

Controlling the risks of fine particulate matter: size, numbers, chemical properties and forcing: how to proceed?

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Particulate matter is responsible for a major part of premature death as a result of bad air quality worldwide. It is also instrumental in climate forcing with positive and negative contributions. Recently, studies on the hitherto not well understood fractions of organic carbon have suggested that they make substantial contributions to adverse health effects and forcing which are additional to those of black carbon.

Protection of humans against exposure to atmospheric particles is currently regulated by setting air quality limit values, expressed presently in the metrics PM₁₀ and PM_{2.5}. The concern about specific risks of the ultrafine fraction of PM, and increased knowledge of the different toxicities of its chemical components, have rendered these metrics less suitable for future, more effective, regulation.

Knowledge of the precise roles of solid and liquid aerosols in climate forcing is still incomplete. Clouds constitute a major factor in the radiation balance; their formation is triggered by atmospheric particles and dependent on particle properties. A fraction-by-fraction approach may fill present gaps in knowledge and is considered in this paper with respect to size and chemical composition. It will be demonstrated that such an approach is likely to increase the effectiveness of present policies. Its implementation in air quality regulation will require the reduction of the emissions of the SLCPs and ozone precursors, hence bringing co-benefits for climate objectives. In addition, a fraction-by-fraction approach would improve understanding of cloud/aerosol interactions and secondary forcing mechanisms.

Keywords: Black Carbon (BC), Brown Carbon (BrC), Primary Organic Aerosols (POA), Secondary Organic Aerosols (SOA), Ultrafine particles

1. Introduction

Particulate pollution probably presents the most challenging and complicated air quality problem. For gaseous pollution, SO₂ served as indicator until the 1940s, when a separate approach for the different components was gradually developed. Particulate pollution varies not just with respect to chemical composition and reactivity, but also to source, size, shape and surface properties. Together, these properties determine its interaction with humans and its toxicity. Technical/scientific barriers have so far prevented development of an approach of the kind developed for gaseous pollutants.

When details of climate forcing dynamics entered the research agenda the situation was comparable: for gases the basic picture was soon more or less complete. Aerosols and the dynamics of cloud formation in which they play a key role, however, proved challenging for the climate science community and a complete understanding continues to be elusive.

In this article a fraction-by-fraction approach for particulate matter is discussed from the viewpoint of delivering improved health protection and reduced climate forcing.

2. Present metrics

The first generation of methods for monitoring of particulate matter can be divided in optical and gravimetric methods. Of these optical methods (Black Smoke) provide a metric for a specific fraction; the method is relatively imprecise. The gravimetric approach provides data for Total Suspended Particles; it does not discriminate between chemical composition nor size ranges of particles. Since the seventies the latter method is used in combination with sampling equipment which allows cut-off of specific size fractions: PM_{10} , $PM_{2.5}$, etc. Its subsequent world-wide adoption in monitoring networks made it the standard metric used in the development of further PM-policies; initially based on epidemiological data for short-term health effects and later, from the nineties, long-term effects, including mortality. In particular, the correlation of these PM metrics with increased mortality, recently reconfirmed by WHO¹, has provided robust arguments for policies to reduce atmospheric levels of PM_{10} and $PM_{2.5}$ in Europe, North America and elsewhere.

During the first decade of this century, however, the conviction increased that the present approach of regulating through inadequately defined metrics for particles was showing too many deficiencies. Discussions were also fuelled by the difficulties found in most EU Member States in developing and implementing policies which could result in compliance with the limit value for PM_{10} . The main objections include:

- Metrics like $PM_{10}/PM_{2.5}$ which cannot be directly related to specific sources or categories of sources make it difficult and sometimes impossible for EU Member States to comply with the respective limit values
- Indications that specific chemical fractions of PM are more toxic than the average of the mixture of all its components have become stronger and are throwing doubt on the effectiveness of present PM regulation for the protection of public health
- The present size-differentiation of PM ignores the strong indications that the ultrafine fractions have an additional size-specific toxicity
- Because $PM_{10}/PM_{2.5}$ metrics do not specify absorptivity they are unsuitable in a 'One atmosphere' approach which integrates climate and clean air policies; by ignoring this in air quality legislation there is no stimulation to select options with the higher overall cost-effectiveness with respect to climate and clean air at national and de-central levels.

