Review of Observation Capacities and Data Availability for Black Carbon in the Arctic Region: EU Action on Black Carbon in the Arctic – Technical Report 1

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Authors
Kjetil Tørseth, Elisabeth Andrews, Eija Asmi, Kostas Eleftheriadis, Markus Fiebig, Andreas Herber, Lin Huang, Arve Kylling, Angelo Lupi, Andreas Massling, Mauro Mazzola, Jacob Klenø Nøjgaard, Olga Popovicheva, Bret Schichtel, Julia Schmale, Sangeeta Sharma, Henrik Skov, Kerstin Stebel, Brian Vasel, Vito Vitale, Cynthia Whaley, Karl Espen Yttri and Marco Zanatta

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Jennifer Balmer

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Zeppelin Observatory, Svalbard: Markus Fiebig / NILU

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Preface

This report presents the results of the *European Union Action on Black Carbon in the Arctic* (EUA-BCA) initiative's review of observation capacities and data availability for black carbon in the Arctic region.

The EUA-BCA is an initiative sponsored by the European Union to contribute to the development of collective responses to reduce black carbon emissions in the Arctic and to reinforce international cooperation to protect the Arctic environment. It provides and communicates knowledge about sources and emissions of black carbon and supports relevant international policy processes:

- Supporting processes aimed at setting clear commitments and/or targets for reducing black carbon emissions from major sources (gas flaring, domestic heating, transport, open burning and maritime shipping).
- Enhancing international cooperation on black carbon policy in the Arctic region – with a special focus on supporting the work of the Arctic Council and Convention on Long-range Transboundary Air Pollution and other national, regional and international initiatives, and building strong collaboration with EU strategic partners.

This technical report reviews the status of black carbon observing capacities and data availability. It focuses on ground-based monitoring sites operated under the UNECE's European Monitoring and Evaluation Programme (EMEP) and the Arctic Council's Arctic Monitoring and Assessment Programme (AMAP) as well as other monitoring networks, but also considers aircraft, ship, satellite-based and snow observations of black carbon. The report aims to identify gaps and proposes measures to fill these gaps. Results of this work will be communicated to relevant bodies under these and other international organizations engaged in work.

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Authors
Kjetil Tørseth, Markus Fiebig, Karl Espen Yttri, Kerstin Stebel, Arve Kylling (NILU – Norwegian Institute for Air Research, Norway), Marco Zanatta, Andreas Herber (Alfred Wegener Institute, Germany), Lin Huang, Sangeeta Sharma, Cynthia Whaley (Environment and Climate Change Canada (Canada), Mauro Mazzola, Vito Vitale, Angelo Lupi (Institute of Atmospheric Sciences and Climate, Italy), Elisabeth Andrews, Brian Vasel (National Oceanic and Atmospheric Administration, USA), Jacob Klenø Nøjgaard, Andreas Massling, Henrik Skov (Aarhus University, Department for Environmental Science, Denmark and iClimate, Aarhus University, Interdisciplinary Centre for Climate Change, Denmark), Kostas Eleftheriadis (Demokritos, Greece), Eija Asmi (Finnish Meteorological Institute, Finland), Olga Popovicheva (Moscow State University, Russia), Julia Schmale (Paul Scherrer Institute, Switzerland) and Bret Schichtel (Colorado State University, USA)

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Executive Summary

Measurements of black carbon (BC) in ambient air are essential for quantifying the atmospheric transport and effects of BC, as well as to follow changes in emissions over time. To meet these objectives, measurements need to be made with adequate spatial and temporal resolution, and with a data quality sufficient to ensure comparability between different sites and instruments. The present report reviews the availability of observational data in the Arctic region, focusing in particular on long-term temporal datasets from sites operated according to international quality assurance standards. Relevant BC data from short-term campaigns, including observations made from ship, aircraft, and satellite, as well as measurements in snow, are also reviewed.

There are few monitoring sites in the Arctic region. Only four sites Barrow (Alaska/USA), Alert (Canada), Summit (Greenland) and Zeppelin (Svalbard/Norway) currently have long-term (multi-decadal) time series for BC measurements. The sustainability of these endeavours, and other short-term BC research projects rely on the participation of engaged scientists and institutions, however, funding to sustain and improve these efforts is limited.

Additionally, there are large regions of the Arctic where no BC observations are made. The Russian part of the Arctic, in particular, is insufficiently monitored. It is extremely important to maintain the monitoring ongoing at existing sites, increase the number of sites to fill geographical gaps, and increase the number of sites with long-term data series.

