We thank the reviewers for their time and comments. Below are detailed responses to each comment. The responses are italicized, and the modified texts are in red.

Response to anonymous referee #1 comments:

This manuscript showed the chemical composition and oxidative potentials (OP) of fine particulate matter (PM2.5) in Atlanta at a year-long time scale. Moreover, the authors investigated the correlation of probe-based aerosol OP with abundance of different PM constituents. They found that dithiothreitol- and ascorbic acid-based OP exhibited moderate correlation with the abundance of water-soluble transition metals (Fe and Cu) and organic compounds (WSOC and brown carbon), whereas the glutathione (GSH)-based OP showed strong correlation with the water-soluble Cu. Finally, the authors developed a multivariate linear regression model to evaluate the plausible contributions of metals, organic compounds, metal–organic and metal–metal interactions to aerosol OP. Overall the topic is interesting. The manuscript cannot be published in its current form, but it may be publishable in *Atmos. Chem. Phys.* if the following comments can be thoroughly responded in the revised paper,

1. **What is the atmospheric implications of aerosol OP, which may merit the current work to be publishable in *ACP* rather than an aerosol or air pollution health related journal? Some relevant discussions may be needed in the section 1 or 4.**

   This paper deals with contrasting relatively new measures of atmospheric aerosol chemical characteristics and is of interest to the atmospheric chemistry community. In the last few years there have been numerous papers published in ACP on aerosol oxidative potential. Our work is motivated by the fact that aerosol OP has been linked to adverse health effects, but our focus here is on how two measures of OP in current use differ in their relationship to aerosol chemical composition.

2. **The authors mainly described the correlations of different aerosol constituents with the OP reflected by different types of acellular assays. However, the manuscript lacks discussions and insight into the underlying chemical mechanisms of the interactions among different probes and PM constituents in water or the synthetic respiratory tract lining fluid.**

   Elucidating the underlying chemical mechanisms is beyond the scope of this paper and specific chemical exposure–response relations were not explored in this study. However, possible mechanisms in the published literature were discussed in the paper as an explanation of our OP results. For example, we explained the antioxidants depletion in RTLF based on reactivity hierarchy of antioxidants and ligand speciation.

3. **In the manuscript especially the Figure 2, the authors only showed the OP values in the unit of nmol/min/m3, which strongly associates with PM2.5 concentrations. In contrast, the OP values in the unit of nmol/min/μg may exhibit stronger correlation with PM2.5 composition. Therefore, the authors should present and discuss the OP values in the unit of nmol/min/μg as well as their dependence on different types of OP assays.**

We agree that the mass-normalized OP could eliminate the collinearity in the correlations due to PM mass and does reflect the intrinsic property of PM resulting from PM composition. However, volume-normalized OP represents the human exposure to redox-active species, and thus is more health-related and useful in interpreting OP–health associations. Furthermore, compared to mass-normalized OP, the levels of volume-normalized OP provide more dynamic range useful for identifying OP-related species or sources. For example, the correlation of volume-normalized OP with BrC and K may suggest the influence of biomass burning, even though the actual drivers of OP metrics are confounded.

Correlation results between mass-normalized OP and species mass fraction have been added in SI (Table. S4). The results do not exhibit stronger correlation between intrinsic OP measures and PM composition, which may be due to nonlinear behavior of species with antioxidant oxidation and the interactions among species.

4. **The Figures 1 and 3 are related to the chemical composition of PM2.5, and the Figures 2 and 4 are for aerosol OP. Thus, it may be more suitable to present the current Figure 3 as Figure 2, and the current Figure 2 as Figure 3.**

   Thank you for this suggestion. The figures were numbered according to their sequence in the text. The primary aim of this work was to compare the OP measures so we presented the temporal variation of OP first, and the PM species provided an explanation for the observed differences in OP measures.

5. **What is the association of water insoluble organic matter and metals in PM2.5 (in Figure 1) with probe-based aerosol OP?**

   In another paper from this study (Gao et al., 2020, submitted to Atmos Environ), in which we focused more on the OP (DTT assay only) contributions from water-insoluble PM components, the association of total or water-insoluble PM species with total PM OP was studied in detail. However, the manuscript is focused only on the water-soluble OP fraction. Compared to the association between water-soluble species and OP measures, the association of water-insoluble PM species with water-soluble OP was less informative about determinants of water-soluble OP, and thus was not discussed in this paper.

   To clarify, the manuscript has been modified.

   Line 276-277: "The OP (DTT assay only) contribution from water-insoluble components were discussed in detail in another paper from this study (Gao et al., accepted)."

6. **L158-172: whether the efficiency of NAPDH and GR to reduce GS-TNB to GSH can be interfered by the co-existence of ascorbic acid? Similarly, to which extent the co-variation of ascorbic acid and GSH concentrations will influence the OPAA and OPGSH?**

   The reviewer is thanked for raising this concern. The presence of AA is not expected to interfere with the reduction of GSSG or GS-TNB to GSH. This reduction reaction is the *key reaction involved in both total and oxidized glutathione measurements. We can check the reduction efficiency by examining the amount of total glutathione (GSx). Within error, the GSx concentration we measured in each plate well is consistent with the expected initial concentration (~200 µM per well), and the amount remains constant during the whole incubation, suggesting that all oxidized form glutathione can be reduced efficiently in GSx determination.*

This study only indicated the antioxidants depletion in RTLF was affected by the RTLF composition. To what extent OP^{AA} *and* OP^{GSH} *are influenced by RTLF composition still needs further investigation.*

7. **L243-244: The sentence of 'However, they could be considered as indicators of other compounds simultaneously produced by the same source' is a vague statement, which needs further clarification.**

   To improve clarity, the manuscript has been modified.

   Line 290-293: "However, the correlations may indicate the emission sources (e.g., as source tracers – vehicular emissions for EC, secondary processing for WSOC and SO_4^{2-}, and biomass burning for BrC and K), which also probably emit the water-soluble species contributing to the measured OP."

8. **L249: What does the "PM species" exactly refer to?**

   To clarify, we modified the manuscript.

   Line 298: "The associations found in this study between OP^{DTT} and PM composition are consistent with a number of previous studies (Fang et al., 2016; Fang et al., 2015b; Verma et al., 2014; Yang et al., 2014), though the correlations in our work were weaker…"

9. **L274 (3.3 Temporal variation): to discuss the seasonal distribution of OP clearly, the averaged PM2.5 OP of different seasons should be presented in Figures 2, 3 or SI, similar like the seasonal distribution of different PM components in Figure 1.**

   Thank you for this suggestion. Figure 2 has been modified to include the averaged OP levels during warm and cold periods. The seasonal averaged PM species concentrations have been added into SI (Fig. S1). We have also modified the manuscript accordingly.

   Fig. 2 caption: "Temporal variation for (a) OP^{DTT} m^{-3} (nmol min^{-1} m^{-3}), (b) OP^{AA} m^{-3} (% depletion of AA m^{-3}), and (c) OP^{GSH} m^{-3} (% depletion of GSH m^{-3}). Warm period: May–Aug; cold period: Jan–Feb and Nov–Dec."

   Line 330: "The time series of the monthly and seasonal averages of different OP measures are shown…"

   Line 337-338: "From the temporal variation of the OP-associated species shown in Fig. 3 (the seasonal averaged concentrations were given in Fig. S1), BrC had an obvious seasonality… Water-soluble Cu is slightly higher in mid-summer (Aug) and water-soluble Fe is slightly higher in fall (Sep), but…"

10. **L281: Except for aerosol composition, the concentration of PM2.5 and size distribution of redox active PM2.5 constituents may also influence the seasonal distribution of OP (Lyu et al., Environ. Sci. Technol. 2018, 52, 6592-6600). Thus, the temporal variation of PM2.5 OP should be discussed deeply.**

    We agree with the reviewer that oxidative potential will vary across PM size fractions which may exhibit seasonal variance. Evaluation of multiple size fractions for PM and chemical composition was beyond the scope of this study. This study was solely based on $PM_{2.5}$ *measurements with no further size distribution information, however, the change of PM composition resulted from seasonal size distribution shifts could be captured in our sampling. Either PM mass concentration or size distribution of PM constituents influence* $PM_{2.5}$ *OP by changing the composition of* $PM_{2.5}$*. Therefore, the PM OP essentially is still related to aerosol composition. This is also consistent with the findings in the reference cited by the reviewer, which demonstrated that the averaged OP levels for all size fractions were significantly correlated with PM redox active species (quinone and water-soluble metals).*

11. **L305-313: It has been found that secondary organic aerosols-bound water-soluble substances such as organic peroxide, highly oxygenated molecules, and semiquinone radicals etc. are redox active in producing reactive oxygen species through reactions with water, antioxidants, or lung cells (Khachatryan et al. Environ. Sci. Technol. 2011, 45, 19, 8559-8566; Tong et al., Environ. Sci. Technol. 2018, 52, 11642-11651; Tong et al., Environ. Sci. Technol. 2019, 53, 12506-12518; Zhou et al., Atmos. Chem. Phys. Discuss., https://doi.org/10.5194/acp-2019-190; Chowdhury et al., Environ. Sci. Technol. Lett. 2018, 5, 424−430; Chowdhury et al., Environ. Sci. Technol. 2019, DOI: 10.1021/acs.est.9b04449), thus the contribution or connection of these and other relevant WSOC substances to the OP of PM2.5 should be discussed properly.**

    Based on the reference cited by the reviewer, the redox active substances the reviewer mentioned are more likely bounded on particles in atmospheric conditions rather than WSOC. Given that we were only measuring water-soluble OP of long-time integrated PM samples, we may fail to capture the effects of these short-lived species or radicals. Therefore, including these substances as part of WSOC-related OP contribution may not be appropriate.

    We have included some of these substances in the introduction to provide a more comprehensive description about OP contributors.

    Line 58-64: "The ability of PM to generate ROS *in vivo,* referred to as the oxidative potential (OP) of particles, has gained increasing attention as possibly a more integrative health-relevant measure of ambient PM toxicity than PM mass concentration which may contain a mix of highly toxic (e.g. polycyclic aromatic hydrocarbons (PAHs), quinones, environmentally persistent free radicals, highly oxygenated organic molecules, and transition metals) to relatively benign (e.g. sulfate and ammonium nitrate) PM components (Frampton et al., 1999; Khachatryan et al., 2011; Lippmann, 2014; Tong et al., 2018; Tong et al., 2019)."

12. **The y-axis title of the upper left panel (for BrC) in Fig. 3 should be corrected.**

    Thank you for pointing this out! The y-axis title for BrC in Fig. 3 has been corrected from "Mm^{-1}" to "1/Mm" so that it remains consistent with the format of other species' units.

Reference:

Gao, D., Mulholland, J. A., Russell, A. G., and Weber, R. J.: Characterization of water-insoluble oxidative potential of PM2.5 using the dithiothreitol assay, Atmos Environ (accepted)

Response to anonymous referee #2 comments:

In this work, the authors compared the results from 3 different acellular assays of oxidative potential in 2 different media. OP has recently become a popular topic of research due to its potential to represent PM's ability to drive oxidative stress and explain PM health effects. Understanding the assays used to measure OP is an important topic for atmospheric chemists, because they will provide insights into sources and/or compounds that may be particularly toxic. The authors found different level of sensitivities of these assays to different components, such as copper, iron, and organic compounds. These relationships were investigated by association, using multilinear regression models. Overall the results are a valuable contribution and are complementary to those currently in the literature. I just one major point of concern, and I hope the authors will consider it while revising the manuscript. I recommend publication in ACP

My major issue with this work is the use of a per-air volume measure of OP (extrinsic OP) rather than a per-PM mass measure. All the comparisons made here are chemical, with the attempt to associate a particular fraction of PM to its contribution to OP. In that case, I would argue that the OP should be an intrinsic measure (i.e. oxidant depletion rate per PM mass). Otherwise the variability could be driven by total PM mass. I understand that the assays were performed on a per filter basis (which is equivalent to a per-volume basis), and it might be difficult to fix the amount of PM mass used to analyze OP. At the very least, there needs to be a discussion examining whether or not the variability in OP (and therefore the reported associations shown here) is driven by the PM mass, rather than its composition.

The reviewer is thanked for the comment, correlation results between intrinsic OP and species mass fraction have been added in SI. As we addressed in the response to reviewer #1, volume-normalized OP can reflect the human exposure to redox-active species and help explain the observed OP–health associations. OP per mass, however, is the intrinsic property of PM which is more applicable to studies of emissions. Since the goal of this study is to compare OP assays that have been found in health studies to be associated with adverse health effects, and to investigate the underlying chemical species that may be driving these associations, we focus on the OP per volume air.

Other minor comments:

1. Does RTLF composition change with different regions in the lung? Given the sensitivity of the assay results to the relative concentrations of AA and GSH, this may be important. (This may seem like an obvious question to medical researchers or toxicologist, but an atmospheric audience for ACP might not understand.)

Yes, RTLF composition changes with different regions in the lung. Based on the reviewer's comment, this point has been explicitly noted in the revised manuscript.

Line 469-473: "There are marked differences in RTLF composition in different levels of respiratory tract. The synthetic RTLF reflects select antioxidants in the lung and other key constituents are not represented in this simplified chemical model. The DTT assay is also subject to similar limitations that DTT cannot fully represent the biological complexity. However, these assays can be used as PM screening tools and provide rapid health-relevant assessment of PM."

2. Samples are collected on a daily basis. Would that bias against sources that vary on shorter timescales (i.e. traffic-related emissions of metals)? If so, that should be stated as a limitation of this study.

Thanks for this suggestion. This limitation has been added in the manuscript.

Line 465-467: "We should note that the filter samples analyzed in this study were averaged over 24 hours, which may dampen variability in the emission sources that contribute to OP and obscure the impact of specific species (e.g., traffic-related metals) on redox activity of PM."

3. Should we really expect a difference between summer and winter, given that the climate in Atlanta is similar between the seasons? What are the known differences in the sources between summer and winter this area? This type of comparison can be somewhat misleading and is likely not generalizable to other regions, because every city might have its own characteristic summer/winter sources. Just seeing "summer" and "winter" in analysis, one could jump to the wrong conclusions.