3. Fraction-by-fraction approach

In a first action EFCA adopted a proposal from the scientific community² to introduce Black Carbon Particles, - which have higher correlation with health effects than $PM_{2.5}$ - as additional metric for air quality in the EU. In its Policy Initiative,³ sent to the European Commission, EFCA also pointed to the co-benefits of a BC-policy for climate objectives.

In addition to a BC-metric, which is mass-based like $PM_{10}/PM_{2.5}$, an approach to protect human health by regulation which reduces Particle Number Concentrations (PNC) has been recommended in Switzerland since the end of the last century⁴. Such a regulation is indeed included in the EUROVI Regulation on emissions by heavy vehicles, in force for new vehicle types from 2012⁵. The new requirement will certainly reduce emissions of black carbon particles as these are in the size range <100 nm. Regulation of PNC does not consider specific toxicities of fractions which are chemically different, however; like $PM_{10}/PM_{2.5}$, PNC is less suitable as a metric for assessing the effectiveness of health protection policies.

Apart from BC, other fractions of PM contribute to its toxicity. In further response to the deficiencies of PM₁₀/PM_{2.5} metrics, EFCA recently suggested a fraction-by-fraction approach for addressing particulate matter^{6,7} In this approach size and chemical composition are considered to be of equal relevance. With respect to size as such, regulation through the metrics PM₁₀/PM_{2.5} is likely to provide protection against respiratory health effects. Protection against cardiovascular and olfactory effects, however, requires a more targeted regulation of specific components of the ultrafine fraction (30-170 nm).

Table 1. Specific health risks of ultrafine particles

Primary	Secondary
Black Carbon (BC)	
Primary Organic Aerosol (POA)	Secondary Organic Aerosol (SOA)
<i>Metals</i> <ul style="list-style-type: none"> ➤ <i>combustion</i> ➤ <i>metallurgical processes</i> ➤ <i>abrasion particles (traffic, other)</i> 	<i>Inorganic aerosol</i> <ul style="list-style-type: none"> ➤ <i>Sulphates (ultrafine?)</i> ➤ <i>Nitrates (ultrafine?)</i>
Natural <ul style="list-style-type: none"> ➤ Sea salt ➤ <i>Saharan dust</i> 	Natural <ul style="list-style-type: none"> ➤ Natural haze
	<i>Resuspended aerosol (ultrafine?)</i>

Ranking: **Top risk** *Medium risk* *Low risk* no risk

Table 1 lists the components which may be found in ultrafine fractions of PM with indications of their relative toxicity. Of these metals are the only ones for which separate policies exist. Inorganic aerosols exist for a substantial part as particles with sizes >PM₁. Black Carbon and Primary (POA) and Secondary Organic Aerosols (SOA) are predominantly found in the ultrafine fraction. BC and POA are emitted from combustion processes; together with SOA, formed in the atmosphere from organic substances, they are considered to be responsible for the higher health risks. Traditionally, the understanding has been that SOA are formed through the conversion of natural terpenes under the influence of sunlight. The resulting haziness in the atmosphere has been considered more a nuisance than a health risk. During recent years this view of organic carbon has gradually changed.

4. Organic Carbon

Combustion processes which are major sources of particles also produce semi-volatile polycyclic aromatics (PCAs), several of which are known to be carcinogenic. At the elevated temperatures of exhaust gases, most PCAs are emitted as gases; at ambient temperatures, however, most of them condense and are deposited on the surfaces of small particles in the atmosphere, usually of black carbon. This Primary Organic Aerosol (POA) explains at least a part of the health risks of PM.