Ideally, Arctic observatories should measure a wide range of chemical, physical, and optical aerosol properties, along with reactive and greenhouse gases. To improve the ability to elucidate and quantify sources and atmospheric transport of BC into, and within, the Arctic, it is recommended that isotopic measurements of elemental carbon (EC) and of organic carbon (OC) made by thermal or thermal-optical analysis be included in the suite of observations collected during monitoring efforts.

Monitoring data are generally open and available, however, this review demonstrated that historically, attention to data reporting has been inadequate, particularly prior to 2010. International programs coordinating monitoring in the Arctic should focus more attention to operational aspects of data reporting and quality assurance. A large number of improvements have been made in the databases of the World Meteorological Organization (WMO) Global Atmosphere Watch (GAW) Programme, European Monitoring and Evaluation Programme (EMEP) and Arctic Monitoring and Assessment Programme (AMAP). This includes correction of erroneous data, improved meta-data documentation, and improved functionality of the user interface to the observational database (EBAS). Such efforts are however limited by the resources available for this work.

Observations made from ship or aircraft, usually as a part of research monitoring campaigns, play a fundamental role in studying episodes of long-range transport of BC to the Arctic. A large number of such studies are reported in the scientific literature, including presentations of data and their interpretation, typically in combination with results of applied atmospheric transport models and/or use of satellite remote-sensing data.

Satellite-based observations cannot, with current capabilities, provide quantitative information of BC in air or snow, but are still valuable for studies on atmospheric transport of air pollution to the Arctic, and other climatic events and ecosystem impacts. Similarly, several analytical challenges currently exist in accurately quantifying BC in snow, and standardised methods for quality assurance are lacking. It is recommended that work be undertaken to refine and standardise analytical methods to improve measurement precision and comparability of BC observations in snow.

Access to data from research activities is best achieved by direct communication with individual research teams/institutions responsible for the studies. Required meta-data associated with such observations differ from those of fixed stations. Furthermore, comparability of data between studies and data-quality evaluation can be challenging, and long-term archiving is not always secured. Therefore, it is not currently recommended to include these data in the databases of GAW, EMEP or AMAP. However, to the extent possible, such data should be made more accessible. One option may be to store them in EBAS, or other open and/or searchable data archives. International data repositories do, however, exist for satellite remote sensing data.

1. Introduction

Carbonaceous aerosols have received considerable interest over the last few decades for their adverse impacts on air quality, human health and climate forcing. The combustion of fossil fuels and biomass forms a number of atmospheric pollutants such as ozone, carbon dioxide (CO_2), other reactive gases, and carbonaceous aerosols, including black carbon (BC). BC is typically a small fraction of the total carbonaceous aerosols produced during combustion but is distinguished by its strong absorption of visible light, making it largely responsible for the positive radiative forcing of aerosols.

Organised monitoring of light-absorbing carbon, or 'black smoke' began in Europe as early as the 1940s (BSI, 1969), however, the collection of high-precision BC measurements at remote and rural sites by international monitoring programs was not initiated until the late 1990s. Today, BC has been identified as a core measurement by the Global Atmosphere Watch (GAW) Program of the World Meteorological Organization (WMO). BC is included in the United Nations Economic Commission for Europe (UNECE) Convention on Long-Range Transboundary Air Pollution (CLRTAP) and the European Monitoring and Evaluation Program (EMEP). Additionally, the pan-European initiative 'Aerosol, Clouds and Trace Gases Research Infrastructure (ACTRIS)' has greatly improved the quality and accessibility of BC data in Europe.

These atmospheric observations, in combination with emission inventories and chemical transport models, have proven instrumental to the international research community for demonstrating how aerosols are transported over regional and continental spatial scales and identifying their role as short-lived climate forcers. Despite these advances, BC observations in the Arctic are still limited.

To this end, one of the objectives of the *European Union Action on Black Carbon in the Arctic* (EUA-BCA) initiative is to improve the knowledgebase necessary for understanding the impact of BC emissions on the Arctic. As part of this effort, this report reviews and updates the availability of atmospheric BC measurements at Arctic locations based on current databases, literature searches, and input from scientists active in BC research.

The present report provides an overview of the properties, standardised terminology, analytical instrumentation and methods used to define and measure BC, before reviewing the availability of BC data for the Arctic region. We primarily consider BC measurements collected by major international monitoring programs at the time of the EUA-BCA project initiation, however additional resources for Arctic BC data originating from institutional efforts, research projects, and short-term campaigns are also provided. We discuss geographical gaps and shortcomings (e.g. data with use limitations) to guide future improvements in data availability and usability for BC assessments in the Arctic.