We thank the reviewer for the comment. While temperature change across seasons in Atlanta (typically varies from 35 °F to 89 °F) is not as extreme as other cities, there are notable differences. Consequentially, the seasonal difference in OP are expected. In previous studies conducted in the same region, obvious seasonal patterns were observed for water-soluble OP^{DTT} *and its related sources (Bates et al., 2015; Verma et al., 2014). The results suggested that* OP^{DTT} *levels in Atlanta were generally higher in the cold months, driven mostly by biomass burning emissions, than in summer when secondary oxidation processes dominated* OP^{DTT}*. The temporal variation in our BrC data (Fig. 3) also supported the seasonally varying emission sources. Moreover, based on our correlation analysis, the association of OP measures with PM species differed by seasons, suggesting possible seasonal differences in OP metrics. Even though the temporal variation in OP from this study was not evident, we believe it is worthwhile to do such seasonality analysis as it may provide a better understanding of the impact of seasonally varying sources or species upon OP metrics.*

To avoid misleading our readers, we have added a reminder in the revised manuscript.

Line 467-469: "Furthermore, all these results were obtained from a specific location in Atlanta and should be interpreted and generalized with caution as the chemical composition or sources of PM varies by region."

4. It would be useful to state in the Methods section the concentration of PM during these assays. PM concentrations should be much lower than those of the antioxidants to ensure one is looking at the catalytic redox cycling.

Thanks for the suggestion. The PM concentration in the water extracts has been specified in the manuscript.

Line 168: "In brief, the PM extract (3.5 mL; 40±15 µg mL^{-1} of PM) was incubated with DTT solution…"

Line 189: "PM water extracts (35±13 µg of PM per mL) were transferred into a 96-well microplate with 180 µL of sample liquid in each well."

5. Limits of detection and quantification for all of the assays should be reported.

The manuscript has been modified accordingly.

In section 2.2.1 DTT assay, Line 183-184: "The limit of detection (LOD), defined as three times of the standard deviation of OP^{DTT} for blanks, is 0.31 nmol min^{-1}...."

In section 2.2.2 RTLF assay, Line 216-217: "The LOD for AA and GSH depletion after 4 h incubation was 4.0 % and 4.5 %, respectively..."

6. The discussion around BrC comparison needs to be better motivated. It is not clear why that comparison was made in the first place, other than that measurement was available and it was convenient to make that comparison. BrC from biomass burning, for example, can be derived from nitrophenols, and is not exclusively HULIS. Unlike the other chemical species, BrC is not chemically defined, but rather an optically defined group of compounds, so their contribution to OP might not be straightforward.

To better motivate the BrC vs. WSOC comparison, we have modified the manuscript.

Line 362-365: "All models captured the contributions from organic species, however, the organic contributions in different models were represented by different measures of organics. In the OP^{DTT} and OP^{GSH} models, the organic contribution was denoted by BrC, whereas WSOC was used in the OP^{AA} model. Although WSOC and BrC were correlated with each other (Table S1–S3), there is a difference between these two parameters."

Regarding the reviewer's 2nd point, the reviewer is correct that BrC likely covers a wide range of aerosol components, which include but are not limited to HULIS. HULIS has been recognized as important components of BrC and has been found to be strongly linked to BrC (Hoffer et al., 2006; Laskin et al., 2015). As mentioned in the manuscript, Verma et al. (2012) passed the water extracts of $PM_{2.5}$ collected at Jefferson Street (the same location as in this study) through C-18 solid extraction columns which were commonly used for HULIS isolation, and they found that roughly 70–90 % of BrC was retained in hydrophobic fraction (i.e., HULIS). Therefore, it is *reasonable to denote the influence of HULIS on OP with BrC in this study. Furthermore, although there is evidence that BrC components may directly contribute to OP (Chen et al., 2019), the presence of BrC in the regression analysis may not imply their direct contribution to OP, but to indicate the possible influence of BrC-denoted aerosol components. It is true that BrC, as an optically defined measure, differs from other PM species in units and scales, which makes it difficult to inter-compare the OP contribution induced by each term. However, this problem was resolved by applying standardized regression, as noted in this paper.*

To clarify, we have added more explanation of the BrC-related OP in the revised manuscript.

Line 366-374: "…there is a difference between these two parameters. The OP contribution from BrC, an optically defined measure, may not be straightforward, however, the optical properties of BrC are related to chemical properties. There is evidence showing that BrC components may directly contribute to OP (Chen et al., 2019). It has been found that BrC predominantly represents the hydrophobic organic fraction…"

7. Why is EC not included in the multilinear regression analysis? It seems to have a reasonable Pearson's r from Table 1.

This manuscript was focused on water-soluble OP which we assume is more driven by water-soluble PM components. Therefore, in the multivariate regression analysis, we used water-soluble species as input to construct the models. Furthermore, EC was also correlated with some of the selected water-soluble species, such as WSOC and water-soluble Mn and Fe (Table S1). In this instance, even if EC was chosen as one of the predictors, the stepwise regression procedure would identify it as a redundant predictor and exclude it from the model. To clarify, the manuscript has been modified.

Line 344-349: "Given that one or more PM components contributed to these measures of OP, multivariate linear regression analysis was conducted to identify the main ~~water-soluble~~ PM components that drive the variability in OP and provide a contrast between the assays. Water-soluble organic species (WSOC or BrC) and metals, mainly Fe, Cu, Mn, were selected as the independent variables to form multivariate linear regression models for OP^{DTT} and OP^{AA}, based on their high correlations, as noted above. EC, though also correlated with OP^{DTT} and OP^{AA}, was not chosen as one of the predictors due to its correlations with selected water-soluble species (e.g., WSOC, water-soluble Mn and Fe)."

Technical/formatting comments:

Line 164: typo after GR

We made a double-check and found no typo here.

Line 169: typo in 2-vinylpyridine; not sure if the abbreviation 2-VP is needed if it is not used again

Typo has been corrected, and the abbreviation was deleted.

Line 208: "5 µL of 2-vinylpyridine was added…"

Line 185: replace "required" with "performed"

Corrected.

Line 227: "For the analysis of water-soluble metals, no digestion was performed."

Line 257: If UA is not studied here, it might be better not to include UA in this comparison

UA has been deleted in the comparison.

Line 306: "...within the antioxidant model with GSH>AA (Zielinski et al., 1999)."

Line 266: "consistent lower" should be "consistently lower"

Corrected.

Line 315: "The consistently lower correlation…"

Line 365: "shown the strongest estimated effect" is a strange word choice. Perhaps "estimated to have the strongest effect"?

The sentence has been modified.

Line 435: "Water-soluble Fe, as the most important determinant of OP^{DTT}, has been estimated to have the strongest effect on cardiovascular outcomes in the Atlanta metropolitan region…"

Line 388-390: The sentence here is stylistically awkward and grammatically incorrect.

The sentence has been modified.

Line 462-463: "However, OP^{DTT} and OP^{AA} are more chemically integrative OP measures compared to OP^{GSH}, and thus may be more informative and helpful in linking OP with health end points..."

Table 2: the number of digits in the exponent are not consistent (some are E-3, and some are E-05)

Corrected.

Reference:

Bates, J. T., Weber, R. J., Abrams, J., Verma, V., Fang, T., Klein, M., Strickland, M. J., Sarnat, S. E., Chang, H. H., Mulholland, J. A., Tolbert, P. E., and Russell, A. G.: Reactive Oxygen Species Generation Linked to Sources of Atmospheric Particulate Matter and Cardiorespiratory Effects, Environ Sci Technol, 49, 13605-13612, 2015.

Chen, Q., Wang, M., Wang, Y., Zhang, L., Li, Y. and Han, Y.: Oxidative Potential of Water-Soluble Matter Associated with Chromophoric Substances in PM2. 5 over Xi'an, China, Environ Sci Technol, 53, 8574-8584, 2019.

Hoffer, A., Gelencsér, A., Guyon, P., Kiss, G., Schmid, O., Frank, G.P., Artaxo, P. and Andreae, M.O.: Optical properties of humic-like substances (HULIS) in biomass-burning aerosols, 2006.

Laskin, A., Laskin, J. and Nizkorodov, S.A.: Chemistry of atmospheric brown carbon, Chemical reviews, 115(10), 4335-4382, 2015

Verma, V., Fang, T., Guo, H., King, L., Bates, J. T., Peltier, R. E., Edgerton, E., Russell, A. G., and Weber, R. J.: Reactive oxygen species associated with water-soluble PM2.5 in the southeastern United States: spatiotemporal trends and source apportionment, Atmos Chem Phys, 14, 12915-12930, 2014.

Verma, V., Rico-Martinez, R., Kotra, N., King, L., Liu, J. M., Snell, T. W., and Weber, R. J.: Contribution of Water-Soluble and Insoluble Components and Their Hydrophobic/Hydrophilic Subfractions to the Reactive Oxygen Species-Generating Potential of Fine Ambient Aerosols, Environ Sci Technol, 46, 11384-11392, 2012.

Characterization and comparison of $PM_{2.5}$ oxidative potential assessed by two acellular assays

Dong Gao[1±], Krystal J. Godri Pollitt[2], James A. Mulholland[1], Armistead G. Russell[1], Rodney J. Weber[3]

[1]School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, GA 30332, USA
[2]Department of Environmental Health Sciences, School of Public Health, Yale University, New Haven, CT 06510, USA
[3]School of Earth and Atmospheric Sciences, Georgia Institute of Technology, Atlanta, GA 30332, USA

± Current address: Department of Environmental Health Sciences, School of Public Health, Yale University, New Haven, CT 06510, USA

Correspondence to: Rodney J. Weber (rweber@eas.gatech.edu)

Deleted: 2

Deleted: ly at

Abstract. The capability of ambient particles to generate *in vivo* reactive oxygen species (ROS), called oxidative potential (OP), is a potential metric for evaluating the health effects of particulate matter (PM) and is supported by several recent epidemiological investigations. Studies using various types of OP assays differ in their sensitivities to varying PM chemical components. In this study, we systematically compared two health-relevant acellular OP assays that track the depletion of antioxidants or reductant surrogates: the synthetic respiratory tract lining fluid (RTLF) assay that tracks the depletion of ascorbic acid (AA) and glutathione (GSH), and the dithiothreitol (DTT) assay that tracks the depletion of DTT. Year-long daily samples were collected at an urban site in Atlanta, GA (Jefferson Street) during 2017 and both DTT and RTLF assays were performed to measure the OP of water-soluble $PM_{2.5}$ components. $PM_{2.5}$ mass and major chemical components, including metals, ions, and organic and elemental carbon were also analyzed. Correlation analysis found that OP as measured by the DTT and AA depletion (OP^{DTT} and OP^{AA}, respectively) were correlated with both organics and some water-soluble metal species, whereas that from the GSH depletion (OP^{GSH}) was exclusively sensitive to water-soluble Cu. These OP assays were moderately correlated with each other due to the common contribution from metal ions. OP^{DTT} and OP^{AA} were moderately correlated with $PM_{2.5}$ mass, with Pearson's r = 0.55 and 0.56, respectively, whereas OP^{GSH} exhibited a lower correlation (r = 0.24). There was little seasonal variation in the OP levels for all assays due to the weak seasonality of OP-associated species. Multivariate linear regression models were developed to predict OP measures from the particle composition data. Variability in OP^{DTT} and OP^{AA} were attributed to not only the concentrations of metal ions (mainly Fe and Cu) and organic compounds, but also antagonistic metal–organic and metal–metal interactions. OP^{GSH} was sensitive to the change in water-soluble Cu and brown carbon (BrC), a proxy for ambient humic-like substances.

Deleted: the

Deleted: relating

Deleted: to health effects

Deleted: However, s

Deleted: in Atlanta

Deleted: applied

Deleted: had

Deleted: significantly

Deleted: The models indicated that the v

Deleted: ities

1 Introduction

Epidemiological studies have consistently reported associations between particulate matter (PM) and increased morbidity and mortality (Brunekreef and Holgate, 2002; Cohen et al., 2017; Lippmann, 2014; Norris et al., 1999;

Deleted: fine

Deleted: $_{2.5}$

Pope et al., 2004; Samet et al., 2000; Sun et al., 2010; Thurston et al., 2017). The capacity of inhaled PM to elicit oxidative stress has emerged as a hypothesis to explain PM-induced adverse health effects. Inhaled PM can directly introduce PM-bound reactive oxygen species (ROS) to the surface of the lung where they react with and deplete lung lining fluid antioxidants, or introduce redox-active PM species which can react with biological reductants and generate ROS *in vivo* (Lakey et al., 2016). The latter can occur in organs beyond the lungs by particles or chemical species being translocated from the lungs throughout the body. Oxidative stress arises when the presence and production of ROS overwhelms the antioxidant defenses, and can lead to cell and tissue damage and induction of chronic and degenerative diseases (Das, 2016; Halliwell, 1994; Pizzino et al., 2017). The ability of PM to generate ROS *in vivo,* referred to as the oxidative potential (OP) of particles, has gained increasing attention as possibly a more integrative health-relevant measure of ambient PM toxicity than PM mass concentration which may contain a mix of highly toxic (e.g. polycyclic aromatic hydrocarbons (PAHs), quinones, environmentally persistent free radicals, highly oxygenated organic molecules, and transition metals) to relatively benign (e.g. sulfate and ammonium nitrate) PM components (Frampton et al., 1999; Khachatryan et al., 2011; Lippmann, 2014; Tong et al., 2018; Tong et al., 2019).