Novel findings in recent years have now confirmed that this POA is also subject to photochemical conversion during the day through the type of reactions which also favour the formation of photochemical smog with its characteristic deepening of the smog in the second half of the day, referred to as 'aged smog'⁸. The development of the technique of Time of Flight Mass Spectrometry⁹ has made it possible to confirm the different chemical character of

the secondary organic aerosols (SOA) and to quantitatively assess the levels of POA and SOA in PM samples separately. The atmospheric conversion process of POA has also been confirmed in simulation experiments with diluted exhaust gases in a smogchamber¹⁰. This process is particularly efficient in the summer season; its impact requires serious attention. In comparison to the POA fraction the resulting 'aged smog' appears to be more reactive in genotoxic tests and, in chemical assays, has the higher 'oxidative capacity'. It is understood that its surface contains more 'reactive oxidative species' (ROS), which are held responsible for 'oxidative stress' as experienced by humans exposed to summersmog. Because BC and POA are emitted by the same sources they travel together when being dispersed during the day; SOA are also found in the same air masses. The mixture of BC, POA and SOA represents a substantial part of the particle mass and numbers in summersmog. With sizes primarily in the ultrafine fraction (<170 nm) they may enter the blood circulation upon inhalation, resulting in a range of adverse effects; the most serious are¹:

- Particles within the circulation system may cause inflammations or embolus, leading to cardiovascular problems;
- The same mechanisms have also been associated with lower birth outcomes in humans;
- It has been claimed that exposure to ultrafine particles accelerates the development of Alzheimer's disease. In this case direct exposure through the olfactory route is also possible. Ultrafine particles may be able to pass through the membranes in the olfactory organ and enter the brain¹¹.

While BC, POA and SOA may all three contribute to the above effects, an estimate of the contribution of each is presently not possible.

The likely contribution of SOA to adverse health effects of particulate matter implies that emission reductions of primary particles alone are insufficient to protect human health; reductions of the precursors of ozone formation, volatile organic compounds (VOC) and nitrogen oxides (NO_x) are also necessary.

5. Biofuels

Results of recent Australian research^{12, 13} added to the existing concern about impacts of the use of biofuels by revealing that in smogchamber experiments exhaust gases from biofuels produce considerably more reactive oxidative species (ROS) than found in experiments with fossil fuels and consequently may carry higher health risks. The interpretation of this work is that oxygenated ingredients like ethanol (petrol) and biodiesel enhance the formation of ROS. This phenomenon is also observed in mixtures with fossil fuels consisting solely of hydrocarbons.

6. Brown carbon

Recently, it has become apparent that organic aerosols represent another link between air pollution and climate change. Organic aerosols are also held responsible for the brown colour of polluted air masses in summer, well known from investigations of the Asian Brown Cloud (ABC) in the beginning of this century¹⁴. In spite of this visible indication, the additional climate forcing of the ABC was initially attributed to BC only. As a result the contribution of organic aerosols is still ignored in most climate models.

In 2006 the term 'brown carbon' was introduced for the light absorbing fraction of organic carbon and the question of its contribution to forcing was raised¹, triggering the investigations discussed below.

Studies into the atmospheric chemistry of biogenic and anthropogenic hydrocarbons revealed that the formation of brown carbon requires a sequence of several reactions^{16,17}. In a first step the hydrocarbon reacts with a hydroxyl radical or with ozone, forming an aldehyde; in a secondary reaction with ozone the aldehyde may be converted into a keto-aldehyde; this was found to happen with limonene. Aldehydes and keto-aldehydes are less volatile than the parent hydrocarbon; their condensation or deposition on particles in the atmosphere results in SOA. In the presence of trace amounts of ammonia in a humid atmosphere the keto-aldehyde is converted into 'brown carbon' compounds (see figure 1). The extent of browning is strongly dependent on the structure of the hydrocarbon precursor. The keto-aldehyde of limonene was found to be a strong precursor of brown carbon (BrC). BrC was also formed with the ammonium ion NH_4^+ or with amino acids.