It should be noted that during the preparation of this review, several opportunities for improvements in data reporting protocols and BC datasets were identified. This report describes the data availability at the time of the review, and in some cases, after corrective measures to the data have been made. However, some improvements are ongoing, and will continue following publication. Therefore, please refer directly to the data sources provided in this report for access to the most recent version of data.

2. Properties of black carbon and their implications for measurement and data reporting

2.1 Defining properties of black carbon

Although the term 'black carbon' is frequently used to refer to light-absorbing carbonaceous aerosols, in reality, atmospheric emissions consist of a highly variable mixture of carbonaceous compounds with different material properties that dictate their atmospheric behaviour and fate (Table 2.1). Furthermore, none of the currently available measurement methods quantify all five properties of BC simultaneously. As a result, reports of BC in the scientific literature can either refer to a specific property of a carbonaceous aerosol or to the method that is used for the measurement, resulting in the use of numerous terms such as 'soot', 'elemental carbon', 'equivalent black carbon', and 'refractory black carbon' that lack strict definitions and can complicate cross-comparisons of datasets.

2.2 Analytical methods

The terms often used to characterise black carbon aerosol particles are primarily associated with their corresponding analytical methods and the properties they measure (Table 2.2). The various methods available for measuring BC have been reviewed previously (Petzold et al., 2013; Lack et al., 2014) and are only briefly mentioned here.

Thermal analysis techniques, including thermal-optical analysis, are the principal methods for measuring the carbon content associated with atmospheric soot. These methods are based on the analysis of gasification products evolving from a heated filter sample and mainly rely on changes in the optical behaviour of carbon in particulate matter (PM) to indicate when elemental carbon (EC) separates thermally from organic carbon (OC) in the sample.

Light absorption methods have been used extensively to measure the light-absorbing fraction of carbonaceous aerosols in the form of an aerosol light absorption coefficient (AAC). Filter absorption photometry employs filters loaded with atmospheric particle samples to measure absorption, and the intensity of light measured before and after passing through a filter loaded with particles is used to derive the AAC. In contrast, photoacoustic photometry measures the acoustic pressure generated by the rapid transference of absorbed optical energy into the surrounding air and a microphone captures the resulting signal, which is proportional to the AAC. The AAC can be converted into a mass of equivalent black carbon (eBC) using a mass absorption coefficient (MAC), which can vary widely among air masses and their sources.

Laser-induced incandescence methods use lasers to subject light-absorbing particles to intense radiation and temperatures. At high temperatures, the particles emit radiation that can be detected and used to derive the mass of the illuminated particles. The resulting carbon mass is referred to as refractory black carbon (rBC) since it is derived by measuring the thermal emission from the carbon component of the particle that absorbs the laser energy.

2.3 Recommended terminology

Until recently, there has been no agreement on clear and unambiguous definitions for carbonaceous aerosols that consider all aspects of their material properties and measurement methods. To address this issue, Petzold et al. (2013) published recommended terminology to describe observations of atmospheric aerosols and their light-absorbing properties. The proposed terminology, developed by the WMO-

Table 2.1. Properties defining black carbon and their consequences for effects and removal (Petzold et al., 2013).

Property	Characteristics	Consequences
Microstructure	Graphite-like structure containing a large fraction of sp^2-bonded carbon atoms.	Low chemical reactivity in the atmosphere; slow removal by chemical processes; strong optical absorption.
Morphology	Fractal-like chain aggregates consisting of small carbon spherules of <10 nm to approximately 50 nm in diameter; fractal dimension ranges from ≤2.0 for fresh combustion particles to ≅3.0 for aged aerosol; specific surface area typically larger than 10 m^2/g and may exceed 100 m^2/g.	High capacity for sorption of other species.
Thermal stability	Refractory material with a volatilization temperature near 4000 K; gasification is possible only by oxidation, which starts at temperature above 340°C.	High stability in the atmosphere; longer atmospheric residence time.
Solubility	Insoluble in any solvent including water.	Slow removal by clouds and precipitation, unless coated with water-soluble compounds; longer atmospheric residence time.
Light absorption	Strong light absorption in the spectral range of visible light with mass-specific absorption coefficient typically greater than 5 m^2/g (at λ=550 nm) for freshly produced particles; weak wavelength dependence of light absorption with absorption Ångström exponent typically 1.0–1.5; characterised by a significant, nonzero and wavelength-independent imaginary part of the refractive index over the visible and near-visible spectral regions.	Reduction of the albedo of clouds, snow, and ice; atmospheric heating; surface cooling – all of which lead to effects on solar radiation and climate.

Table 2.2. Black carbon (BC) analytical methods and recommended terminology for reported values adapted from Petzold et al., 2013.