Deleted: particulate

Deleted: matter (PM)

Deleted: $_{2.5}$

Deleted:

A variety of acellular assays have been developed to assess PM OP (Ayres et al., 2008; Bates et al., 2019). In general, these assays involve the incubation of PM extracts or suspension with chemical reagents/probes, and the response is recorded over time or after incubation. The responses recorded include the depletion of reductant surrogate, such as the dithiothreitol (DTT) assay (Cho et al., 2005), and depletion of specific antioxidants in a composite solution, such as a synthetic respiratory tract lining fluid (RTLF) model (Godri et al., 2011; Mudway et al., 2004; Zielinski et al., 1999). In contrast, other assays measure ROS generation (e.g., the dichlorofluorescein assay (Huang et al., 2016; Venkatachari et al., 2005)), or hydroxyl radical formation in the presence of H_2O_2 (e.g., electron paramagnetic/spin resonance (EPR/ESR) (Shi et al., 2003a; Shi et al., 2003b)). The assays based on exposing PM species to antioxidants are currently more commonly used. The DTT assay (Cho et al., 2005) is a chemical system that mimics the *in vivo* PM-catalyzed electron transfer process. In this assay, DTT acts as a surrogate of the cellular reductant (NADH or NADPH), donating electrons to oxygen and producing ROS with the catalytic assistance of PM redox-active species. PM OP (i.e., OP^{DTT} in this case) is determined by measuring the depletion of DTT over time, which is assumed to be proportional to the concentration of redox-active compounds in PM. For the RTLF assay, RTLF is constructed to simulate the aqueous environment that particles first encounter when inhaled into the lungs and deposited. The antioxidants in RTLF, specifically the major low-molecular-weight antioxidants, ascorbic acid (AA), uric acid (UA), and reduced glutathione (GSH), provide protective defenses against PM-induced oxidative damage. The extent to which they are depleted by PM over time reflects a direct measure of PM oxidative activity by this assay, expressed as OP^{AA}, OP^{UA}, and OP^{GSH} (Kelly et al., 1996; Mudway et al., 2004; Zielinski et al., 1999). Some studies (DiStefano et al., 2009; Fang et al., 2016; Janssen et al., 2015; Mudway et al., 2005) have used a simplified alternative approach to AA analysis in RTLF, where only the single antioxidant AA is contained in the solution. If not explicitly stated, OP^{AA} in this paper represents OP^{AA} obtained from the RTLF model.

Recently, a growing number of epidemiological studies have used these OP assays to examine the link between particle OP and adverse health outcomes. OP^{DTT} of ambient fine particles has been found to be more strongly associated with multiple cardiorespiratory outcomes, such as airway inflammation (Delfino et al., 2013; Janssen et al., 2015; Yang et al., 2016), asthma (Abrams et al., 2017; Bates et al., 2015; Fang et al., 2016; Yang et al., 2016) and congestive heart failure (Bates et al., 2015; Fang et al., 2016), than PM mass. Multiple population-scale studies employed the RTLF assay to assess OP of PM$_{2.5}$, and found that OP^{GSH} was associated with lung cancer, cardiometabolic mortality (Weichenthal et al., 2016a), emergency room visits for respiratory illness (Weichenthal et al., 2016c), myocardial infarction (Weichenthal et al., 2016b), and adverse birth outcomes (Lavigne et al., 2018). The association between airway inflammation in asthmatic children and OP^{GSH} of PM$_{2.5}$ personal exposure was also reported (Maikawa et al., 2016). In the study of Strak et al. (2012), no association was found between OP^{GSH} and acute airway inflammation in healthy volunteers after 5 h of exposure. A population-scale study in London, UK found no association between OP^{GSH} and mortality and hospital admission (Atkinson et al., 2016). For the AA depletion, either in the composite RTLF model or in a simplified AA-only model, no association with adverse health end points has been found, including asthma, cause-specific mortality, and cardiorespiratory emergency department visits (Fang et al., 2016; Maikawa et al., 2016; Weichenthal et al., 2016a; Weichenthal et al., 2016b; Weichenthal et al., 2016c). Bates et al. (2019) provide a review of the relationships of various OP assays with adverse health effects.

The differences in observed health effects may be due to the different sensitivity of OP assays to various PM species. Past studies have shown that specific assays are correlated with different PM components. OP^{DTT} has been found to be sensitive to transition metals (Charrier and Anastasio, 2012; Fang et al., 2016; Verma et al., 2015a) and organic species, especially more oxygenated aromatic organics, such as quinones and hydroxyquinones (Cho et al., 2005; Kumagai et al., 2002; McWhinney et al., 2011; Verma et al., 2015b). OP^{AA} obtained from the simplified AA-only model are mostly responsive to the metal content of PM (Fang et al., 2016; Maikawa et al., 2016; Yang et al., 2014). Antioxidants (AA and GSH) within the synthetic RTLF are responsive to a slightly different group of metals. For example, OP^{AA} responds to iron and OP^{GSH} is related to aluminum (Godri et al., 2010). But both OP^{AA} and OP^{GSH} are sensitive to copper (Ayres et al., 2008). Studies performed on real PM samples or standard solutions indicate that quinones also drive the oxidative losses of both antioxidants (Ayres et al., 2008; Calas et al., 2018; Kelly et al., 2011; Pietrogrande et al., 2019).

Since different assays capture different chemical fractions of the oxidative activity of PM, it is challenging to synthesize the findings from OP-health studies. There remains a need to compare different assays on identical particle samples to advance our understanding of the effects of PM species on OP measures, and in turn assess the results of the health studies that use OP. In this study, we used two acellular OP assays, DTT and RTLF, to measure the water-soluble OP of ambient PM$_{2.5}$ collected from urban Atlanta, GA over one-year period. These two assays were chosen since they are currently most commonly used and have shown significant associations with adverse health outcomes in some studies. A suite of chemical components was also measured on these samples and univariate and multivariate linear regression analyses were performed to identify and evaluate the contribution of major chemical components to each of these OP metrics.

Deleted: number

Deleted: some of

Deleted: age

Deleted: a

Deleted: a

Deleted: conducted in Canada

Deleted: and

Deleted: However, a human exposure study in the Netherlands did not find an association between OP^{GSH} and acute airway inflammation after 5 h of exposure (Strak et al., 2012).

Deleted: by PM assay

2 Methods

2.1 Sampling

Year-long sampling was conducted in 2017 from 1 January to 30 December at the Jefferson Street SEARCH (Southeastern Aerosol Research and Characterization) site (Edgerton et al., 2006, 2005). Jefferson Street is situated roughly 4.2 km northwest of downtown Atlanta and 2.3 km from a major interstate highway and is representative of urban Atlanta region. The site has been extensively used in past studies characterizing urban-Atlanta air quality (Hansen et al., 2006) and the data used in OP and epidemiological studies (Abrams et al., 2017; Bates et al., 2015; Fang et al., 2016; Sarnat, 2008; Verma et al., 2014).

Deleted: b

Ambient $PM_{2.5}$ were collected daily (from midnight to midnight, 24 h integrated samples) onto pre-baked 8×10 in. quartz filters (Pallflex Tissuquartz, Pall Life Sciences) using high-volume samplers (HiVol, Thermo Anderson, nominal flow rate 1.13 m^3 min^{-1}, $PM_{2.5}$ impactor). A total of 349 filter samples were collected for analysis; missing days were due to instrumentation issues. The HiVol quartz filters were wrapped in pre-baked aluminum foil after collection and stored at -18 °C until analysis. $PM_{2.5}$ mass concentration was monitored continuously by a tapered element oscillating microbalance (TEOM, Thermo Scientific TEOM 1400a), the sample stream dried at 30 °C using a Sample Equilibration System (Meyer et al., 2000). A Sunset semi-continuous OCEC analyzer (Sunset Laboratory) was used to provide in situ measurements of organic and elemental carbon (OC/EC) content of fine PM. The data were obtained hourly by using 1 h cycles in which the instrument sampled ambient air through an activated carbon denuder for 45 min and analyzed the particles collected on the quartz filter for 15 min using NIOSH 5040 analysis protocol (Birch and Cary, 1996).

Deleted: fine particles

Formatted: Subscript

Deleted: e

2.2 Oxidative potential measurements

Two acellular assays, DTT and RTLF assays, were performed to measure the oxidative potential of water-soluble $PM_{2.5}$. The DTT analysis was completed at Georgia Institute of Technology, and all filters were analyzed within one month after collection. The RTLF assay was conducted at Yale University during Oct. 2018. Prior to the OP analyses, a fraction of each HiVol filter (5.07 cm^2 for DTT and 4.5 cm^2 for RTLF) was punched out, placed in a sterile polypropylene centrifuge vial (VWR International LLC, Suwanee, GA, USA) and then extracted in 5 mL of deionized water (DI, >18 MΩ cm^{-1}) via 30 min sonication. The water extract was filtered through a 0.45 µm PTFE syringe filter (Fisherbrand, Fisher Scientific) and then used for OP analysis.

2.2.1 DTT assay

The DTT assay was performed with a semi-automated system developed by Fang et al. (2015b), following the protocol described by Cho et al. (2005). In brief, the PM extract (3.5 mL; 40±15 µg mL^{-1} of PM) was incubated with DTT solution (0.5 mL; 1 mM) and potassium phosphate buffer (1 mL; pH~7.4, Chelex-resin treated) at 37 °C. A small aliquot (100 µL) of the mixture was withdrawn at designated times (0, 4, 13, 23, 31 and 41 min) and mixed with trichloroacetic acid (TCA, 1 % w/v) to quench the DTT reactions. After addition of Tris buffer (pH ~8.9), the remaining DTT was reacted with 5,5'-dithiobis-(2-nitrobenzoic acid) (DTNB) to form a colored product which absorbs light at 412 nm. The final mixture was pushed through a 10 cm path length liquid waveguide capillary cell (LWCC; World Precision Instruments, Inc., FL, USA), and the light absorption was recorded by an online

Formatted: Superscript

spectrometer, which included a UV-Vis light source (DT-mini-2, Ocean Optics, Inc., Dunedin, FL, USA) and a multi-wavelength light detector (USB4000 Miniature Fiber Optic Spectrometer). The DTT consumption rate, used as a measure of OP, was determined from the slope of the linear regression of DTT residual vs. time. Good linearity was found for all samples with correlation coefficients (R^2) larger than 0.98. In parallel with all sample batches, at least one field blank and one positive control (9,10-phenanthraquinone) was analyzed, and their OP values remained constant throughout the analysis. The limit of detection (LOD), defined as three times of the standard deviation of OP^{DTT} for blanks, was 0.31 nmol min^{-1}. The PM OP measured by this assay (i.e., OP^{DTT}) was blank-corrected and normalized by the air volume that passed through the extracted filter fraction, expressed as nmol DTT min^{-1} per m^3. This approach did not involve the use of PM samples with constant mass, which is sometimes employed to limit nonlinear DTT response to certain metal ions (Charrier et al., 2016).

Formatted: Superscript

2.2.2 RTLF assay

The RTLF assay is based on the protocol adopted by Maikawa et al. (2016). PM water extracts (35±13 µg of PM per mL) were transferred into a 96-well microplate with 180 µL of sample liquid in each well. 20 µL of synthetic RTLF (pH ~7.0) containing equimolar concentrations (2 mM) of AA, UA and GSH was added into each well, resulting in a final starting concentration of 200 µM of antioxidants. The PM-RTLF mixture was incubated in a plate reader (SpectraMax190, Molecular Devices, LLC, San Jose, CA, USA) for 4 hours at 37 °C with gentle mixing. Following incubation, the concentrations of AA and GSH were analyzed immediately. UA concentration was not measured since studies have consistently suggested that no depletion of UA was observed in the presence of PM (Kunzli et al., 2006; Mudway et al., 2004; Zielinski et al., 1999).

AA concentration was determined with the plate reader by measuring the light absorbance at 260 nm. The GSH concentration was indirectly quantified by measuring total glutathione (GSx) and oxidized glutathione (GSSG) concentrations, both compounds determined using the enzymatic recycling method (Baker et al., 1990). The incubated PM-RTLF mixture was diluted 49-fold with 100 mM sodium phosphate buffer (pH ~7.5) containing ethylenediaminetetraacetic acid (EDTA). To measure the GSx concentration, 50 µL of each diluted sample was dispensed onto a microplate. 100 µL of reaction mixture (0.15 mM DTNB, 0.2 mM NADPH and 1 U glutathione reductase (GR)) was added to each well. In the mixture, GSH reacted with DTNB, forming a yellow colored product 5-thio-2-nitrobenzoic acid (TNB) and the mixed disulfide GS-TNB. In the presence of NAPDH and GR, GSSG and GS-TNB were reduced back to GSH, leading to more TNB production. The plate was analyzed on the plate reader for two minutes under constant mixing to continuously monitor the formation of TNB. The TNB formation rate, which is proportional to the GSH concentration, was measured at an absorbance of 405 nm. For GSSG measurement, 5 µL of 2-vinylpyridine was added to 130 µL of the diluted sample to conjugate GSH. The solution was incubated at room temperature for 1 hour, followed by similar procedures performed for the GSx measurement. The GSH concentration was calculated by subtracting two times the GSSG concentration from the measured GSx concentration.

Deleted: ly

Deleted: (2-VP)

Field blanks and known controls (e.g. positive controls: H_2O_2 and Cu; negative control: Zn) were run in parallel with all sample batches. All samples and controls were measured in triplicate. The percentage of AA and GSH depletion after 4 h incubation for each PM sample was calculated relative to the field blank. The LOD for AA and GSH depletion after 4 h incubation was 4.0 % and 4.5 %, respectively. PM OP obtained from this assay, i.e., OP^{AA} and OP^{GSH}, was determined by normalizing the percentage loss with the sampled air volume, in unit of % depletion per m^3.

2.3 Chemical analysis on PM filters

2.3.1 Elemental analysis

Both total and water-soluble trace metals were determined by inductively coupled plasma-mass spectrometry (ICP-MS) (Agilent 7500a series, Agilent Technologies, Inc., CA, USA), including magnesium (Mg), aluminum (Al), potassium (K), calcium (Ca), chromium (Cr), manganese (Mn), iron (Fe), copper (Cu) and zinc (Zn). For the determination of concentrations of total metals, a 1.5 cm^2 filter punch from the HiVol quartz filter was acid-digested for 20 min using aqua regia (HNO_3+3HCl). The acid-digested sample was then diluted in DI water to 10 mL, filtered with a 0.45 µm PTFE syringe filter. For the analysis of water-soluble metals, no digestion was performed. In this case, one circular punch (1 in. diameter) was extracted in 5 mL of DI via 30 min sonication. The extract was filtered using a 0.45 µm PTFE syringe filter, and then acid-preserved by adding concentrated nitric acid (70 %) to a final concentration of 2 % (v/v).