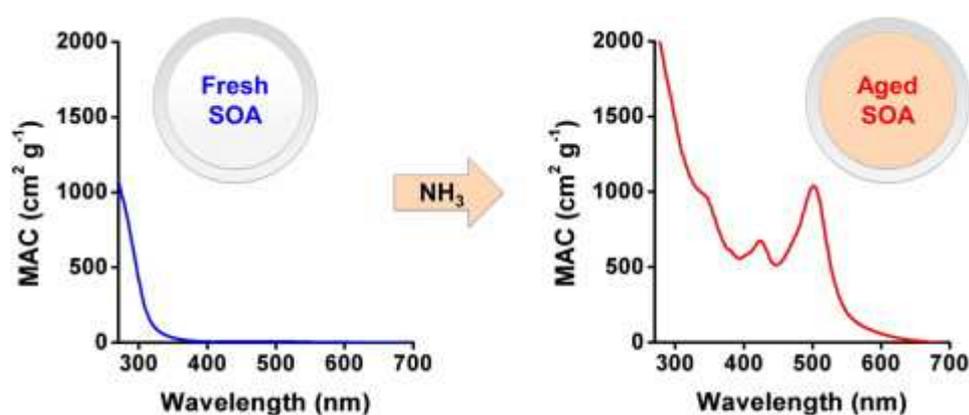


Figure 1. Mass Absorption Coefficients (MAC) of fresh and aged SOA (from ref. 16)

Apart from limonene also sesquiterpenes were found to be effective precursors for BrC.

Combustion is a further pathway to BrC. In addition to fossil fuels, biomass burning is a very large source of atmospheric pollution in many regions of the world. Measurements in the marine boundary layer of the Bay of Bengal and the Arabian Sea show that BrC is also being transported into the marine atmosphere¹⁸. It is therefore likely that light absorbing organic aerosols from biomass burning play a significant role in radiative forcing over continental and oceanic regions.

Studies into the spectral properties of BrC¹⁹ have revealed a difference between source areas: where biomass burning is the dominant source, in South America and Southern Africa for example, the SOA formed are absorbing moderately; in regions with higher anthropogenic emissions the SOA absorb more strongly. By using a global chemical transport model and a radiative transfer model an estimate was made of the enhanced absorption of solar radiation by BrC. At a wavelength of 550 nm the aerosol absorption optical depth increases by 18%, and 3% respectively for the strongly and moderately absorbing BrC; at a wavelength of 380 nm the increase is, respectively, 56% and 38%. The simulations suggest that the strongly absorbing BrC is responsible for 19% of the absorption by anthropogenic aerosols; 72% is attributed to black carbon and 9% could result from absorption by sulphates and non-absorbing organic aerosols coated on black carbon. Absorption of sunlight at the top of the atmosphere has a direct warming effect; indirectly, the reduced insolation, in particular over source regions, reduces photochemical scavenging of pollutants, including SLCFs and thus can play an important role in photochemistry and the hydrological cycle.

BrC is a mixture of a wide range of poorly characterised compounds with low volatility which exhibit considerably different absorptivity. This complicates parameterisation of BrC in estimating its contribution to global warming. In smog chamber experiments on organic aerosols in biomass burning emissions under a range of conditions, it was shown that the effective absorptivity can be parameterised as a function of the ratio of BC to organic aerosol²⁰. The implication is that the conditions of burning rather than the type of biomass determine aerosol absorptivity. It would be of interest to know whether a similar relationship exists for the absorptivity of organic aerosols from anthropogenic sources.

7. Fraction-by-fraction approach in climate research

Recent work on BrC, in addition to that on BC suggests that a good understanding of the contributions from different fractions and, consequently a fraction-by-fraction approach, is also relevant for estimating their effects on the climate system. From the other fractions of PM, metallic particles may have to be taken into account, depending on their absorptivity.

The situation here is more complex, however, because the processes of cloud formation, in which particles play a central role, also have to be considered.

Cloud formation in the clean atmosphere is favoured by the presence of inorganic nuclei, such as nanoparticles of ocean spray, in an atmosphere of elevated relative humidity. The liquid aerosol particles tend to disperse radiation, which makes them visible as white clouds, which in turn have a cooling effect as they reflect incoming sunlight. When the size of liquid aerosol particles increases, droplets will be formed, possibly followed by precipitation.