Monitoring Type[1]	BC Property Measured	Reported Value	Analytical Method	Instrumentation	Vendors
Offline	Carbon content	Elemental carbon (EC) Organic carbon (OC)	Thermal or Thermal-optical	Lab OC-EC Aerosol Analyzer	Sunset Laboratory Inc.
				Multi-Wavelength Thermal/ Optical Carbon Analyzer	Magee Scientific
Online	Light absorption	Aerosol absorption coefficient (AAC) Equivalent black carbon (eBC)	Filter Absorption Photometry	Aethalometer (AE)	Magee Scientific
				Multi-angle Absorption Photometers (MAAP)	Thermo Scientific Inc.
				Particle Soot Absorption Photometer (PSAP)	Radiance Research
				Continuous Light Absorption Photometer (CLAP)[2]	National Oceanic and Atmospheric Administration (NOAA)
	Light absorption	Aerosol absorption coefficient (AAC)	Photoacoustic Photometry	Photo-Acoustic Soot Spectrometer (PASS)	Droplet Measurement Technologies
	Refraction	Refractory black carbon (rBC)	Laser-induced Incandescence (LII)	Single Particle Soot Photometer (SP2)	Droplet Measurement Technologies
				Soot Particle-Aerosol Mass Spectrometer (SP-AMS)	Aerodyne Inc.
				Pulsed-shot LII	Artium Inc.

[1] Offline monitoring involves on-site sampling followed by laboratory analysis; online monitoring provides real-time measurements
[2] Functionally equivalent to PSAP

GAW Scientific Advisory Group on Aerosols, has found general approval by the scientific community, and is used in most internationally-organised efforts to measure regional- and global-scale atmospheric properties. An ongoing European Metrology Programme for Innovation and Research project (no. 16ENV02) continues to address metrology related to BC measurements (www.empirblackcarbon.com).

We repeat here and in Table 2.2 some specific highlights and recommendations given by Petzold et al. (2013), being of relevance for this EUA-BCA review:

- **Total carbon mass is used to describe the mass of all carbonaceous matter in airborne particles.** Total carbon mass is a well-defined property that can be measured with precision better than 10% by evolved carbon methods.
- **Black carbon (BC) is a useful qualitative description when referring to light-absorbing carbonaceous substances in atmospheric aerosol; however, for quantitative applications the term requires clarification of the underlying determination.** In the absence of a method for uniquely determining the mass of BC, the authors recommend that the term 'BC' should be used as a qualitative and descriptive term when referring generally to material that shares some of the characteristics of BC (Table 2.1), in particular its carbonaceous composition combined with its light-absorbing properties. 'BC' is already used this way in atmospheric modelling and assessment studies. For quantitative applications like reporting data from observations or building inventories, we suggest using more specific terminology that refers to the particular measurement method as defined in the following. One strong recommendation, however, is to avoid using the term 'BC' for evolved carbon methods.
- **Equivalent black carbon (eBC) should be used instead of black carbon for data derived from optical absorption methods, together with a suitable mass-specific absorption cross section (MAC) for the conversion of light absorption coefficient into mass concentration.** In the absence of a standard reference material, it is recommended to report such measurements as aerosol light absorption coefficient (AAC), thus avoiding the additional uncertainty introduced by assuming a MAC value. When reporting eBC, i.e. mass concentration, it is crucial to identify the MAC value used for the conversion and to specify the approach used for separating potential contributions of brown carbon or mineral dust to the AAC.
- **Elemental carbon (EC) should be used instead of black carbon for data derived from methods that are specific to the carbon content of carbonaceous matter.** It is recommended to report data from evolved carbon methods and aerosol mass spectrometry methods as EC.
- **Refractory black carbon (rBC) should be used instead of black carbon for measurements derived from incandescence methods.** For methods based on laser-induced incandescence, like LII, SP2, and SP-AMS, it is recommended to report data as rBC, since these methods mainly address the thermal stability of the carbonaceous matter and require light-absorbing efficiency of the analysed particulate matter.
- **Soot is a useful qualitative description when referring to carbonaceous particles formed from incomplete combustion.** The term soot generally refers to the source mechanism of incomplete combustion of hydrocarbon fuels rather than to a material property. It is widely used in research on the formation of carbonaceous particles in combustion processes, and on the emission of particulate

matter from combustion sources as well as in the field of particulate matter-related health effects. Thus, terming particles emitted from a combustion source as soot particles is in agreement with the recommended terminology.

- **Mixed particles containing a BC fraction should be termed BC-containing particles instead of BC particles or soot particles.** Since atmospheric research usually addresses mixed and aged particles that can no longer be associated with any combustion source process, the recommendation is to avoid using the terms soot or BC particle for atmospheric aerosol. It is also recommended to refer to the BC components of individual particles as the BC cores without any confusion about non-BC mass either internally or externally mixed with the BC. Reported BC fractions of particle mass should be consistently referred to as rBC, EC, or eBC fractions, depending on the measurement technique.