Deleted: required

2.3.2 Water-soluble organic carbon (WSOC) and brown carbon (BrC)

Two 1.5 cm^2 filter punches from the HiVol filter were extracted in 15 mL DI in a pre-baked glass centrifuge vial (DWK Life Sciences, Rockwood, TN, USA) by 30 min sonication. The extracts filtered with 0.45 µm PTFE syringe filters were used to measure water-soluble organic carbon (WSOC) and its light absorption properties (BrC, used as a source tracer). A fraction (~6 mL) of filter extract was injected by a syringe pump (Kloehn, Inc., NV, USA) into a 2.5 m path length LWCC (World Precision Instruments, Inc., FL, USA), with an internal volume of 500 µL. The absorbance at 365 nm wavelength (BrC) was measured by an online spectrophotometer. The remaining liquid extract was drawn into Sievers total organic carbon (TOC) analyzer (Model 900, GE Analytical Instruments, Boulder, CO, USA) for determination of WSOC concentration. The TOC was calibrated with a series of prepared sucrose standards.

2.3.3 Water-soluble ionic species

One 1.5 cm^2 filter punch from the HiVol filter was extracted in 10 mL DI via sonication. The inorganic ions (SO_4^{2-}, NO_3^- , and NH_4^+) in the filtered water extracts were measured by ion-exchange chromatography (IC) with conductivity detection (Anion: Metrosep A Supp 5–150/4.0 anion separation column; eluent: 3.2 mM Na_2CO_3, 1.0 mM $NaHCO_3$, eluent flow rate 0.78 mL/min. Cation: Metrosep C 4–150/4.0 cation separation column; eluent: 1.7 mM HNO_3, 0.7 mM dipicolinic acid, eluent flow rate 0.9 mL/min) with an automated sampler (Dionex AS40, Thermo Fisher Scientific, Waltham, MA).

2.4 Multivariate regression models

Multivariate linear regression models were developed to predict OPs based on PM speciation data and investigate the relative importance of species on different OPs. Prior to the regression analysis, boxplots were used to identify

Deleted: the

the outliers and test the normality of data. Extreme values (a total of ~3 % of the OP measurements) were removed from the data set. Linear regression was performed between PM components and the various OPs. To simplify the analysis, PM components correlated with OP ($r>0.4$, $p<0.05$) were selected as the independent variables of the models. A stepwise regression was applied to the data set using Matlab R2016a to form the multivariate regression models. To evaluate the performance of the final models, 5-fold cross validation was employed and repeated 50 times. For each OP measure, the average mean-squared error over 50 iterations was within 25 % of the mean OP value (23.4 %, 17.9 % and 12.2 % for OP^{DTT}, OP^{AA} and OP^{GSH}, respectively).

Deleted: The e

Deleted: around

3 Results and discussion

3.1 Ambient PM composition

Figure 1 shows the time series of $PM_{2.5}$ mass concentration and the averaged chemical composition of ambient particles collected at the site. A factor of 1.6 was applied to convert organic carbon to organic matter (Turpin and Lim, 2001; Weber, 2003). Reconstituted mass from measured chemical species agreed well with $PM_{2.5}$ mass measured by the TEOM with Pearson's r=0.84, and accounted for more than 80 % of the $PM_{2.5}$ mass. The missing mass may result from other species not measured, semi-volatile material lost from the filter, and the uncertainty in converting measured carbon mass to organic matter (factor of 1.6 used).

Fractions of various chemical components in $PM_{2.5}$ are consistent with previous observations (Edgerton et al., 2005; Verma et al., 2014). In general, PM mass was dominated by organic compounds (WSOM+WIOM~50 %), followed by inorganic ions (10 % SO_4^{2-}, 4–7 % NH_4^+, and 1–8 % NO_3^-). Metals constituted 6–13 % of the PM mass, among which water-soluble metals were at trace amounts (1–2 %). EC accounted for a small fraction of the PM mass (5–6 %). NH_4^+, and NO_3^-, which are semi-volatile, accounted for a larger fraction of fine particle mass during the cold season. The metal fraction also increased in winter, whereas the fractions of other PM components did not vary significantly during the sampling period.

Although insoluble PM components also play an important role in OP (Gao et al., 2017; Verma et al., 2012), this study solely focuses on water-soluble OP measurements, and thus the water-soluble PM components are the primary focus in this study. The OP (DTT assay only) contribution from water-insoluble components were discussed in detail in another paper from this study (Gao et al., accepted).

3.2 Association of OP with PM components

Pearson's correlation coefficients for the linear regression between OP and select chemical components are shown in Table 1. The detailed correlation matrices for different seasonal periods are given in Table S1–S3. We defined the strength of the absolute correlation coefficient value as strong for values ≥ 0.65, moderate from 0.40 to 0.65, and weak for values < 0.4. The OP assays were moderately inter-correlated over the sampling year. In all cases (whole year and summer or winter), OP^{AA} and OP^{GSH} had the highest correlations, which may in part be due to these measurements being conducted on the same sample extracts. As for OP^{DTT}, the correlations with OP^{AA} and OP^{GSH} varied, but were largely similar. The correlations between the OP measures and various PM components varied, highlighting the different sensitivities of OP assays to various PM components. Note these correlations do not imply that the compounds are responsible for the OP as some of them are not redox active compounds. However, the correlations may indicate the emission sources (e.g., as source tracers – vehicular emissions for EC, secondary processing for WSOC and SO_4^{2-}, and biomass burning for BrC and K), which also probably emit the water-soluble species contributing to the measured OP.

As shown in Table 1, OP^{DTT} was correlated with OC and WSOC, indicating a contribution from PM organic compounds. The correlations between OP^{DTT} and certain water-soluble metals, such as Fe, Cu and Mn, were also observed. A moderate correlation of EC with OP^{DTT} (r=0.51) and somewhat with metals and OC (r=0.55, 0.43 and 0.83 for Fe, Mn and OC, respectively; Table S1) suggests that incomplete combustion could be one of their common sources. The associations found in this study between OP^{DTT} and PM composition are consistent with a number of previous studies (Fang et al., 2016; Fang et al., 2015b; Verma et al., 2014; Yang et al., 2014), though the correlations in our work were weaker ($r > 0.5$ compared with $r>0.65$ in other studies).

Similar to OP^{DTT}, OP^{AA} was moderately correlated with OC, WSOC and water-soluble metals, mainly Fe and Cu (r=0.47–0.55). The results are compared with a previous study conducted in the same Atlanta region by Fang et al. (2016) wherein a simplified AA assay was applied to assess water-soluble OP of $PM_{2.5}$. The AA depletion in the AA-only model was found to be strongly correlated with water-soluble Cu with Pearson's $r > 0.65$, and associations with WSOC (or BrC) and metals were also observed. The weaker sensitivity of AA to water-soluble Cu observed in our study is possibly due to the reactivity hierarchy existing within the antioxidant model with GSH>AA (Zielinski et al., 1999). This is further supported by other studies. In the study of Charrier et al. (2011), ligand speciation modeling indicated that GSH was a stronger ligand compared to AA and caused a dramatic shift in Cu speciation by forming Cu–GSH complexes. The experimental results in the study of Pietrogrande et al. (2019) showed that the response of the acellular AA assay was strongly dependent on the composition of synthetic RTLF used and the presence of GSH and UA would lower the sensitivity of AA response to Cu. The correlations of organics and EC which comprised a large fraction of PM mass (Fig. 1), with OP^{DTT} and OP^{AA}, likely account for the OP^{DTT} and OP^{AA} correlations with PM mass.

In contrast to OP^{DTT} and OP^{AA}, OP^{GSH} was found to be exclusively correlated with water-soluble Cu with Pearson's $r > 0.7$. The consistently lower correlation of OP^{AA} with water-soluble Cu than OP^{GSH} with Cu, is consistent with GSH outcompeting AA in the RTLF in forming Cu complexes. The results are also consistent with other studies (Aliaga et al., 2010; Ayres et al., 2008; Godri et al., 2011).

The correlations differed by seasons. In winter, OP^{AA} and OP^{DTT} were more correlated with organic species, with stronger associations with WSOC, BrC and K, indicating biomass burning as a common source of OP^{AA} and OP^{DTT}. In summer, all OP assays tended to be metal-driven. OP^{AA} and OP^{DTT} were more correlated with Cu, along with SO_4^{2-}, suggesting possible influence of secondary processing on metal mobilization (Fang et al., 2017; Ghio et al., 1999) and resulting in a strong inter-correlation between different OP metrics.

Formatted: Subscript

Formatted: Superscript

Deleted: they could be considered as indicators of other compounds simultaneously produced by the same source.

Deleted: of

Deleted: with

Deleted: species

Deleted: >> UA

3.3 Temporal variation

The time series of the monthly and seasonal averages of different OP measures are shown in Fig. 2. Significant seasonal variability in these OP measures was not evident; only a subtle seasonal variation observed for $\mathrm{OP^{DTT}}$ and no variations for $\mathrm{OP^{AA}}$ and $\mathrm{OP^{GSH}}$. $\mathrm{OP^{DTT}}$ was slightly higher during the cold period (Jan–Feb and Nov–Dec) with an average level of 0.24±0.08 nmol $\mathrm{min^{-1}}$ $\mathrm{m^{-3}}$ compared to 0.20±0.04 nmol $\mathrm{min^{-1}}$ $\mathrm{m^{-3}}$ in the warm period (May–Aug) and a median $\mathrm{OP^{DTT}}$ ratio between two periods of 1.20. However, $\mathrm{OP^{AA}}$ and $\mathrm{OP^{GSH}}$ had more similar levels across seasons, with median ratios between cold and warm periods of 1.10 and 0.97, respectively.

The seasonality in OP measures should result from the temporal variations in PM species driving the various OP. From the temporal variation of the OP-associated species shown in Fig. 3 (the seasonal averaged concentrations were given in Fig. S1), BrC had an obvious seasonality, higher in winter and lower in summer, which is due to the stronger influence of biomass burning in winter. The variation in BrC may lead to the small variation in $\mathrm{OP^{DTT}}$, considering the good correlation between $\mathrm{OP^{DTT}}$ and BrC in winter. Water-soluble Cu is slightly higher in mid-summer (Aug) and water-soluble Fe is slightly higher in fall (Sep), but these trends are not seen in the various measures of OP.

3.4 Multivariate model

Given that one or more PM components contributed to these measures of OP, multivariate linear regression analysis was conducted to identify the main PM components that drive the variability in OP and provide a contrast between the assays. Water-soluble organic species (WSOC or BrC) and metals, mainly Fe, Cu, Mn, were selected as the independent variables to form multivariate linear regression models for $\mathrm{OP^{DTT}}$ and $\mathrm{OP^{AA}}$, based on their high correlations, as noted above. EC, though also correlated with $\mathrm{OP^{DTT}}$ and $\mathrm{OP^{AA}}$, was not chosen as one of the predictors due to its correlations with selected water-soluble species (e.g., WSOC, water-soluble Mn and Fe). For $\mathrm{OP^{GSH}}$, WSOC and BrC were used as input in addition to water-soluble Cu to include the possible influence of organic species on $\mathrm{OP^{GSH}}$. The resulting linear relationships between different OP measures and PM components are shown in Table 2. The time series of measured and predicted OPs and the contributions of model variables to each OP measure are given in Fig. S2. Overall, the multivariate models explained variability in OP measures reasonably well with the coefficients of determination between modeled and measured OPs (R^2) greater than 0.4, with the models better capturing the $\mathrm{OP^{AA}}$ and $\mathrm{OP^{GSH}}$ variability. In the regression results for $\mathrm{OP^{DTT}}$ and $\mathrm{OP^{AA}}$, components including water-soluble Fe, Cu and BrC (or WSOC) and interaction terms between metal–organic and metal–metal were included, suggesting that the variability of $\mathrm{OP^{DTT}}$ or $\mathrm{OP^{AA}}$ is dependent upon not only bulk concentrations of PM components but also interactions between species. The regression model for $\mathrm{OP^{GSH}}$ captured the contributions from Cu and BrC but had no interaction terms. The intercept in each regression model, though large and accounting for over 50 % of the mean of OP measures (Fig. S2), is practically meaningless, because the regression models are applicable only when the PM components are at ambient concentrations.

All models captured the contributions from organic species, however, the organic contributions in different models were represented by different measures of organics. In the $\mathrm{OP^{DTT}}$ and $\mathrm{OP^{GSH}}$ models, the organic contribution was denoted by BrC, whereas WSOC was used in the $\mathrm{OP^{AA}}$ model. Although WSOC and BrC were correlated with each

Deleted: water-soluble

Formatted: Superscript

Formatted: Superscript

Deleted: 1

Deleted: 1

Formatted: Superscript

Deleted: Note that BrC and WSOC are present in different models.

Deleted: they

Formatted: Superscript

other (Table S1–S3), there is a difference between these two parameters. The OP contribution from BrC, an optically defined measure, may not be straightforward, however, the optical properties of BrC are related to chemical properties. There is evidence showing that BrC components may directly contribute to OP (Chen et al., 2019). It has been found that BrC predominantly represents the hydrophobic organic fraction (i.e., the humic-like substances (HULIS) fraction) in PM (Verma et al., 2012) and is largely from incomplete combustion (mainly biomass burning) (Hecobian et al., 2010). For example, quinones, as a subset of the HULIS fraction (Verma et al., 2015b), can be estimated better with BrC than with WSOC. WSOC also includes organic compounds present in the hydrophilic fraction, e.g., levoglucosan, (Lin and Yu, 2011) and low molecular weight organic acids (Sullivan and Weber, 2006) and thus is a more integrative measure of organic compounds compared to BrC. The difference between BrC and WSOC is also supported by the different seasonal variation observed in BrC and WSOC (Fig. 3).