In polluted atmospheres this process is likely to be modified. Inorganic pollutants may play a similar role to condensation nuclei; it is unclear, however, whether the less hygroscopic organic and elemental carbon in a plume may have a similar propensity for developing into droplet size. Also, in plumes with a high concentration of small particles, competition for the available water vapour may soon prevent sufficient growth of particles.

It has indeed been observed that precipitation is reduced in areas downwind of a polluted urban area.

8. Discussion

While the database of atmospheric levels of PM₁₀ and PM_{2.5} includes data from all developed countries and an increasing number of developing countries, data on the fractions of PM₁₀ and PM_{2.5} are sparse: There is some available data on POA, SOA or BrC from scientific studies; a relatively small number of networks regularly publish data on BC. Although for polycyclic aromatics (PCA), many research studies have produced information about their prevalence as gases or as aerosol, systematic monitoring of PCA in a network remains scarce.

It is also noteworthy that, for the above fractions, measurement methods used in these networks are not referred to international standard methods.

Given the present uncertainty about the contribution of each of these fractions to adverse health effects associated with PM-level, it is highly desirable to reach agreement on standard methods for monitoring for each of the relevant fractions and to gradually extend existing networks using them..

The situation for emission data on these fractions is even worse. Emission data on particulate matter are supposed to represent the sum of all fractions without further specification.

Scientists that are highly dependent on such data for modelling purposes are already trying to fill this gap and develop their own databases from the limited material in literature.

This kind of information is highly important for understanding the actual impact of particulate matter on public health and climate. Without it, it will not be possible to start epidemiological studies to obtain dose/effect relations between individual fractions and specific health effects or to identify the fractions with the higher impact. That information may further a more targeted policy for the protection of public health.

This type of information is also required to improve existing climate models targeting the short-lived climate forcers (SLCFs). The particulate matter problem is deeply interwoven with atmospheric chemistry and has to be considered in relation to the precursors of the formation of ozone and secondary aerosols. A more detailed knowledge of these processes is essential for understanding the contributions of SLCFs to global warming and, consequently to a process of ranking policy measures according to cost-effectiveness.

Responsible bodies at regional and national scales have, through the support they provide to improving knowledge in this area, the possibility of improving the cost-effectiveness of their air quality and climate policies and creating important co-benefits.

9. Conclusions

1. Protection of human health against particulate matter and reliable assessment of the contribution of particulate matter to climate forcing requires a fraction-by-fraction (FBF) approach.
2. Deficiencies of the PM₁₀/PM_{2.5} metrics are well known; gaps in knowledge, however, in particular with respect to BC and primary and secondary organic aerosols (POA and SOA), prevent cost-effective protection of human health against exposure to particulate matter. An FBF-approach may improve this situation.
3. Brown Carbon (BrC), a mixture of organic aerosols should be considered as a fourth short-lived climate pollutant, in addition to BC, methane and ozone. Its formation in polluted atmospheres for a major part runs parallel to the formation of SOA from precursors which originate from combustion processes. The recommended FBF-approach for particulate matter will therefore also support BrC control.
4. Particulate matter results from primary emissions of particles and their atmospheric conversion and from gases under conditions which favour photochemical ozone formation. Its control will, therefore, require emission reductions of particles and of the precursors of ozone, VOC and NO_x.
5. Development of an FBF-approach includes research activities in several areas:
 - source strengths of relevant (groups of) components
 - compiling of emission inventories for these components with due attention to biogenic and anthropogenic contributions
 - development and standardisation of methods for monitoring different fractions of particulate matter
 - studies on the characterisation and atmospheric behaviour of individual PM fractions
 - studies aimed at detailing the aerosol/cloud interactions of different fractions of particulate matter

10. References

1. WHO Europe. 2013. Review of evidence on health effects of air pollution – REVIHAAP. www.euro.who.int/
2. EFCA. July 2011. Impressions from UFP-3. EFCA Newsletter No. 12, 8-11 <http://www.efca.net/efca2/index.php?page=newsletters>