2.4 Implications for data reporting and comparisons

Data on light-absorbing carbonaceous aerosols can be collected using various protocols and instrumentation (Table 2.2), however, the choice of methodology may influence measurement results in unique ways. For example, Particle Soot Absorption Photometers (PSAPs), Multi-angle Absorption Photometers (MAAP), and Aethalometers (AE) all provide AAC measurements, but differ in the way they account for absorption and scattering (Zanatta et al., 2016). Likewise, EC measurements obtained by thermal or thermal-optical methods can differ by as much as a factor of two (Cavalli et al., 2010). Moreover, differences in analytical methodologies (e.g. AAC versus EC measurements, or use of the National Institute for Occupational Safety and Health (NIOSH) 5040 method versus the European Supersites for Atmospheric Aerosol Research (EUSAAR) 2 method) will have a profound impact on measurement results (Cavalli et al., 2016). Furthermore, the added use of size-selective inlets produces BC measurements based on specific aerosol particle sizes (typically 1 μm, 2.5 μm, or 10 μm size fractions).

The variability imparted by differences in methodology presents a challenge for research initiatives and emission inventories that rely on standardised datasets in order to provide accurate analyses. Thus, it is fundamentally important to be able to distinguish between datasets that are, and are not, directly comparable; in other words, it is critical to select measurements collected with the same method and operating procedures. Comprehensive metadata that describes data collection methods needs to accompany datasets so that any differences are apparent to the data user. In this regard, older time series that are often missing metadata related to instrumentation, data processing, and quality assurance, can be difficult to interpret with confidence.

In line with the definitions set forth by Petzold et al. (2013), this report reviews the availability of Arctic datasets reporting equivalent black carbon (eBC), aerosol absorption coefficient (AAC), and elemental carbon (EC) measurements, which are highly complementary measurements, but not directly comparable. Measurements of refractory black carbon (rBC) have not been found at any of the Arctic sites, probably due to the high maintenance requirements making this method less suitable. Special attention was paid to verifying the comparability of datasets using associated metadata. Additionally, as a result of this work, improvements were made to the metadata of the BC datasets submitted to EBAS, thus ensuring their future usefulness and functionality.

3. Sources of black carbon observations in the Arctic

Several types of observations are of interest when studying the atmospheric transport and temporal trends of BC emissions. Here we mainly focus on high-precision, long-term measurements made in air from remote monitoring sites that offer consistent data collection in space and time (years-to-decades). Although not the primary focus of this assessment, data collected over shorter durations, or with less attention on traceability to recommended standards, are also important. Measurements from shorter duration campaigns utilizing aircraft- or ship-based instrumentation or stand-alone research projects, can offer data useful for case studies, model development, and model validation. This report primarily reviews long-term BC measurements made at Arctic sites, but highlights aircraft-, ship-, and satellite-based observations and measurements in snow where deemed relevant. This report has not considered any measurements of emission fluxes.

Atmospheric observational data for BC are generally openly accessible to allow public access to synoptic-scale information on meteorology and atmospheric composition data for transport studies. Several international conventions (WMO and CLRTAP) have established international data centers to collect and disseminate data to users and in doing so, formed the basis for open-access and fair-use data policies. Associated monitoring programs also define data quality criteria and aim to harmonise observations to the extent possible. Through establishing reporting requirements and obligations, international monitoring programs are vital in securing long-term observations. The resulting data are used in many applications including prediction modeling and effectiveness evaluation under international agreements and are used to determine future monitoring and research needs.

The Norwegian Institute for Air Research (NILU) hosts the data centers of all major international monitoring programs addressing atmospheric BC in the Arctic, including but not limited to EMEP, WMO-GAW, ACTRIS, and the Arctic Monitoring and Assessment Programme (AMAP). These data are stored in a relational database named EBAS (http://ebas.nilu.no). EBAS datasets, including time series, can be affiliated with multiple official frameworks used to define reporting compliance, data-use policies, and acknowledgments, among other requirements. In the present report, no particular focus has been given to the formal affiliations of the data; rather, this report focuses on the data and time series available for individual Arctic observatories and sites. Data users should, however, take issues of data ownership and origin into consideration and ensure proper acknowledgment and use as defined by specific data policies. This information accompanies data upon its export or download from the EBAS database.