Deleted: and both represent the contribution from organic species,

For $\mathrm{OP}^{\mathrm{DTT}}$ results, the presence of Cu and BrC in the equation is as expected, since Cu and organic species have been found active in DTT oxidation (Charrier and Anastasio, 2012; Cho et al., 2005). However, Fe, which has a low intrinsic DTT activity (Charrier and Anastasio, 2012), was found to be predictive of $\mathrm{OP}^{\mathrm{DTT}}$, likely suggesting that Fe represents surrogate measures of constituents with intrinsic redox active properties which were not quantified. This is also supported by the evidence that Fe had correlations with other PM constituents such as OC and EC (Table S1–S3) which may suggest that Fe in the PM water extracts is solubilized by forming complexes with combustion-derived organic species. The interaction terms, along with their negative coefficients, suggest antagonistic interactions between Cu and organic compounds and between Cu and Fe. The interaction between metal and organics, though not taken into account when applying multivariate regression analysis in previous studies (Calas et al., 2018; Verma et al., 2015a), is consistent with experimental results (Yu et al., 2018) wherein antagonistic interactions between Cu and ambient HULIS were observed in the DTT consumption. However, the interaction between metals contrasts with experiments which showed additive effects for metal mixtures (Yu et al., 2018). But it should be noted that the interactions among metals were usually tested with mixtures of individual species, which can poorly represent the complex chemistry of ambient PM.

For RTLF assay, the variability of $\mathrm{OP}^{\mathrm{AA}}$ was attributed to the concentrations of Fe, Cu and WSOC, antagonistic metal–organic interaction between Fe and organic compounds and metal–metal competition between Fe and Cu. Even though the RTLF assay in previous studies was generally used to measure the OP of methanol-extracted PM suspension, the contributions from metals and organics observed in our water-soluble OP agree with previous results (Ayres et al., 2008; Kelly et al., 2011; Pietrogrande et al., 2019). The presence of interaction terms is novel and is supported by little empirical evidence. The antagonistic interaction between Fe and WSOC is reasonable. Fe in the water extracts has been found largely complexed with organic compounds (Wei et al., 2019). Since AA is not a strong ligand for Fe (Charrier and Anastasio, 2011), the complexation between Fe and organic compounds can prevent Fe from reacting with AA. For $\mathrm{OP}^{\mathrm{GSH}}$, despite weak correlation of $\mathrm{OP}^{\mathrm{GSH}}$ with BrC, BrC still accounted for the variability in $\mathrm{OP}^{\mathrm{GSH}}$, consistent with previous findings that $\mathrm{OP}^{\mathrm{GSH}}$ is responsive to quinones (Ayres et al., 2008; Calas et al., 2018).

Deleted: are in agreement

It is noteworthy that the multivariate regression models do not account for the possible nonlinear behavior of species with OP responses. For example, nonlinear concentration–response curves have been found for DTT oxidation by dissolved Cu and Mn (Charrier and Anastasio, 2012), which may not be characterized in the multivariate regression model, potentially affecting the accuracy of the OP^{DTT} model. We note that the variables in the models not only represent the contribution from individual species, but also show a possible influence from co-emitted unquantified components. There are also interactions existing among PM species, affecting the relationships between PM compounds and OP metrics.

To further investigate the sensitivity of different OP assays to PM species, standardized regression was applied to rescale the variables measured in different units and make the coefficients in the regression equations comparable. It is also an effective way to reduce collinearity induced by the inter-correlated nature of PM species and the existence of interaction terms. The standardized coefficient of a specific component indicates the estimated change in an OP measure for every one-unit increase in component. The higher the absolute value of the standardized coefficient, the stronger the effect of the PM species on the OP measure.

Figure 4 shows the relative importance of each PM component to OP metrics based on the calculation of standardized coefficients. As shown in Fig. 4, water soluble Fe was the most important variable in the model of OP^{DTT}, followed by BrC, Cu and antagonistic interactions. Even though OP^{DTT} is not responsive to water-soluble Fe, Fe may be a surrogate measure of compounds co-emitted with Fe from brake/tire wear and secondary formation which have been identified as two major sources of Fe in the southeastern US (Fang et al., 2015a). For OP^{AA}, the strength of the effects of Fe, Cu and WSOC on OP^{AA} was similar. OP^{GSH} was approximately four times more sensitive to Cu than to BrC, with standardized coefficients of 0.70 and 0.18 for Cu and BrC, respectively. These results show clear contrasts between the assays, where OP^{DTT} and OP^{AA} are more similar and both have significant contrasts to OP^{GSH}.

In all these cases, it must also be kept in mind that the measurements were performed on the PM water extracts, which are not the conditions that are found in the ambient aerosol. Thus, inferring associations between species in the extracts and applying to ambient conditions is not straightforward, however, this analysis is useful for interpreting and contrasting the possible causes for associations between these types of assays and any health effects.

Water-soluble Fe, as the most important determinant of OP^{DTT}, has been estimated to have the strongest effect on cardiovascular outcomes in the Atlanta metropolitan region (Ye et al., 2018), which may account for associations between OP^{DTT} and health outcomes observed in this region. OP^{GSH} is strongly dependent on a limited number of PM components, and thus associations between OP^{GSH} and health outcomes may vary more significantly by regions than other assays do and associations could be expected if the PM toxicity in a region is mainly driven by specific species, such as water-soluble Cu. OP^{AA} is affected by the composition of synthetic lung fluid, and thus the AA responses obtained from RTLF and AA-only model are not comparable and should be distinguished from each other. In the RTLF model, the response of OP^{AA} metric by PM is diminished due to the presence of GSH, possibly leading to weaker associations between OP^{AA} and health endpoints.

Deleted: has shown the strongest estimated effect

Deleted: to

Deleted: samples

4 Conclusions

In this study, a comparison was made between two of the most common techniques used for the assessment of PM oxidative potential based on antioxidant depletion from a complex synthetic RTLF (OP^{AA} and OP^{GSH}) and DTT oxidation (OP^{DTT}). These two assays were used to quantify the water-soluble OP of ambient $PM_{2.5}$ collected in urban Atlanta over a one-year period based on daily filter samples. We observed moderate correlations among the OP assays, suggesting different sensitivities of OP measures to PM species. Univariate and multivariate regression analyses indicated that OP^{DTT} and OP^{AA} were correlated to organic species and water-soluble metals (Fe and Cu) and were negatively affected by the interactions among species. At a more detailed level, for organic components, OP^{DTT} was associated specifically with HULIS and incomplete combustion products identified by BrC, whereas OP^{AA} was associated to a more general measure of organic components, WSOC. OP^{GSH}, though also affected by organic species, was predominantly sensitive to water-soluble Cu. Subtle temporal variation in OP^{DTT} and no seasonal variations in OP^{AA} and OP^{GSH} were observed, which appears to be due to little seasonality in the combined PM constituents affecting each assay. A small OP^{DTT} variation was associated with variation in BrC that was higher in the cold seasons.

This study suggests that all three OP metrics are associated with transition metal ions. However, OP^{DTT} and OP^{AA} are more chemically integrative OP measures compared to OP^{GSH}, and thus may be more informative and helpful in linking OP with health end points. The multivariate regression models for different OP measures indicate the degree to which OP variability in the PM water extracts is predicted by PM constituents.

Deleted: when try to find linkage between OP and

We should note that the filter samples used in this study were averaged over 24 hours, which may dampen variability in the emission sources that contribute to OP and obscure the impact of specific species (e.g., traffic-related metals) on redox activity of PM. Furthermore, all these results were obtained from a specific location in Atlanta, GA and should be interpreted and generalized with caution as the chemical composition or sources of PM varies by region. There are marked differences in RTLF composition in different levels of respiratory tract. The synthetic RTLF reflects select antioxidants in the lung and other key constituents are not represented in this simplified chemical model. The DTT assay is also subject to similar limitations that DTT cannot fully represent the biological complexity. However, these assays can be used as PM screening tools and provide rapid health-relevant assessment of PM.

Data availability. All data are available at http://doi.pangaea.de/10.1594/PANGAEA.908043

Deleted: Data can be assessed by request (rweber@eas.gatech.edu).

Author contributions. DG collected and analyzed the data and drafted the manuscript. KJGP assisted with RTLF measurements. JAM and AGR helped with model development. The data were interpreted by DG and RJW. RJW conceived, designed and oversaw the study. All authors discussed the results and contributed to the final manuscript.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. This publication was made possible by Georgia Tech EAS Jefferson St Funds which was a generous gift from Georgia Power/Southern Company. We would like to thank Linghan Zeng, Gigi Pavur, Joseph Caggiano and Allison Weber for assisting with the sampling campaigns and the lab work.

References

Abrams, J. Y., Weber, R. J., Klein, M., Sarnat, S. E., Chang, H. H., Strickland, M. J., Verma, V., Fang, T., Bates, J. T., Mulholland, J. A., Russell, A. G., and Tolbert, P. E.: Associations between Ambient Fine Particulate Oxidative Potential and Cardiorespiratory Emergency Department Visits (vol 125, 2017), Environ Health Persp, 125, 2017.

Aliaga, M. E., Carrasco-Pozo, C., Lopez-Alarcon, C., and Speisky, H.: The Cu(I)-glutathione complex: factors affecting its formation and capacity to generate reactive oxygen species, Transit Metal Chem, 35, 321-329, 2010.

Atkinson, R. W., Samoli, E., Analitis, A., Fuller, G. W., Green, D. C., Anderson, H. R., Purdie, E., Durister, C., Aitlhadj, L., Kelly, F. J., and Mudway, I. S.: Short-term associations between particle oxidative potential and daily mortality and hospital admissions in London, Int J Hyg Envir Heal, 219, 566-572, 2016.

Ayres, J. G., Borm, P., Cassee, F. R., Castranova, V., Donaldson, K., Ghio, A., Harrison, R. M., Hider, R., Kelly, F., Kooter, I. M., Marano, F., Maynard, R. L., Mudway, I., Nel, A., Sioutas, C., Smith, S., Baeza-Squiban, A., Cho, A., Duggan, S., and Froines, J.: Evaluating the toxicity of airborne particulate matter and nanoparticles by measuring oxidative stress potential - A workshop report and consensus statement, Inhal Toxicol, 20, 75-99, 2008.

Baker, M. A., Cerniglia, G. J., and Zaman, A.: Microtiter Plate Assay for the Measurement of Glutathione and Glutathione Disulfide in Large Numbers of Biological Samples, Anal Biochem, 190, 360-365, 1990.

Bates, J. T., Fang, T., Verma, V., Zeng, L. H., Weber, R. J., Tolbert, P. E., Abrams, J. Y., Sarnat, S. E., Klein, M., Mulholland, J. A., and Russell, A. G.: Review of Acellular Assays of Ambient Particulate Matter Oxidative Potential: Methods and Relationships with Composition, Sources, and Health Effects, Environ Sci Technol, 53, 4003-4019, 2019.

Bates, J. T., Weber, R. J., Abrams, J., Verma, V., Fang, T., Klein, M., Strickland, M. J., Sarnat, S. E., Chang, H. H., Mulholland, J. A., Tolbert, P. E., and Russell, A. G.: Reactive Oxygen Species Generation Linked to Sources of Atmospheric Particulate Matter and Cardiorespiratory Effects, Environ Sci Technol, 49, 13605-13612, 2015.

Birch, M. E. and Cary, R. A.: Elemental carbon-based method for monitoring occupational exposures to particulate diesel exhaust, Aerosol Sci Tech, 25, 221-241, 1996.

Brunekreef, B. and Holgate, S. T.: Air pollution and health, Lancet, 360, 1233-1242, 2002.

Deleted: a

Deleted: Bates, J. T., Weber, R. J., Abrams, J., Verma, V., Fang, T., Klein, M., Strickland, M. J., Sarnat, S. E., Chang, H. H., Mulholland, J. A., Tolbert, P. E., and Russell, A. G.: Reactive Oxygen Species Generation Linked to Sources of Atmospheric Particulate Matter and Cardiorespiratory Effects, Environ Sci Technol, 49, 13605-13612, 2015b.

Calas, A., Uzu, G., Kelly, F. J., Houdier, S., Martins, J. M. F., Thomas, F., Molton, F., Charron, A., Dunster, C., Oliete, A., Jacob, V., Besombes, J. L., Chevrier, F., and Jaffrezo, J. L.: Comparison between five acellular oxidative potential measurement assays performed with detailed chemistry on PM10 samples from the city of Chamonix (France), Atmos Chem Phys, 18, 7863-7875, 2018.

Charrier, J. G. and Anastasio, C.: Impacts of antioxidants on hydroxyl radical production from individual and mixed transition metals in a surrogate lung fluid, Atmos Environ, 45, 7555-7562, 2011.

Charrier, J. G. and Anastasio, C.: On dithiothreitol (DTT) as a measure of oxidative potential for ambient particles: evidence for the importance of soluble transition metals, Atmos Chem Phys, 12, 9321-9333, 2012.

Charrier, J. G., McFall, A. S., Vu, K. K. T., Baroi, J., Olea, C., Hasson, A., and Anastasio, C.: A bias in the "mass-normalized" DTT response - An effect of non-linear concentration-response curves for copper and manganese, Atmos Environ, 144, 325-334, 2016.

Chen, Q., Wang, M., Wang, Y., Zhang, L., Li, Y. and Han, Y.: Oxidative Potential of Water-Soluble Matter Associated with Chromophoric Substances in PM2. 5 over Xi'an, China, Environ Sci Technol, 53, 8574-8584, 2019.

Cho, A. K., Sioutas, C., Miguel, A. H., Kumagai, Y., Schmitz, D. A., Singh, M., Eiguren-Fernandez, A., and Froines, J. R.: Redox activity of airborne particulate matter at different sites in the Los Angeles Basin, Environ Res, 99, 40-47, 2005.

Cohen, A. J., Brauer, M., Burnett, R., Anderson, H. R., Frostad, J., Estep, K., Balakrishnan, K., Brunekreef, B., Dandona, L., Dandona, R., Feigin, V., Freedman, G., Hubbell, B., Jobling, A., Kan, H., Knibbs, L., Liu, Y., Martin, R., Morawska, L., Pope, C. A., Shin, H., Straif, K., Shaddick, G., Thomas, M., van Dingenen, R., van Donkelaar, A., Vos, T., Murray, C. J. L., and Forouzanfar, M. H.: Estimates and 25-year trends of the global burden of disease attributable to ambient air pollution: an analysis of data from the Global Burden of Diseases Study 2015, Lancet, 389, 1907-1918, 2017.

Das, S. K.: SPECIAL ISSUE ON "FREE RADICALS AND ANTIOXIDANTS IN HEALTH & DISEASES" Preface, Indian J Exp Biol, 54, 681-683, 2016.