3. EFCA. July 2012. Black Carbon Particles: Opportunities to strengthen policies on Air Quality and Climate Change in Europe. EFCA Policy Initiative No. 3
<http://efca.net/uploads/file/Policy%20Initiative%20No.%203%20E.pdf>
4. For Swiss regulations see:
 - a. Mayer, A., Particle Number PN complementing Particle Mass PM for vehicle engine emission measurement (2013). Proc. 4th EFCA Ultrafine Particles symposium, May 2013
<http://ufp.efca.net>
 - b. Stäubli, A.; Kropf, R. 2004: Air Pollution Control at Construction Sites – Construction Guideline Air. Environment in practice. Swiss Agency for the Environment, Forests and Landscape, BUWAL, Bern
 - c. Ordinance of the Swiss Confederation on Air Pollution Control – Amendment of Section 4a on ‘Requirements on construction machines and their particle filter systems’ (2009)
 - d. Particle Filter Systems for Exhaust Gas After-treatment of Internal Combustion Engines. Testing Method SN 277206. Swiss Association for Standardisation (<http://www.snv.ch>; 2011)
5. [Regulation \(EC\) No 595/2009 of the European Parliament and of the Council](#) of 18 June 2009 on type-approval of motor vehicles and engines with respect to emissions from heavy duty vehicles (Euro VI) and on access to vehicle repair and maintenance information
6. Van Ham, J, T. Reichert and J. Murlis. 2013. Towards a robust European policy on particulate matter, Pollution Atmosphérique No. 220, Oct-Dec 2013, <http://lodel.irevues.inist.fr/pollution-atmospherique/index.php?id=2424>
7. [EFCA. 2014. Controlling the risks of particulate matter – state of play. EFCA Newsletter No. 20, 5-8. 14 April 2014, http://www.efca.net/efca2/index.php?page=news](#)
8. Sioutas, C. 2013. Sources, formation mechanisms and physicochemical properties of UF. Proceedings 4th EFCA symposium on Ultrafine particles, Brussels 2013. Karlsruhe Institute of Technology (K.F. Ziegahn, ed.), Karlsruhe 2013. ISBN 978-3-923704-81-1. www.kit.edu
9. Prévot, A. 2013. Aerosol Mass Spectrometry, source attribution and secondary aerosols. Proceedings 4th EFCA symposium on Ultrafine particles, Brussels 2013. Karlsruhe Institute of Technology (K.F. Ziegahn, ed.), Karlsruhe 2013. ISBN 978-3-923704-81-1. www.kit.edu
10. Platt, S.M. 2013. Secondary aerosol production from modern diesel and gasoline cars. Proc. 17th ETH Conference on Combustion Generated Particles, Zurich, 2013 (K. Boulouchos and H. Burtscher, eds); Zurich, ISBN 978-3-033-04114-1; www.nanoparticles.ethz.ch
11. Schins, R. 2013. Ultrafine particles and neurodegenerative diseases. Proceedings 4th EFCA symposium on Ultrafine particles, Brussels 2013. Karlsruhe Institute of Technology (K.F. Ziegahn, ed.), Karlsruhe 2013. ISBN 978-3-923704-81-1. www.kit.edu
12. Ristovski, Zoran, Svetlana Stevanovic, Branka Miljevic, Nicholas Surawski, Steve Bottle, Richard Brown. 2013. Particle emissions from diesel engines - looking beyond carbon soot emissions. Proceedings 4th WeBIOPATR conference, Belgrade, 2013; <http://www.vin.bg.ac.rs/webiopatr/>
13. Stevanovic, S., M. Rahman, A. Pourkhesalian, P. Pham, H. Wang, R. J. Brown, A. Masri, B. Miljevic, Z.D. Ristovski. 2013. The influence of different biodiesel feedstocks on the oxidative potential of diesel particulate matter. Proceedings 4th WeBIOPATR conference, Belgrade, 2013; <http://www.vin.bg.ac.rs/webiopatr/>
14. Ramanathan, V., Crutzen, P. J., Lelieveld, J., Mitra, A. P., Althausen, D., Anderson, J., Andreae, M. O., Cantrell, W., Cass, G. R., Chung, C. E., *et al.* 2001. *J. Geophys. Res.* **106**, 28371–28399.
15. Andreae, M. O. and A. Gelencsér. 2006. Black carbon or brown carbon? The nature of light-absorbing carbonaceous aerosols. *Atmos. Chem. Phys.*, **6**, 3131–3148
16. Updike, Katalyn M., Tran B. Nguyen and Sergey A. Nizkorodov. 2012. Formation of brown carbon via reactions of ammonia with secondary organic aerosols from biogenic and anthropogenic precursors. *Atmospheric Environment* **63**, 22-31
17. Nguyen, Tran B., Alexander Laskin, Julia Laskin and Sergey A. Nizkorodov. 2013. Brown carbon formation from ketoaldehydes of biogenic monoterpenes. *Faraday Discussions* **165**, 473-494
18. Srinivas, Bikina and M.M. Sarin. 2013. Light absorbing organic aerosols (brown carbon) over the tropical Indian Ocean: impact of biomass burning emissions. *Environ. Res. Lett.* **8** 044042. Online at <http://stacks.iop.org/ERL/8/044042>
19. Feng, Y., V. Ramanathan and V.R. Kotamarthi. 2013. Brown carbon: a significant atmospheric absorber of solar radiation? *Atmos. Chem. Phys. Discuss.* 25 January 2013; in revised form 2 Sept. 2013
20. Saleh, Rawad, Ellis S. Robinson, Daniel S. Tkacik, Adam T. Ahern, Shang Liu, Allison C. Aiken, Ryan C. Sullivan, Albert A. Presto, Manvendra K. Dubey, Robert J. Yokelson, Nell M. Donahue