Data collected from empirical, hypothesis-driven research activities are typically more dynamic than those collected for monitoring purposes, and will often focus on specific research questions, such as understanding the influence of local-scale processes and interactions on atmospheric composition and transport. Airborne- or ship-based sensors and instrumentation, and most recently, unmanned aerial systems (UAS), yield short-term observations that are quite different in their representation and scope than the long-term time series data collected from stationary monitoring sites. Due to the individual project-based nature of such empirical research, data are generally less accessible, as compared to the network-based monitoring described above. Research data are typically held by the individual research teams or by their institutions in internal data repositories. These data are mainly accessible through personal contact and networking, rather than web-based portals. Further, such measurements do not always comply with quality assurance and quality control (QA/QC) standards employed by the international monitoring programs, and therefore, may not be directly comparable to datasets obtained from long-term monitoring efforts.

This review primarily considers BC measurements from relevant databases of internationally-coordinated monitoring programs (EMEP, WMO-GAW, AMAP). Data originating from research projects and campaigns were obtained through contact with individual scientists and institutions (after literature searches or through networking) to collect additional (but not necessarily comprehensive) information about Arctic BC data from independent research initiatives.

The goal is to provide a simplified overview of datasets that can serve as a basis for proposing technically-feasible actions to improve the availability of BC data and metadata in the Arctic region.

4. Availability of black carbon observations in air at Arctic monitoring sites

Following the discovery of Arctic haze as a seasonal atmospheric pollution phenomenon originating from the industrialised South in the 1970s, long-term observatories were established throughout the Arctic region. Core monitoring sites (listed from west to east) include Barrow (Alaska, USA), Alert (Canada), Summit (Greenland, Denmark), Villum Research Station at Station Nord (Greenland, Denmark), Zeppelin at Ny-Ålesund (Svalbard, Norway), Pallas (Finland), and Tiksi (Russia) (Figure 4.1). Periodical observations are also performed at a recently built research station, Ice Base Cape Baranova (Severnaya Zemlya archipelago, Russia). In addition, there are observatories at lower latitudes, such as Kevo and Oulanka in Northern Scandinavia, and in Alaska, USA. Mid- and low-latitude sites are important for research investigating the atmospheric transport of pollutants from southern regions to the Arctic, but these are not discussed in the present report.

Here we primarily review the availability of BC measurements, time-series, and data gaps from the EBAS database, which hosts Arctic BC data for the major international programmes (EMEP, WMO-GAW, ACTRIS, AMAP). Where noted, other data sources, including national databases, research projects, and publications are also considered. Data availability is reviewed by site, sequentially by country (west to east), and alphabetically.

It should be noted that during the preparation of this review, several improvements with respect to the EBAS web interface and data reporting protocols were made, including the addition of an 'instrument reference' category in the EBAS search and display section, omission of erroneous datasets, updated metadata, and further provisioning of Level 1.5 data which is used in quality assurance and Real-Real-Time data processing (i.e. delivery of data with less than a three-hour delay). However, please note that Level 2 data are the primary focus of this report as these data are typically the most relevant for end-users, (see also: https://ebas-submit.nilu.no/Submit-Data/Data-Reporting/Comments/Modules/data-level-description).

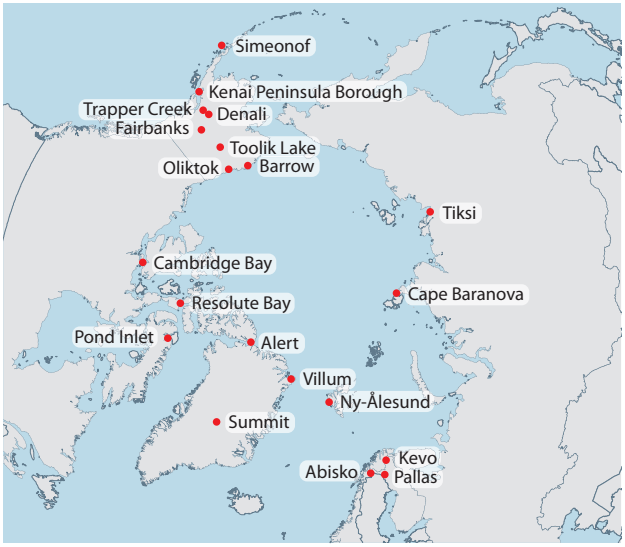

Figure 4.1. Location of Arctic sites where BC measurements have been undertaken, including long-term monitoring observatories.

Some of these corrections are described herein, while other anticipated changes are still pending. A major resubmission of data is expected in relation to a series of papers planned before the next Intergovernmental Panel on Climate Change (IPCC) deadline in 2019.