Delfino, R. J., Staimer, N., Tjoa, T., Gillen, D. L., Schauer, J. J., and Shafer, M. M.: Airway inflammation and oxidative potential of air pollutant particles in a pediatric asthma panel, J Expo Sci Env Epid, 23, 466-473, 2013.

DiStefano, E., Eiguren-Fernandez, A., Delfino, R. J., Sioutas, C., Froines, J. R., and Cho, A. K.: Determination of metal-based hydroxyl radical generating capacity of ambient and diesel exhaust particles, Inhal Toxicol, 21, 731-738, 2009.

Edgerton, E. S., Hartsell, B. E., Saylor, R. D., Jansen, J. J., Hansen, D. A., and Hidy, G. M.: The Southeastern Aerosol Research and Characterization Study, part 3: Continuous measurements of fine particulate matter mass and composition, J Air Waste Manage, 56, 1325-1341, 2006.

Edgerton, E. S., Hartsell, B. E., Saylor, R. D., Jansen, J. J., Hansen, D. A., and Hidy, G. M.: The southeastern aerosol research and characterization study: Part II. Filter-based measurements of fine and coarse particulate matter mass and composition, J Air Waste Manage, 55, 1527-1542, 2005.

Fang, T., Guo, H., Verma, V., Peltier, R. E., and Weber, R. J.: PM2.5 water-soluble elements in the southeastern United States: automated analytical method development, spatiotemporal distributions, source apportionment, and implications for heath studies, Atmos Chem Phys, 15, 11667-11682, 2015a.

Fang, T., Guo, H. Y., Zeng, L. H., Verma, V., Nenes, A., and Weber, R. J.: Highly Acidic Ambient Particles, Soluble Metals, and Oxidative Potential: A Link between Sulfate and Aerosol Toxicity, Environ Sci Technol, 51, 2611-2620, 2017.

Fang, T., Verma, V., Bates, J. T., Abrams, J., Klein, M., Strickland, M. J., Sarnat, S. E., Chang, H. H., Mulholland, J. A., Tolbert, P. E., Russell, A. G., and Weber, R. J.: Oxidative potential of ambient water-soluble PM2.5 in the southeastern United States: contrasts in sources and health associations between ascorbic acid (AA) and dithiothreitol (DTT) assays, Atmos Chem Phys, 16, 3865-3879, 2016.

Fang, T., Verma, V., Guo, H., King, L. E., Edgerton, E. S., and Weber, R. J.: A semi-automated system for quantifying the oxidative potential of ambient particles in aqueous extracts using the dithiothreitol (DTT) assay: results from the Southeastern Center for Air Pollution and Epidemiology (SCAPE), Atmos Meas Tech, 8, 471-482, 2015b.

Frampton, M. W., Ghio, A. J., Samet, J. M., Carson, J. L., Carter, J. D., and Devlin, R. B.: Effects of aqueous extracts of PM(10) filters from the Utah Valley on human airway epithelial cells, Am J Physiol-Lung C, 277, L960-L967, 1999.

Gao, D., Fang, T., Verma, V., Zeng, L. G., and Weber, R. J.: A method for measuring total aerosol oxidative potential (OP) with the dithiothreitol (DTT) assay and comparisons between an urban and roadside site of water-soluble and total OP, Atmos Meas Tech, 10, 2821-2835, 2017.

Gao, D., Mulholland, J. A., Russell, A. G., and Weber, R. J.: Characterization of water-insoluble oxidative potential of PM2.5 using the dithiothreitol assay, Atmos Environ (accepted).

Ghio, A. J., Stoneheurner, J., McGee, J. K., and Kinsey, J. S.: Sulfate content correlates with iron concentrations in ambient air pollution particles, Inhal Toxicol, 11, 293-307, 1999.

Godri, K. J., Duggan, S. T., Fuller, G. W., Baker, T., Green, D., Kelly, F. J., and Mudway, I. S.: Particulate Matter Oxidative Potential from Waste Transfer Station Activity, Environ Health Persp, 118, 493-498, 2010.

Godri, K. J., Harrison, R. M., Evans, T., Baker, T., Dunster, C., Mudway, I. S., and Kelly, F. J.: Increased Oxidative Burden Associated with Traffic Component of Ambient Particulate Matter at Roadside and Urban Background Schools Sites in London, Plos One, 6, 2011.

Halliwell, B.: Free-Radicals, Antioxidants, and Human-Disease - Curiosity, Cause, or Consequence, Lancet, 344, 721-724, 1994.

Hansen, D. A., Edgerton, E., Hartsell, B., Jansen, J., Burge, H., Koutrakis, P., Rogers, C., Suh, H., Chow, J., Zielinska, B., McMurry, P., Mulholland, J., Russell, A., and Rasmussen, R.: Air quality measurements for the aerosol research and inhalation epidemiology study, J Air Waste Manage, 56, 1445-1458, 2006.

Hecobian, A., Zhang, X., Zheng, M., Frank, N., Edgerton, E. S., and Weber, R. J.: Water-Soluble Organic Aerosol material and the light-absorption characteristics of aqueous extracts measured over the Southeastern United States, Atmos Chem Phys, 10, 5965-5977, 2010.

Huang, W., Zhang, Y. X., Zhang, Y., Fang, D. Q., and Schauer, J. J.: Optimization of the Measurement of Particle-Bound Reactive Oxygen Species with 2 ',7 '-dichlorofluorescin (DCFH), Water Air Soil Poll, 227, 2016.

Janssen, N. A. H., Strak, M., Yang, A., Hellack, B., Kelly, F. J., Kuhlbusch, T. A. J., Harrison, R. M., Brunekreef, B., Cassee, F. R., Steenhof, M., and Hoek, G.: Associations between three specific a-cellular measures of the oxidative potential of particulate matter and markers of acute airway and nasal inflammation in healthy volunteers, Occup Environ Med, 72, 49-56, 2015.

Kelly, F., Anderson, H. R., Armstrong, B., Atkinson, R., Barratt, B., Beevers, S., Derwent, D., Green, D., Mudway, I., Wilkinson, P., and Committee, H. E. I. H. R.: The impact of the congestion charging scheme on air quality in London. Part 2. Analysis of the oxidative potential of particulate matter, Res Rep Health Eff Inst, 2011. 73-144, 2011.

Kelly, F. J., Cotgrove, M., and Mudway, I. S.: Respiratory tract lining fluid antioxidants: the first line of defence against gaseous pollutants, Cent Eur J Public Health, 4 Suppl, 11-14, 1996.

Khachatryan, L., Vejerano, E., Lomnicki, S. and Dellinger, B.: Environmentally persistent free radicals (EPFRs). 1. Generation of reactive oxygen species in aqueous solutions, Environ Sci Technol, 45, 8559-8566, 2011.

Kumagai, Y., Koide, S., Taguchi, K., Endo, A., Nakai, Y., Yoshikawa, T., and Shimojo, N.: Oxidation of proximal protein sulfhydryls by phenanthraquinone, a component of diesel exhaust particles, Chem Res Toxicol, 15, 483-489, 2002.

Kunzli, N., Mudway, I. S., Gotschi, T., Shi, T. M., Kelly, F. J., Cook, S., Burney, P., Forsberg, B., Gauderman, J. W., Hazenkamp, M. E., Heinrich, J., Jarvis, D., Norback, D., Payo-Losa, F., Poli, A., Sunyer, J., and Borm, P. J. A.: Comparison of oxidative properties, light absorbance, and total and elemental mass concentration of ambient PM2.5 collected at 20 European sites, Environ Health Persp, 114, 684-690, 2006.

Lakey, P. S. J., Berkemeier, T., Tong, H. J., Arangio, A. M., Lucas, K., Poschl, U., and Shiraiwa, M.: Chemical exposure-response relationship between air pollutants and reactive oxygen species in the human respiratory tract, Sci Rep-Uk, 6, 2016.

Lavigne, É., Burnett, R.T., Stieb, D.M., Evans, G.J., Godri Pollitt, K.J., Chen, H., van Rijswijk, D. and Weichenthal, S.: Fine particulate air pollution and adverse birth outcomes: effect modification by regional nonvolatile oxidative potential, Environmental health perspectives, 126, 077012, 2018.

Lin, P. and Yu, J. Z.: Generation of Reactive Oxygen Species Mediated by Humic-like Substances in Atmospheric Aerosols, Environ Sci Technol, 45, 10362-10368, 2011.

Lippmann, M.: Toxicological and epidemiological studies of cardiovascular effects of ambient air fine particulate matter (PM2.5) and its chemical components: Coherence and public health implications, Crit Rev Toxicol, 44, 299-347, 2014.

Maikawa, C. L., Weichenthal, S., Wheeler, A. J., Dobbin, N. A., Smargiassi, A., Evans, G., Liu, L., Goldberg, M. S., and Pollitt, K. J. G.: Particulate Oxidative Burden as a Predictor of Exhaled Nitric Oxide in Children with Asthma, Environ Health Persp, 124, 1616-1622, 2016.

McWhinney, R. D., Gao, S. S., Zhou, S. M., and Abbatt, J. P. D.: Evaluation of the Effects of Ozone Oxidation on Redox-Cycling Activity of Two-Stroke Engine Exhaust Particles, Environ Sci Technol, 45, 2131-2136, 2011.

Meyer, M. B., Patashnick, H., Ambs, J. L., and Rupprecht, E.: Development of a sample equilibration system for the TEOM continuous PM monitor, J Air Waste Manage, 50, 1345-1349, 2000.

Mudway, I.S., Duggan, S.T., Venkataraman, C., Habib, G., Kelly, F.J. and Grigg, J.: Combustion of dried animal dung as biofuel results in the generation of highly redox active fine particulates, Particle and fibre toxicology, 2, 6, 2005.

Mudway, I. S., Stenfors, N., Duggan, S. T., Roxborough, H., Zielinski, H., Marklund, S. L., Blomberg, A., Frew, A. J., Sandstrom, T., and Kelly, F. J.: An in vitro and in vivo investigation of the effects of diesel exhaust on human airway lining fluid antioxidants, Arch Biochem Biophys, 423, 200-212, 2004.

Norris, G., YoungPong, S. N., Koenig, J. Q., Larson, T. V., Sheppard, L., and Stout, J. W.: An association between fine particles and asthma emergency department visits for children in Seattle, Environ Health Persp, 107, 489-493, 1999.

Pietrogrande, M. C., Bertoli, I., Manarini, F., and Russo, M.: Ascorbate assay as a measure of oxidative potential for ambient particles: Evidence for the importance of cell-free surrogate lung fluid composition, Atmos Environ, 211, 103-112, 2019.

Pizzino, G., Irrera, N., Cucinotta, M., Pallio, G., Mannino, F., Arcoraci, V., Squadrito, F., Altavilla, D., and Bitto, A.: Oxidative Stress: Harms and Benefits for Human Health, Oxid Med Cell Longev, doi: Artn 8416763

10.1155/2017/8416763, 2017. 2017.

Pope, C. A., Burnett, R. T., Thurston, G. D., Thun, M. J., Calle, E. E., Krewski, D., and Godleski, J. J.: Cardiovascular mortality and long-term exposure to particulate air pollution - Epidemiological evidence of general pathophysiological pathways of disease, Circulation, 109, 71-77, 2004.

Samet, J. M., Dominici, F., Curriero, F. C., Coursac, I., and Zeger, S. L.: Fine particulate air pollution and mortality in 20 US Cities, 1987-1994., New Engl J Med, 343, 1742-1749, 2000.

Sarnat, J. A.: Fine Particle Sources and Cardiorespiratory Morbidity: An Application of Chemical Mass Balance and Factor Analytical Source Apportionment Methods, Epidemiology, 19, S44-S44, 2008.

Shi, T., Knaapen, A. M., Begerow, J., Birmili, W., Borm, P. J. A., and Schins, R. P. F.: Temporal variation of hydroxyl radical generation and 8-hydroxy-2 '-deoxyguanosine formation by coarse and fine particulate matter, Occup Environ Med, 60, 315-321, 2003a.

Shi, T. M., Schins, R. P. F., Knaapen, A. M., Kuhlbusch, T., Pitz, M., Heinrich, J., and Borm, P. J. A.: Hydroxyl radical generation by electron paramagnetic resonance as a new method to monitor ambient particulate matter composition, J Environ Monitor, 5, 550-556, 2003b.

Strak, M., Janssen, N. A. H., Godri, K. J., Gosens, I., Mudway, I. S., Cassee, F. R., Lebret, E., Kelly, F. J., Harrison, R. M., Brunekreef, B., Steenhof, M., and Hoek, G.: Respiratory Health Effects of Airborne Particulate Matter: The Role of Particle Size, Composition, and Oxidative Potential-The RAPTES Project, Environ Health Persp, 120, 1183-1189, 2012.

Sullivan, A. P. and Weber, R. J.: Chemical characterization of the ambient organic aerosol soluble in water: 1. Isolation of hydrophobic and hydrophilic fractions with a XAD-8 resin, J Geophys Res-Atmos, 111, 2006.

Sun, Q. H., Hong, X. R., and Wold, L. E.: Cardiovascular Effects of Ambient Particulate Air Pollution Exposure, Circulation, 121, 2755-2765, 2010.

Thurston, G. D., Kipen, H., Annesi-Maesano, I., Balmes, J., Brook, R. D., Cromar, K., De Matteis, S., Forastiere, F., Forsberg, B., Frampton, M. W., Grigg, J., Heederik, D., Kelly, F. J., Kuenzli, N., Laumbach, R., Peters, A., Rajagopalan, S. T., Rich, D., Ritz, B., Samet, J. M., Sandstrom, T., Sigsgaard, T., Sunyer, J., and Brunekreef, B.: A joint ERS/ATS policy statement: what constitutes an adverse health effect of air pollution? An analytical framework, Eur Respir J, 49, 2017.

Tong, H., Lakey, P.S., Arangio, A.M., Socorro, J., Shen, F., Lucas, K., Brune, W.H., Pöschl, U. and Shiraiwa, M.: Reactive oxygen species formed by secondary organic aerosols in water and surrogate lung fluid, Environ Sci Technol, 52, 11642-11651, 2018.

Tong, H., Zhang, Y., Filippi, A., Wang, T., Li, C., Liu, F., Leppla, D., Kourtchev, I., Wang, K., Keskinen, H.M. and Levula, J.T.: Radical formation by fine particulate matter associated with highly oxygenated molecules, Environ Sci Technol, 53, 12506-12518, 2019.