and Allen L. Robinson. 2014. Brownness of organics in aerosols from biomass burning linked to their black carbon content. *Nature Geoscience* **7**, 647–650

Table 1. Specific health risks of ultrafine particles

Primary	Secondary
Black Carbon (BC)	
Primary Organic Aerosol (POA)	Secondary Organic Aerosol (SOA)
<u>Metals</u> <ul style="list-style-type: none"> ➤ <u>combustion</u> ➤ <u>metallurgical processes</u> ➤ <u>abrasion particles (traffic, other)</u> 	<i>Inorganic aerosol</i> <ul style="list-style-type: none"> ➤ <i>Sulphates (ultrafine?)</i> ➤ <i>Nitrates (ultrafine?)</i>
Natural <ul style="list-style-type: none"> ➤ Sea salt ➤ <u>Saharan dust</u> 	Natural <ul style="list-style-type: none"> ➤ Natural haze
	<i>Resuspended aerosol (ultrafine?)</i>

Ranking: **Top risk** Medium risk *Low risk* no risk

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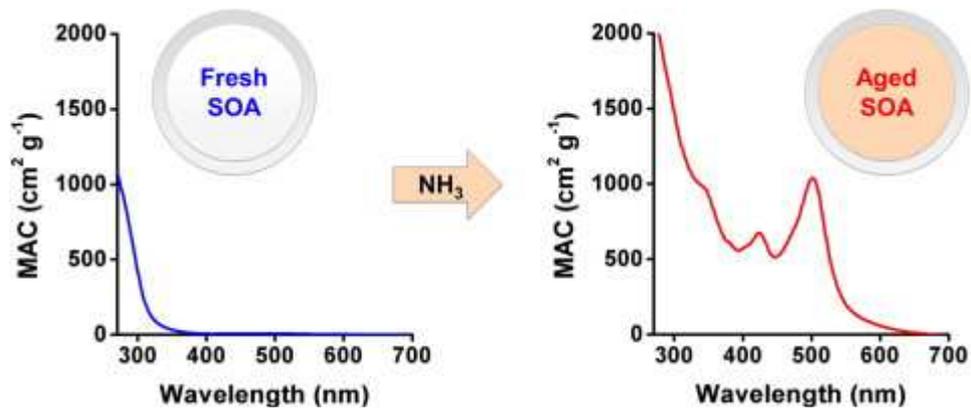


Figure 1. Mass Absorption Coefficients (MAC) of fresh and aged SOA (from ref. 16)