter, see Figure 4) in our study and also cooking contribution to organic aerosols (19±4\%) previously reported in Beijing\textsuperscript{14}. The
remaining OC was shared by fossil-derived POC (29±4%), primary biomass-burning
OC (22±11%) and fossil-derived SOC (15±4%). For fossil-fuel derived OC, primary
emissions dominated over secondary formation in almost all cases.

A clear seasonal variation of biomass-burning source was observed with the
highest contribution in autumn (27±13%) and spring (26±14%), followed by winter
(19±10%) and summer (16±9%). The enhanced biomass-burning activities in autumn
in Beijing and other areas in Northeast China have also been reported by
measurements of biomass-burning markers such as levoglucosan and K³⁺ as well as
stable carbon isotopic composition, which can be attributed to agricultural waste
and/or fallen leaves burning 62, 63. POC⁻FF contributions were significantly higher in
summer and winter. A large fraction of POC⁻FF could be from vehicle emissions
elucidated by a lower mean OC⁻FF/EC⁻FF ratio in summer (i.e., mean: 0.6; range: 0.5-0.7)
compared to other seasons (i.e., mean: 1.70; range: 0.5-3.8). In winter, the
enhancement was observed for both the POC⁻FF (33±4%) and SOC⁻FF (26±10%)
contributions, associated with increasing emissions from coal combustion for heating.
However, the SOC contribution in PM1 samples was obviously lower than those
reported for a severe haze episode across East China in winter 2013 40, implying
relatively larger SOC contribution to PM2.5 than PM1.

To further investigate the relative contributions of biomass burning, cooking
emissions and secondary formation to non-fossil OC, ¹⁴C-based source apportionment
results were integrated with AMS-PMF results. Average mass concentrations of OC
determined by filter-based OC/EC analyzer and on-line AMS methods (OC-AMS) are
shown in Figure 4. Due to analytical uncertainties in either method, a mean OC-AMS/OC-Sunset ratio was 1.1±0.2, and such a difference was also reported in other studies. In the following, only relative contributions from each source to OC were compared to remove possible influences from differences in absolute concentrations (Figure 4). In spring and winter of Beijing, non-fossil OC was mostly derived from cooking and biomass-burning emissions. OOC, a proxy for secondary OC, comprised only a minor non-fossil fraction (15%). The results suggest that SOC was dominated by fossil fuel emissions in Beijing at least in these two seasons.

It should be noted that BBOC resolved from the AMS-PMF approach was smaller than POC\textsubscript{BB} obtained from the \textsuperscript{14}C-LHS method. The difference between the AMS-PMF and \textsuperscript{14}C-LHS results can be explained by the uncertainties in both methods. Biomass-burning contribution may be underestimated by the AMS-PMF if aged BBOC was not included in the PMF model when biomass-burning OA was subject to substantial aging during regional transport. It may also be possible that POC\textsubscript{BB} was overestimated by the \textsuperscript{14}C method if a too low (EC/POC)\textsubscript{BB} was used in the LHS calculation, which was also reported during the DAURE campaign in Northeast Spain. With a combination approach with \textsuperscript{14}C and AMS-PMF methods, coal combustion was estimated to account for 62% and 56% of fossil-derived POC in winter and spring, respectively, implying an overall importance of coal combustion to OC aerosol in Beijing. The biogenic/biomass-burning derived SOC (i.e., estimated as OOC\textsubscript{NF}) contributions accounted for 7% and 9% of OC in Beijing during winter and spring, respectively, demonstrating that OC was dominated by anthropogenic emissions.
including biomass burning, cooking emissions as well as primary and secondary OC from fossil-fuel emissions.