Turpin, B. J. and Lim, H. J.: Species contributions to PM2.5 mass concentrations: Revisiting common assumptions for estimating organic mass, Aerosol Sci Tech, 35, 602-610, 2001.

Venkatachari, P., Hopke, P. K., Grover, B. D., and Eatough, D. J.: Measurement of particle-bound reactive oxygen species in rubidoux aerosols (vol 50, pg 49, 2005), J Atmos Chem, 52, 325-326, 2005.

Verma, V., Fang, T., Guo, H., King, L., Bates, J. T., Peltier, R. E., Edgerton, E., Russell, A. G., and Weber, R. J.: Reactive oxygen species associated with water-soluble PM2.5 in the southeastern United States: spatiotemporal trends and source apportionment, Atmos Chem Phys, 14, 12915-12930, 2014.

Verma, V., Fang, T., Xu, L., Peltier, R. E., Russell, A. G., Ng, N. L., and Weber, R. J.: Organic Aerosols Associated with the Generation of Reactive Oxygen Species (ROS) by Water-Soluble PM2.5, Environ Sci Technol, 49, 4646-4656, 2015a.

Verma, V., Rico-Martinez, R., Kotra, N., King, L., Liu, J. M., Snell, T. W., and Weber, R. J.: Contribution of Water-Soluble and Insoluble Components and Their Hydrophobic/Hydrophilic Subfractions to the Reactive Oxygen Species-Generating Potential of Fine Ambient Aerosols, Environ Sci Technol, 46, 11384-11392, 2012.

Verma, V., Wang, Y., El-Afifi, R., Fang, T., Rowland, J., Russell, A. G., and Weber, R. J.: Fractionating ambient humic-like substances (HULIS) for their reactive oxygen species activity - Assessing the importance of quinones and atmospheric aging, Atmos Environ, 120, 351-359, 2015b.

Weber, R.: Short-term temporal variation in PM2.5 mass and chemical composition during the Atlanta supersite experiment, 1999, J Air Waste Manage, 53, 84-91, 2003.

Wei, J. L., Yu, H. R., Wang, Y. X., and Verma, V.: Complexation of Iron and Copper in Ambient Particulate Matter and Its Effect on the Oxidative Potential Measured in a Surrogate Lung Fluid, Environ Sci Technol, 53, 1661-1671, 2019.

Weichenthal, S., Crouse, D. L., Pinault, L., Godri-Pollitt, K., Lavigne, E., Evans, G., van Donkelaar, A., Martin, R. V., and Burnett, R. T.: Oxidative burden of fine particulate air pollution and risk of cause-specific mortality in the Canadian Census Health and Environment Cohort (CanCHEC), Environ Res, 146, 92-99, 2016a.

Formatted: Font:(Default) Times New Roman

Formatted: Font:(Default) Times New Roman

Formatted: Font:(Default) Times New Roman

Formatted: Font:Not Italic

Formatted: Font:(Default) Times New Roman

Formatted: Font:(Default) Times New Roman, Not Italic

Formatted: Font:(Default) Times New Roman

Formatted: Font:(Default) Times New Roman

Weichenthal, S., Lavigne, E., Evans, G., Pollitt, K., and Burnett, R. T.: Ambient PM2.5 and risk of emergency room visits for myocardial infarction: impact of regional PM2.5 oxidative potential: a case-crossover study, Environ Health-Glob, 15, 2016b.

Weichenthal, S. A., Lavigne, E., Evans, G. J., Pollitt, K. J. G., and Burnett, R. T.: Fine Particulate Matter and Emergency Room Visits for Respiratory Illness Effect Modification by Oxidative Potential, Am J Resp Crit Care, 194, 577-586, 2016c.

Yang, A., Janssen, N. A. H., Brunekreef, B., Cassee, F. R., Hoek, G., and Gehring, U.: Children's respiratory health and oxidative potential of PM2.5: the PIAMA birth cohort study, Occup Environ Med, 73, 154-160, 2016.

Yang, A., Jedynska, A., Hellack, B., Kooter, I., Hoek, G., Brunekreef, B., Kuhlbusch, T. A. J., Cassee, F. R., and Janssen, N. A. H.: Measurement of the oxidative potential of PM2.5 and its constituents: The effect of extraction solvent and filter type, Atmospheric Environment, 83, 35-42, 2014.

Ye, D. N., Klein, M., Mulholland, J. A., Russell, A. G., Weber, R., Edgerton, E. S., Chang, H. H., Sarnat, J. A., Tolbert, P. E., and Sarnat, S. E.: Estimating Acute Cardiovascular Effects of Ambient PM2.5 Metals, Environ Health Persp, 126, 2018.

Yu, H. R., Wei, J. L., Cheng, Y. L., Subedi, K., and Verma, V.: Synergistic and Antagonistic Interactions among the Particulate Matter Components in Generating Reactive Oxygen Species Based on the Dithiothreitol Assay, Environ Sci Technol, 52, 2261-2270, 2018.

Zielinski, H., Mudway, I. S., Berube, K. A., Murphy, S., Richards, R., and Kelly, F. J.: Modeling the interactions of particulates with epithelial lining fluid antioxidants, Am J Physiol-Lung C, 277, L719-L726, 1999.

Table 1. Pearson's r between OP and PM composition

	Overall			Summer			Winter		
	OP^{AA}	OP^{GSH}	OP^{DTT}	OP^{AA}	OP^{GSH}	OP^{DTT}	OP^{AA}	OP^{GSH}	OP^{DTT}
OP^{GSH}	**0.67****			**0.78****			0.62**		
OP^{DTT}	0.61**	0.45**		**0.66****	**0.70****		0.53**	0.50**	
$PM_{2.5}$ mass	0.56**	0.24**	0.55**	0.23*	0.19	0.49**	**0.70****	0.36**	0.54**
OC	0.50**	0.10	0.55**	0.16	0.03	0.40**	0.61**	0.26**	0.50**
EC	0.49**	0.13*	0.51**	0.11	0.01	0.39**	0.60**	0.28**	0.44**
WSOC	0.55**	0.19**	0.52**	0.24*	0.20	0.41**	**0.66****	0.38**	0.54**
BrC	0.36**	0.04	0.41**	0.33**	0.14	0.51**	0.51**	0.33**	**0.69****
SO_4^{2-}	0.41**	0.37**	0.34**	0.42**	0.35**	0.48**	0.33**	0.27**	0.18*
WS-K	0.49**	0.30**	0.50**	0.32**	0.08	0.46**	0.52**	0.33**	0.56**
WS-Fe	0.47**	0.17**	0.50**	0.43**	0.21	0.59**	0.52**	0.24**	0.48**
WS-Cu	0.50**	**0.74****	0.36**	0.51**	**0.79****	**0.65****	0.60**	**0.78****	0.31**
WS-Mn	0.38**	0.19**	0.37**	0.34**	0.13	0.61**	0.49**	0.28**	0.37**
WS-Zn	0.31**	0.31**	0.34**	0.32**	0.11	0.46**	0.41**	0.14	0.31**

Note: **p-value<0.01; *p-value<0.05. Correlations not statistically significant (p>0.05) are in grey, r>0.65 are bold. All metals listed are water-soluble metals.

Table 2. Multivariate linear regression models for OP metrics.

	Fe	Cu	WSOC	BrC	metal–organic		metal–metal		intercept	R^2
OP^{DTT}	2.28E-3	2.69E-3		5.75E-2	-1.36E-3	Cu*BrC	-4.09E-5	Fe*Cu	0.13	0.40
OP^{AA}	1.17E-1	1.07E-1	9.32E-1		-1.30E-2	Fe*WSOC	-2.05E-3	Fe*Cu	4.38	0.54
OP^{GSH}		7.41E-2		2.77E-1					3.65	0.56

Note: All metals are water-soluble metals. The values represent the coefficients for variables. Cell is left blank where the corresponding variable is not included in the equation. As an example, the linear equation of OP^{DTT} is as follows: OP^{DTT} = 2.28E-3*Fe +2.69E-3*Cu +5.75E-2*BrC-1.36E-3*(Cu*BrC)-4.09E-5*(Fe*Cu)+0.13. The concentrations of water-soluble metals are in units of ng m^{-3}, whereas the units for WSOC and BrC are µg m^{-3} and Mm^{-1}, respectively.

Deleted: 0

Deleted: PM components are in units of µg m^{-3},

Deleted: is

Deleted: .

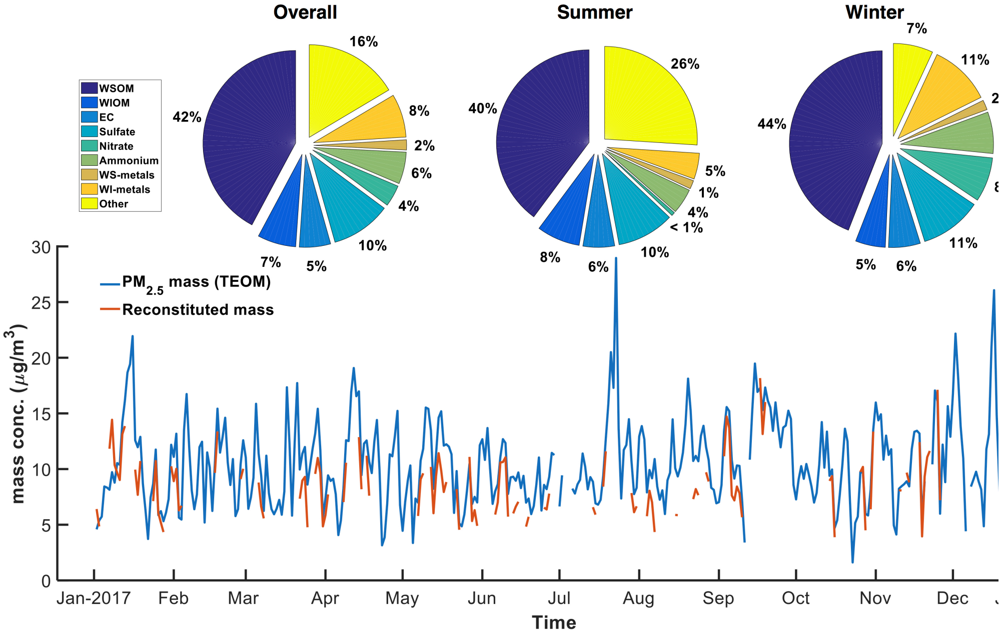


Figure 1: Time series of PM$_{2.5}$ mass concentration. The pie charts show the average aerosol composition based on PM$_{2.5}$ mass measured by the TEOM during the whole sampling year, summer and winter. WSOM: water-soluble organic matter (=WSOC*1.6); WIOM: water-insoluble organic matter (=OM-WSOM); WS-metals: sum of water-soluble metals, including Al, Mg, Ca, K, Fe, Cu, Mn, Zn; WI-metals: water-insoluble metals (=total_metals-WS_metals). Summer: Jun–Aug; winter: Jan–Feb and Nov–Dec.

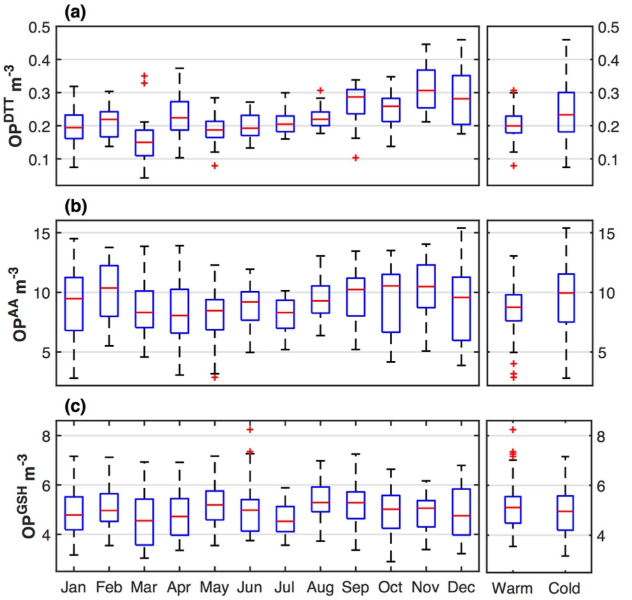


Figure 2: Temporal variation for (a) OP^{DTT} m^{-3} (nmol min^{-1} m^{-3}), (b) OP^{AA} m^{-3} (% depletion of AA m^{-3}), and (c) OP^{GSH} m^{-3} (% depletion of GSH m^{-3}). Warm period: May–Aug; cold period: Jan–Feb and Nov–Dec.

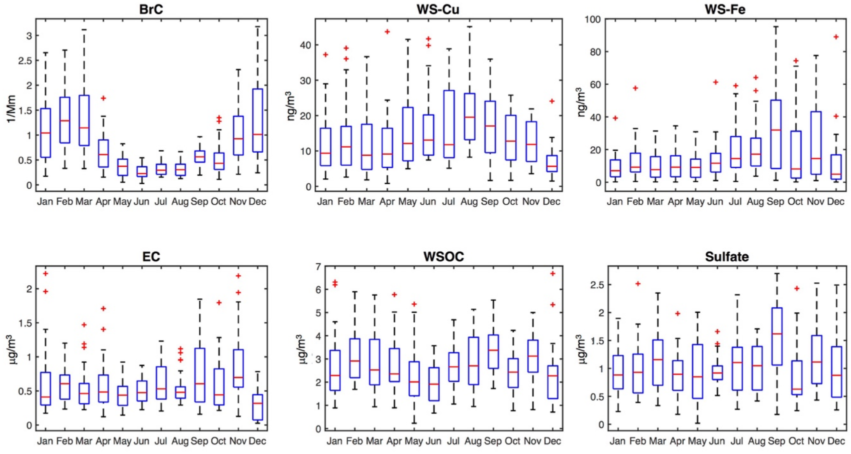
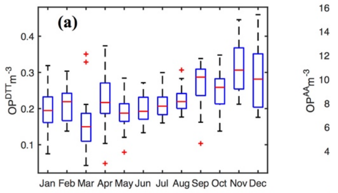
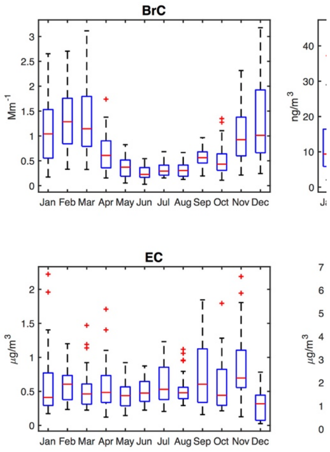


Figure 3: Temporal variation for select PM species.



