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WMO AEROSOL BULLETIN

INTEGRATED OBSERVATIONS OF ATMOSPHERIC AEROSOLS

The Role of Black Carbon in Atmospheric and Climate Research

Think of the recent strong smog episodes over large cities like Beijing or Paris, when a hazy atmosphere blocks the sunlight from reaching the ground, or the intense wild fires that regularly darken the skies over California in summer, or dust storms in Africa or Australia that may affect wide areas and cause massive health effects, or the grayish layer covering melting glaciers that forces deglaciation.

In all cases, small particles suspended in the atmosphere called aerosols are key culprits. Aerosols scatter and absorb sunlight to varying degrees depending on their physical and optical properties. One consequence is that aerosols alter the Earth's radiation balance and modify the life cycle of Earth's ice and snow covers. In general, aerosols have a cooling effect on climate, which partially counterbalances the heating effect of greenhouse gases. Under certain circumstances, however, aerosols may also cause an additional heating of the atmosphere.

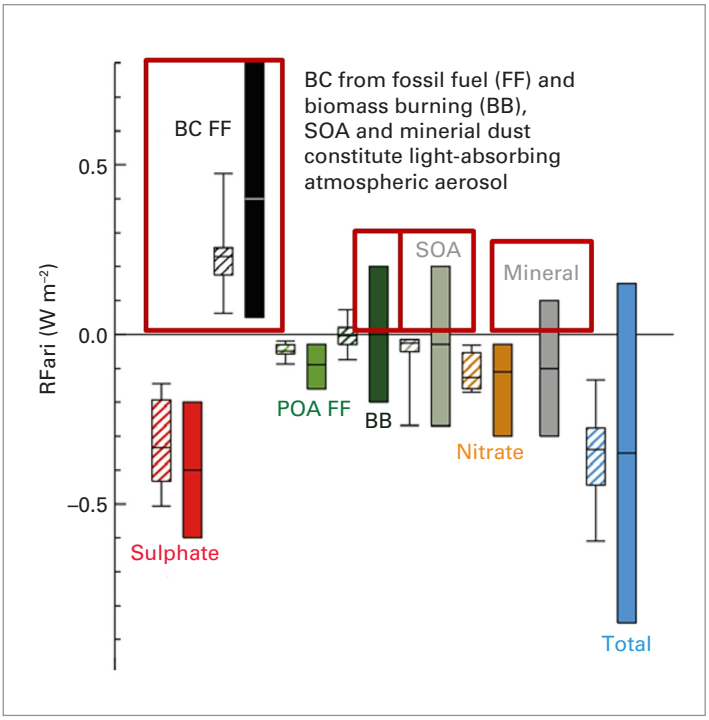

Figure 1. *Annual mean top-of-atmosphere aerosol radiative forcing from aerosol-radiation interaction (Rfari) in W m^{-2} due to different anthropogenic aerosol types, for the 1750 to 2010 period (IPCC 2013, Chapter 7).*

Although global events like the latest United Nations Conference on Climate Change (COP21) in Paris in November 2015, focus exclusively on reducing the emissions of greenhouse gases like CO_2, light-absorbing aerosol particles have gained increasing attention due to their warming effect on climate. In that respect, a Green Freight Action Plan was discussed at COP21 to reduce the emissions of fine particle pollutants from global transportation.

Among the light-absorbing aerosol particles, those composed predominantly of carbon-containing matter, such as black carbon (BC), have been identified as the second-most important climate forcing agent after CO_2, and as one of the most important so-called short-lived climate forcers. It has also become a key target for investigating the impact of aerosols on climate and related mitigation strategies.

The latest IPCC report (2013) summarizes the contributions of major aerosol types to the aerosol radiative forcing from aerosol-radiation interaction; see Figure 1. Positive radiative forcing, and thus potential global warming, is associated with BC resulting from the incomplete combustion of fossil fuel (BC FF) and biofuel, primary organic aerosol from fossil fuel (POA FF) and biofuel, aerosol from biomass burning (BB), secondary organic aerosol (SOA), and mineral dust.

Black Carbon in the Arctic

One region of particular interest for studying long-term trends in BC mass concentrations is the Arctic, which faces the strongest environmental impacts from a changing climate globally. There exist only minor inner-Arctic sources of BC, yet the impact of light-absorbing BC particles deposited on snow or ice coverage can be huge. Long-term monitoring of BC in the Arctic is critical to understanding sources and transport pathways in this region, and to provide essential information for the development and implementation of mitigation options.