3.4 Fossil and non-fossil sources of WSOC and WIOC

WSOC can be directly emitted as primary particles mainly from biomass burning or produced as secondary organic aerosol (SOA)\(^ {65-67}\). Ambient studies provide evidence that SOA produced through the oxidation of volatile organic compounds (VOCs) followed by gas-to-particle conversion contains more polar compounds and thus may be a more important source of WSOC\(^ {66-69}\) compared to primary organic aerosols. WSOC is therefore thought to be a good proxy of secondary organic carbon (SOC) in the absence of biomass burning\(^ {67}\). The average WSOC/OC ratio in our study was 0.53±0.19 (ranging from 0.21 to 0.84). And WSOC/OC mass concentration ratio and non-fossil fraction of OC (i.e., \(f_{\text{NF}}(\text{OC})\)) show a very similar temporal variation (Figure 5) with a good correlation (\(r=0.60, p<0.05\)), indicating that non-fossil source was an important contributor of WSOC. To confirm this hypothesis, \(^{14}\)C measurement was also performed on sub-fractions of OC including WSOC and water-insoluble OC (WIOC) of two samples for each season. Based on these measurements, the WSOC concentrations from non-fossil sources (WSOC\(_{\text{NF}}\)) ranged from 0.6 to 7.6 µg/m\(^3\), whereas the corresponding range for WSOC from fossil-fuel emissions (WSOC\(_{\text{FF}}\)) was 0.5 to 11.6 µg/m\(^3\). Non-fossil sources were major if not dominate contributors of WSOC for nearly all studied samples with a mean contribution of 58%±9% (Figure 6). The only exception (i.e., \(f_{\text{NF}}(\text{WSOC})=0.39\)) was the aerosol sample collected from 2013/12/2 to 2013/12/26 when the highest OC concentration during the whole sampling periods was observed. The highest fossil source contribution was also found for the WIOC fraction (i.e., \(f_{\text{NF}}(\text{WIOC})=0.31\)) for the same sample. These results showed that during this haze episode, fossil emission was the most important source of OC. WSOC\(_{\text{NF}}\) can be further apportioned to WSOC from biomass burning (i.e., WSOC\(_{\text{BB}}\)) and non-fossil SOC (i.e., WSOC\(_{\text{NF,SO}}\)):

\[
\text{WSOC}_{\text{NF}} = \text{WSOC}_{\text{NF,SO}} + \text{WSOC}_{\text{BB}}
\]
WSOC_{BB} = POC_{BB} \times (WSOC/OC)_{BB}

where POC_{BB} was previously estimated (see Sec.3.3). SOC-to-OC emission ratios of biomass burning (i.e., (WSOC/OC)_{BB}) is assigned as 0.8±0.2 (ranging from 0.6 to 1.0) in this study according to observations of different biomass types around the world. Therefore, primary biomass burning and non-fossil derived SOC accounted for 62%±17% and 38%±17% of WSOC_{NF}, respectively. This suggest that biomass burning was generally a major contributor of non-fossil WSOC in Beijing. Furthermore, WSOC_{FF} was significantly correlated (r=0.94, p<0.01) with SOC_{FF} (see Sec. 3.3), suggesting that an importance contribution of fossil-derived SOC to WSOC_{FF}. On the yearly-basis, non-fossil contributions to WSOC were larger than those to WIOC (Figure 6), although most of the data is not statistically significant from the 1:1 line and some opposite cases were also found occasionally. Similar observations were published for other locations in Asia, Europe, and the USA, which is due to relatively high water solubility of major sources of WSOC such as biomass-burning OC and SOC that are composed of a large fraction of polar and highly oxygenated compounds.

4 Implications

Despite dominant fossil-fuel contribution to EC particles due to large emissions from traffic and coal combustion, our study demonstrates that non-fossil emissions are generally a dominant contributor of OC including WIOC and WSOC fractions in a heavily polluted megacity in China. Such an important non-fossil contribution to OC agrees with source information identified in OC aerosols obtained in the Northern Hemisphere at urban, rural, semi-urban, and background sites in Asia, Europe and USA (Figure 7). The $^{14}$C-based source apportionment database shows a mean non-fossil fraction of 68±13% across all sites (Figure 7). $^{14}$C results of EC/TC/WSOC were not compiled for the comparisons since these carbonaceous fractions cannot
fully represent OC aerosols. As discussed in the previous section, WSOC/OC ratios
and non-fossil contribution of OC in Beijing have very similar temporal variations,
indicating that biomass-burning emissions and biogenic-derived SOC formation were
very important contributors of non-fossil OC. Indeed, WSOC/OC ratios may be also
increased due to organic aerosol aging during regional and/or long-range transport, so
it can be anticipated that the regional-transported non-fossil OC from rural sites to
urban areas would also increase non-fossil OC fraction in urban regions. As shown in
Figure 7, fossil contribution is apparently higher in the USA (i.e., with fossil
contribution of 44±11%) and East Asia (i.e., 39±13%) than those observed in Europe
(i.e., 25±9%). This may be because most \(^{14}\)C-based studies in the USA and East Asia
have been conducted within, near and downwind of urban areas. Furthermore, wood
burning emissions have recently become a more important contributor of European
aerosols. This would be especially the case in winter, decreasing fossil contribution.