4.1 Barrow, Alaska (USA)

The longest time series of BC measurements come from an observatory at Barrow, AK operated by the National Oceanic and Atmospheric Administration (NOAA) (Table 4.1, Figure 4.2). Early measurements of eBC from AE deployments have been described by Bodhaine et al. (1989) and Bodhaine (1995). Updated descriptions with

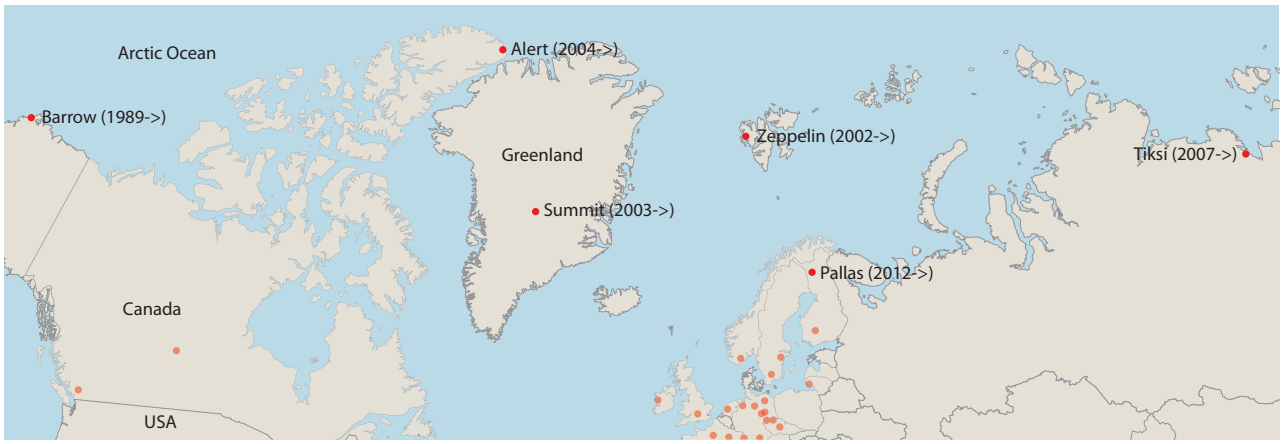

Figure 4.2. Locations and collection start dates of aerosol absorption coefficient (AAC) time series from the WMO-GAW, EMEP, and AMAP at the start of the EUA-BCA project. As shown, of the Arctic stations only Barrow, Alaska had reported data to the EBAS database prior to 2002.

Table 4.1. Overview of available time series for aerosol absorption coefficient (AAC) and elemental carbon (EC) measurements for individual stations identified in this review. Key: 0=no data, 1=data from publication or originator, 2=data from international database (WMO-GAW, EMEP, ACTRIS, or AMAP).

		1965-1987	1988	1989	1990	1991	1992	1993	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Barrow (US)	AAC	0	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Barrow (US)	EC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	0	0	0	0	0
Fairbanks (US)	AAC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fairbanks (US)	EC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oliktok (US)	AAC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	
Oliktok (US)	EC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Alert (CA)	AAC	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Alert (CA)	EC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2	2	2	2	2	2	2	2	1	1	1
Alert (CA)	13C of EC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	1	1	1	1	1	1	1	1	1	1	1	0	0	0
Alert (CA)	14C of EC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0	0
Cambridge Bay (CA)	AAC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0
Cambridge Bay (CA)	EC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Pond Inlet (CA)	AAC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1
Pond Inlet (CA)	EC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Resolute Bay (CA)	AAC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0
Resolute Bay (CA)	EC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Summit (DK)	AAC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Summit (DK)	EC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
Villum (DK)	AAC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	1	0	1	1
Villum (DK)	EC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1
Ny-Ålesund, Gruvebadet, CNR (NO)	AAC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1
Ny-Ålesund, Gruvebadet, CNR (NO)	EC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1
Ny-Ålesund, Gruvebadet, India Station (NO)	AAC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0
Ny-Ålesund, Gruvebadet, India Station (NO)	EC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ny-Ålesund, Zeppelin (NO)	AAC	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Ny-Ålesund, Zeppelin (NO)	EC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1
Abisko (SE)	AAC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Abisko (SE)	EC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0	0	0	0
Kevo (FI)	AAC	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
Kevo (FI)	EC	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0
PALLAS (FI)	AAC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2	2	2	2
PALLAS (FI)	EC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	2	2	2	2	2
Cape Baranova (RU)	AAC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1
Cape Baranova (RU)	EC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	0	0
Tiksi (RU)	AAC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	2	0	2	2	2	2	2	2	2	2	2	2	2
Tiksi (RU)	EC	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	0	0

Table 4.2. Black carbon time series available for Barrow, Alaska in EBAS as of June 2019.