The WMO Global Atmosphere Watch (GAW) programme operates a network of global measurement stations. Three of these stations are located on the coast of the Arctic Ocean: Alert (Nunavut, Canada), Barrow (Alaska, USA) and Ny-Ålesund (Svalbard, Norway). Alert and Barrow have the longest measurement records (1989 to present), which allows meaningful trends to be determined. Routine observations of BC mass concentrations did not begin at Ny-Ålesund until 1998 and trends there cannot be compared directly to the other two sites. However, from 2002 to 2012, daily average BC mass concentrations at Ny-Ålesund were similar to those at Barrow and Alert, in spite of the geographical separation, indicating the ubiquity of BC in the high Arctic.

Overall, there has been a 55% decline in BC mass burden at Alert and a 45% decline at Barrow between 1990-1993 and 2009-2012; see Figure 2. The declines are related to decreasing emissions due to the economic collapse of the former Soviet Union during the early 1990s (Sharma et al., 2013; Quinn et al., 2008; Hirdman et al., 2010). The BC burden at Arctic stations has not increased since 2000, despite rising fossil fuel BC emissions in the source regions (Sharma et al., 2013), especially in East Asia. Further exploration of contributions from the East Asian region to the BC loading of the Arctic lower atmosphere are warranted given the increasing emissions from fossil fuel and biomass burning in this region.

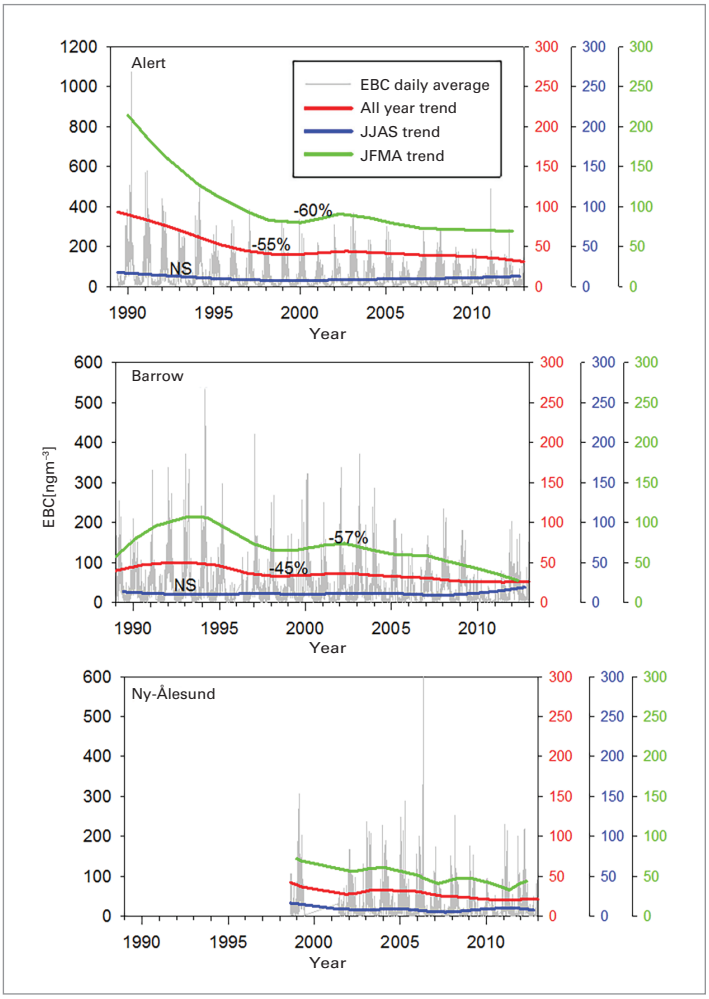

Figure 2. *Daily surface average equivalent black carbon (eBC) at Alert and Barrow. The red line includes all eBC data, the green line is the average for January to April (JFMA), and the blue line is the average for June to September (JJAS). The % change in eBC between 1990-1993 and 2009-2012 is given for each trend line for Alert and Barrow. No significant (NS) change occurred in summer at those locations; Published in Arctic Report Card 2013.*

Several global atmospheric transport models have investigated the atmospheric transport pathways into the lower Arctic atmosphere. They confirmed that emissions from Europe and the former Soviet Union contribute up to 85% at the three sites (Sharma et al., 2013; Hirdman et al., 2010), whereas BC from East Asia contributes only a small proportion of total deposition in the Arctic because it is transported at higher altitudes than BC from Europe and the former Soviet Union (Sharma et al., 2013).

Besides the long-range transport of BC and fine particulate matter from industrialized regions of the northern hemisphere, the growing impact of inner-Arctic sources like Arctic shipping and flaring is identified and carefully monitored.