This study shows that a combined approach of AMS-PMF and \(^{14}\)C methods
provide more comprehensive picture of the source and formation information of
carbonaceous aerosols than either method alone. Therefore, such approaches are
recommended to be used as a routine basis in a long-term monitoring network (e.g. at
supersites) for a better source apportionment. Our study also provides a direct
evidence that non-fossil source plays a major role in organic aerosol concentrations
not only in rural/remote areas but also in many polluted urban sites, which seems to
be contrasting to the fact that fossil fuel emissions (e.g., coal combustion and vehicle
exhaust) often dominate EC aerosols (i.e., an excellent marker for primary
carbonaceous aerosols) in urban areas. This unexpectedly high non-fossil contribution to OC in urban areas may be explained by urban non-fossil carbon emissions (e.g. cooking emissions and associated SOA), regional transported or locally season-dependent biomass burning emissions \(^75\), \(^76\), as well as biogenic/biomass-burning SOA linked with complex and combined atmospheric mechanisms such as enhancement by anthropogenic emissions \(^77\).

Notes

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Table 1. Equations for $^{14}$C-based source apportionment model. See Sec 2.5 for the details.

Equations

\[ EC_{NF} = f_{NF}(EC) \times EC \]
\[ EC_{FF} = EC - EC_{NF} \]
\[ OC_{NF} = f_{NF}(OC) \times OC \]
\[ OC_{FF} = OC - OC_{NF} \]
\[ POC_{FF} = EC_{FF} / (EC/POC)_{FF} \]
\[ SOC_{FF} = OC_{FF} - POC_{FF} \]
\[ POC_{BB} = EC_{NF} / (EC/POC)_{BB} \]
\[ OC_{ONF} = OC_{NF} - POC_{BB} \]
\[ OC_{AMS} = OA_{AMS} / (OM/OC)_{AMS} \]
Figure 1. Temporal variations of OC and EC mass concentrations as well as OC/EC ratio of PM1 samples in Beijing.
Figure 2. (a) Temporal variations of non-fossil contribution to OC, EC and TC and (b) average source apportionment results of TC in each season of PM1 samples in Beijing. The numbers below the pie chart represent the average TC concentrations for each season.
Figure 3. Fractions of each source (i.e., POC\textsubscript{FF}, SOC\textsubscript{FF}, POC\textsubscript{BB}, OC\textsubscript{ONF}) in OC of PM\textsubscript{1} samples in Beijing derived from the Latin-Hypercube Sampling (LHS) simulations for summer, autumn, winter, spring, and the annual-average (from left to right). The box denotes the 25\textsuperscript{th} (lower line), 50\textsuperscript{th} (middle line) and 75\textsuperscript{th} (top line) percentiles; the empty squares within the box denote the mean values; the end of the vertical bars represents the 10\textsuperscript{th} (below the box) and 90\textsuperscript{th} (above the box) percentiles. POC: primary organic carbon, SOC: secondary organic carbon. FF: fossil fuel, NF: non-fossil, ONF: other non-fossil sources (details see the main text).
Figure 4. Average mass concentration measured by filter-based Sunset OC/EC analyzer method (OC-Sunset) and AMS method (OC-AMS) during winter (n=4) and spring (n=2) (top) and relative contributions to OC from different sources with a combination of $^{14}$C-LHS and AMS-PMF methods (bottom). OC_{FF}: fossil-fuel derived OC; OC_{NF}: non-fossil OC; CCOC: primary coal combustion OC; HOC: hydrocarbon-like OC; OOC_{FF}: fossil-fuel oxygenated OC; OOC_{NF}: non-fossil oxygenated OC; COC: primary cooking OC; BBOC: primary biomass burning OC.
Figure 5. Temporal variations of non-fossil contribution to OC and WSOC/OC ratio of PM$_1$ samples in Beijing.
Figure 6. Relationship between $f_{NF}(\text{WSOC})$ and $f_{NF}(\text{WIOC})$. 
Figure 7. Fossil and non-fossil sources of OC aerosols at different locations around the world. The results are obtained from this study and previous $^{14}$C-source apportionment studies $^1, 13, 18, 26-28, 40, 46, 71, 78-88$. The map is created by MeteoInfo Java Edition 1.3 (http://www.meteothinker.com/).