Deleted:

Formatted: Font:(Default) Times New Roman, 12 pt, Bold



Deleted:

Formatted: Font:(Default) Times New Roman, 12 pt

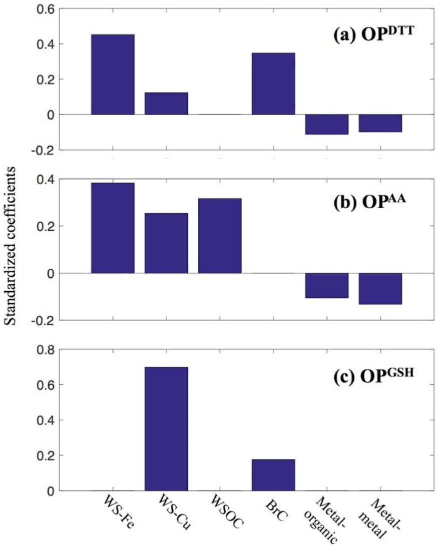


Figure 4: Standardized regression coefficients for different OP measures with selected PM components.

Table S1. Correlation matrix for various PM components and OP metrics over the one-year sampling period.

	DTT	AA	GSH	WSOC	BrC	SO4	WS-K	WS-Mn	WS-Fe	WS-Cu	WS-Zn	OC	EC
AA	**0.606**												
GSH	0.455	**0.669**											
WSOC	0.524	0.551	0.190										
BrC	0.408	0.357	0.045	**0.602**									
SO4	0.343	0.413	0.374	0.370	0.093								
WS-K	0.174	0.486	0.304	0.071	0.042	0.482							
WS-Mn	0.387	0.377	0.191	0.553	0.380	0.404	0.363						
WS-Fe	0.502	0.472	0.169	0.483	0.137*	0.377	-0.007	0.461					
WS-Cu	0.341	0.500	**0.740**	0.203	-0.078	0.426	0.533	0.294	0.176				
WS-Zn	0.343	0.309	0.314	0.191	0.137*	0.450	**0.907**	0.483	0.179	0.510			
OC	0.546	0.497	0.105	**0.774**	0.426	0.245	0.054	0.437	0.599	0.143	0.223		
EC	0.513	0.488	0.126*	0.584	0.392	0.184	0.093	0.434	0.552	0.173	0.312	**0.833**	
PM mass	0.552	0.555	0.239	**0.747**	0.414	0.554	0.314	0.539	0.511	0.313	0.418	**0.774**	**0.639**

Note: r>0.6 are highlighted. Black without superscript: p-value<0.01; *p-value<0.05; grey: not statistically significant.

Table S2. Correlation matrix for PM components and OP metrics (Summer, Jun-Aug/2017).

Summer	DTT	AA	GSH	WSOC	BrC	SO4	WS-K	WS-Mn	WS-Fe	WS-Cu	WS-Zn	OC	EC
AA	**0.656**												
GSH	**0.695**	**0.784**											
WSOC	0.412	0.244*	0.202										
BrC	0.510	0.330	0.137	**0.818**									
SO4	0.477	0.425	0.350	0.479	0.323								
WS-K	0.464	0.322	0.085	**0.708**	0.566	0.442							
WS-Mn	**0.611**	0.345	0.134	0.457	0.410	0.319	**0.616**						
WS-Fe	0.587	0.428	0.212	**0.683**	**0.762**	0.395	0.500	0.428					
WS-Cu	**0.648**	0.515	**0.791**	0.400	0.300	0.479	0.220	0.312	0.418				
WS-Zn	0.457	0.326	0.110	0.526	0.518	0.168	0.426	0.518	0.573	0.262*			
OC	0.400	0.161	0.030	**0.810**	**0.761**	0.405	**0.643**	0.418	**0.730**	0.266*	**0.624**		
EC	0.386	0.114	0.007	0.442	0.540	0.082	0.233*	0.284	**0.668**	0.197	**0.678**	**0.640**	
PM mass	0.486	0.229*	0.188	**0.606**	0.459	0.578	0.451	0.384	0.455	0.264*	0.312	**0.728**	0.368

Note: r>0.6 are highlighted. Black without superscript: p-value<0.01; *p-value<0.05; grey: not statistically significant.

Table S3. Correlation matrix for PM components and OP metrics (Winter, Jan-Feb/2017 and Dec/2017).

Winter	DTT	AA	GSH	WSOC	BrC	SO4	WS-K	WS-Mn	WS-Fe	WS-Cu	WS-Zn	OC	EC
AA	0.534												
GSH	0.498	**0.616**											
WSOC	0.538	**0.659**	0.383										
BrC	**0.689**	0.514	0.332	**0.758**									
SO4	0.183*	0.332	0.268	0.275	0.067								
WS-K	0.563	0.523	0.333	**0.779**	**0.682**	0.288							
WS-Mn	0.373	0.492	0.284	0.589	0.540	0.220	**0.651**						
WS-Fe	0.483	0.518	0.239	0.422	0.213*	0.294	0.259	0.429					
WS-Cu	0.308	**0.601**	**0.776**	0.437	0.209*	0.339	0.343	0.227	0.294				
WS-Zn	0.309	0.414	0.140	0.461	0.450	0.016	0.368	0.524	0.495	0.185*			
OC	0.501	**0.613**	0.256	**0.748**	0.506	0.152	0.456	0.433	0.508	0.346	0.549		
EC	0.439	0.600	0.282	0.574	0.380	0.110	0.347	0.403	0.481	0.370	**0.667**	**0.874**	
PM mass	0.542	**0.701**	0.361	**0.825**	**0.645**	0.397	**0.720**	0.499	0.513	0.385	0.540	**0.789**	**0.670**

Note: r>0.6 are highlighted. Black without superscript: p-value<0.01; *p-value<0.05; grey: not statistically significant.

Table S4. Pearson's r between mass-normalized OP and mass fraction of PM species.

	Overall			Summer			Winter		
	OP^{AA}	OP^{GSH}	OP^{DTT}	OP^{AA}	OP^{GSH}	OP^{DTT}	OP^{AA}	OP^{GSH}	OP^{DTT}
OP^{GSH}	**0.78****			**0.94****			**0.68****		
OP^{DTT}	**0.74****	0.75**		**0.81****	**0.85****		0.52**	**0.66**	
OC	-0.06	-0.13*	0.07	-0.02	-0.14	0.03	-0.26*	-0.26*	-0.27*
EC	0.17**	0.04	0.22**	0.27*	0.21	0.34**	-0.14	-0.22*	-0.34**
WSOC	0.21**	0.18**	0.20**	0.17	0.06	0.16	0.12	0.16	-0.07
BrC	0.08	0.02	0.12*	0.17	0.05	0.27*	-0.06	-0.02	0.14
SO_4^{2-}	0.19**	0.24**	0.13*	0.35**	0.34**	0.31**	0.29**	0.35**	0.19
WS-K	0.06	0.08	0.11	0.15	0.03	0.22	-0.08	-0.13	-0.10
WS-Fe	-0.04	-0.22**	-0.07	0.10	-0.04	0.14	-0.08	-0.37**	-0.34**
WS-Cu	0.48**	0.49**	0.30**	0.44**	0.58**	0.44**	0.38**	0.49**	0.07
WS-Mn	0.01	0.10	0.01	0.08	-0.02	0.09	0.00	0.03	-0.09
WS-Zn	0.30**	0.21**	0.41**	0.17	0.08	0.19	0.17	0.16	0.25*

Note: **p-value<0.01; *p-value<0.05. Correlations not statistically significant (p>0.05) are in grey, r>0.65 are bold. All metals listed are water-soluble metals.

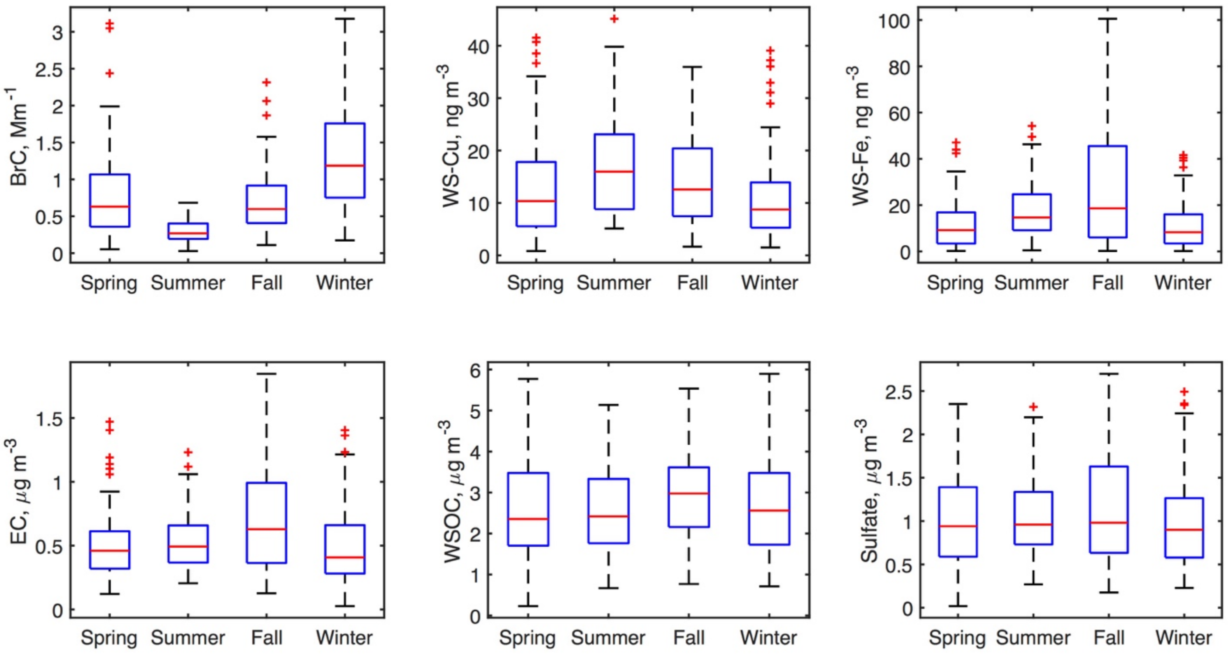


Figure S1. Seasonal variation of PM species. Spring: Mar–May; Summer: Jun–Aug; Fall: Sep–Nov; Winter: Jan–Feb, Dec.

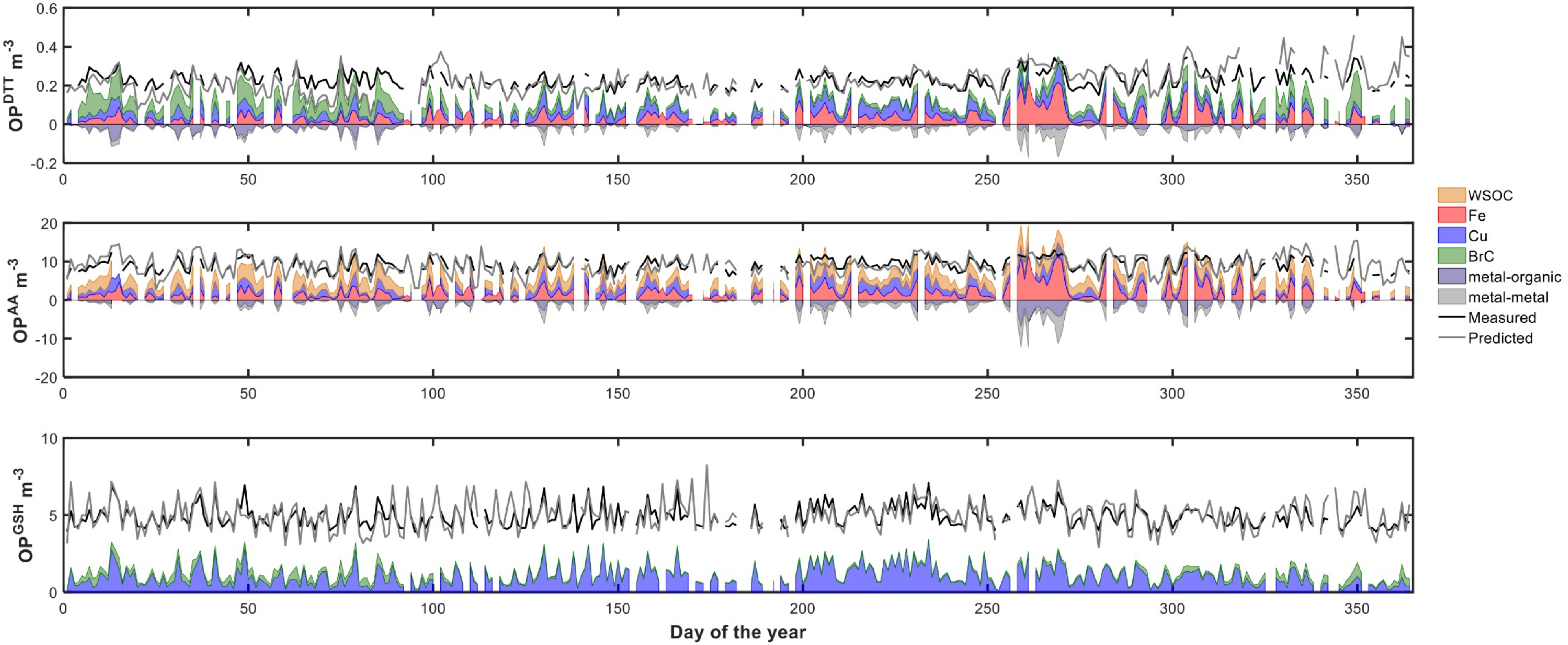


Figure S2. Time series of measured and predicted OP measures and the contributions of model variables to OPs (intercepts are not shown).