Measuring Black Carbon in the GAW Network

Most observation networks worldwide rely on optical methods for measuring aerosol light absorption and equivalent BC (eBC) mass concentration. In the Arctic, the longest records of eBC mass concentration are measured by a filter-based optical instrument known as an Aethalometer. This instrument or the Multi-Angle Absorption Photometer (MAAP) are simple and robust and therefore widely used techniques in monitoring networks.

The principal measurement of any optical method is the aerosol light absorption coefficient σ_{abs}, which describes the amount of light extinguished from the incoming sunlight by aerosol light absorption per unit length of the penetrated atmospheric column. This quantity is converted into an eBC mass concentration via the relationship $eBC = \sigma_{abs} / MAC$. The mass absorption cross-section (MAC) depends strongly on particle properties such as chemical composition, size and others and varies between observation sites and seasons. Traditionally, the change in optical transmission is assumed to be due solely to BC. Today, the need for correcting eBC data to account for other aerosols is well established and various correction schemes have been developed.

Whereas the measurement of aerosol light absorption is established, the scientific community continues to debate a standard method for the determination of MAC values. Europe has established a "European regional background" value MAC = 10.8 ± 3.0 $m^2 g^{-1}$ (wavelength 637 nm; Zanatta et al. (2016)) from long-term observations at 10 European regional background super-sites, with values varying from 6 to 16 $m^2 g^{-1}$ between measurement sites, air mass origin or season; see Figure 3. MAC values are a very critical parameter because each research group uses a different approach to obtain it, resulting in large differences in reported BC mass concentrations.

Reporting Black Carbon Observations

Despite its recognized importance for the global climate, current estimates of top-of-atmosphere radiative forcing

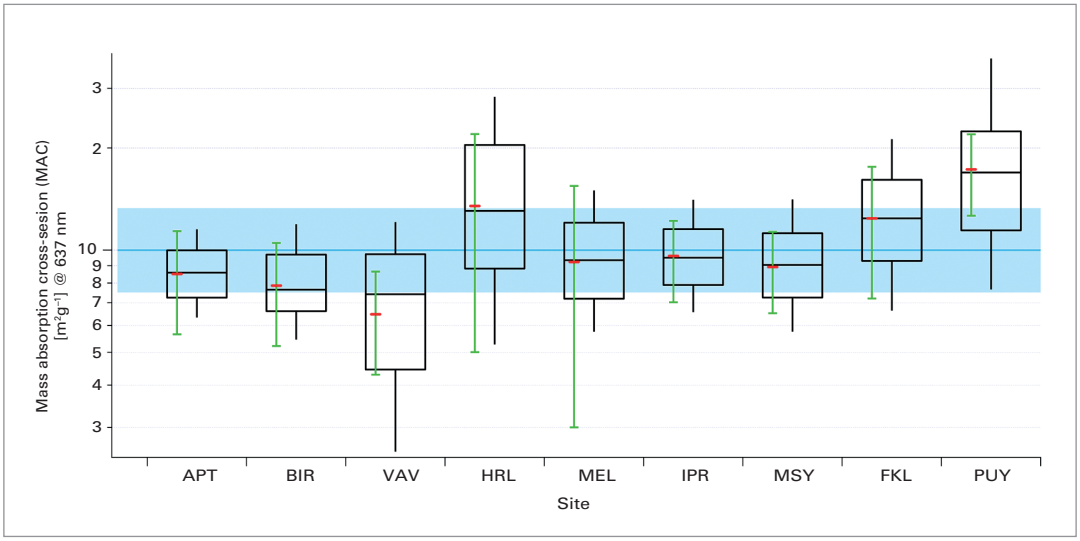

Figure 3. *Mass absorption cross-section (MAC) for nine European Supersites. The green error bars indicate the 1σ uncertainties of the geometric mean value, which depend on the applied measurement technique. The blue line and shading in panel indicate the geometric mean ± geometric SD of the geometric mean MAC values from all sites (Zanatta et al., 2016).*

from short-lived climate forcers still remain uncertain, in part due to the lack of a coherent definition of carbonaceous aerosol components and respective measurement methods.

Carbonaceous matter composed mainly of carbon atoms and structured like graphite (Elemental Carbon) is strongly light-absorbing and thus characterized by its black appearance (Black Carbon), while showing a strong thermal refractivity. Carbonaceous matter built of complex carbon-hydrogen-oxygen compounds (Organic Carbon) is thermally less refractive and characterized by a transparent or brownish appearance. These distinct properties (see Figure 4) are related to the underlying molecular structure of the aerosol constituent and give rise to a highly diverse set of measurement techniques.

Atmospheric research lacks an unambiguous definition of BC and a clear terminology for reporting BC observations in global atmospheric observation networks. Furthermore, constructing consistent inventories for sources and sinks of light-absorbing carbon particles is another essential pre-requisite for reducing the large diversity in existing estimates of the climate effect of carbonaceous aerosol.

Key challenges associated with the measurement of BC are associated with the following facts:

- carbonaceous matter does not appear in atmospheric aerosols as a pure substance;
- measurements may refer to the same quantity of the carbonaceous aerosol but with different names; e.g. black carbon or elemental carbon;
- measurements of different quantities may be referred to with the same name;
- current methods respond to different BC properties;
- correlation between different BC measurement methods are frequently high, but relationships vary among sites, seasons and aerosol types.

The GAW Scientific Advisory Group (SAG) on Aerosols has undertaken the effort of harmonizing the terminology and clarifying the reporting of BC-related data in global monitoring networks. Measurement methods of relevance

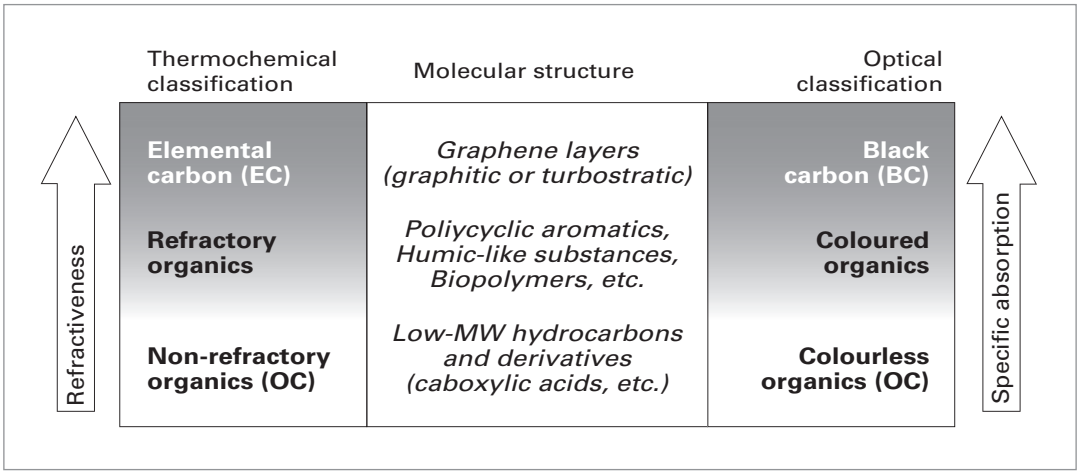

Figure 4. *Classification of carbonaceous aerosol matter (Pöschl, 2003).*

for routine observations of carbonaceous aerosol can be grouped in three main "families of methods":

Evolved carbon methods consist of combined thermal and gas-analytical approaches for the analysis of gasification products evolving from a heated filter sample and make use of the thermal resistivity of the "elemental carbon" fraction.

Light absorption methods connect to the volumetric cross-section for light absorption, commonly called the light absorption coefficient (σ_{abs}), such as the optical technique described earlier.

Laser-induced incandescence methods detect carbon-containing particles by absorption of intense radiative energy which is transformed into heat and results in the re-emission of thermal radiation.

In addition, there are numerous approaches in use based on Raman or electron microscopy or mass spectrometry; see Petzold et al. (2013) for details.

Recommended Terminology

The GAW SAG on Aerosols proposes the following consistent terminology based on targeted material properties:

- Total carbon (TC) mass to describe the mass of all carbonaceous matter in airborne particles.
- Black carbon (BC) to qualitatively describe light-absorbing carbon-containing substances in the aerosol. For quantitative applications the term requires clarification.
- Equivalent black carbon (eBC) to be used instead of BC for data derived from optical absorption methods, together with a suitable MAC value for the conversion of light absorption into mass concentration.
- Elemental carbon (EC) to be used instead of BC for data derived from methods that are specific to the carbon content of carbonaceous matter.
- Refractory black carbon (rBC) to be used instead of BC for data derived from incandescence methods.
- Soot is a useful qualitative term when referring to carbonaceous particles formed from incomplete combustion.

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What is the Aerosol Bulletin?	The Aerosol Bulletin provides general information on the aerosol component of GAW and focuses on specific components or applications of GAW aerosol measurements
How do I join GAW?	The procedure is described at http://www.wmo.int/pages/prog/arep/gaw/join_GAW.html
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