Matrix[1]	BC reported value[2]	Instrument type[3]	Instrument reference	Start date	End date
aerosol	eBC	AE	US06L_Magee_AE8_BRW	01/01/1991	01/01/2002
aerosol	eBC/AAC	AE	US06L_Magee_AE31_BRW	01/01/2010	01/01/2015
pm1	AAC	PSAP	US06L_RadianceResearch_PSAP-1W_BRW_pm1	06/10/1997	12/08/2006
pm1	AAC	PSAP	US06L_RadianceResearch_PSAP-3W_BRW_pm1	12/08/2006	15/08/2014
pm1	AAC	CLAP	US06L_GMD_CLAP-3W_BRW_pm1	21/08/2014	01/01/2019
pm10	AAC	PSAP	US06L_RadianceResearch_PSAP-1W_BRW_pm10	06/10/1997	12/08/2006
pm10	AAC	PSAP	US06L_RadianceResearch_PSAP-3W_BRW_pm10	01/01/2007	15/08/2014
pm10	AAC	CLAP	US06L_GMD_CLAP-3W_BRW_pm10	21/08/2014	01/01/2019

[1] aerosol=total aerosol particle phase; pm1=aerosol particle phase in the size fraction less than 1 micrometer mean aerodynamic diameter; pm10=aerosol particle phase in the size fraction less than 10 micrometers mean aerodynamic diameter
[2] AAC: aerosol absorption coefficient; eBC: equivalent black carbon
[3] AE: Aethalometer; CLAP: Continuous Light Absorption Photometer; PSAP: Particle Soot Absorption Photometer

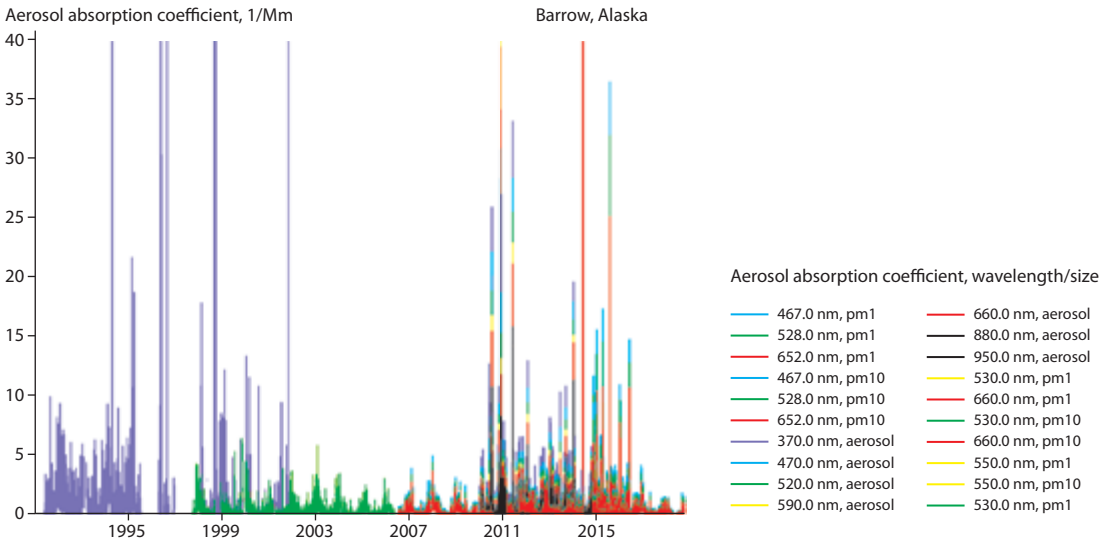

Figure 4.3. Time series of aerosol absorption coefficient (AAC) Level 2 EBAS data from Barrow, Alaska as of June 2019.

newer instruments have also been published (Delene and Ogren, 2002; Eckhardt et al., 2015; Sharma et al., 2004, 2006, 2013; AMAP 2015; Sinha et al., 2017; Schmeisser et al., 2018).

Long-term AAC measurements for Barrow, Alaska from 1991 to the end of 2018 are available in the EBAS database (Table 4.2; Figure 4.3). Details on the measurement instruments in use have been provided by NOAA (Table 4.3). Deviations between the instrument metadata listed in Tables 4.2 and 4.3 are still being investigated, and are expected to be fully resolved at a later stage.

In contrast, there are no long-term EC measurements at Barrow. EC measurements for the period July 2012 to June 2013 are reported in recent papers by Winiger et al. (2019) and Barrett et al. (2017), where the NIOSH 5040 method (NIOSH, 2003) was used to analyse $PM_{2.5}$ aerosol filter samples collected in a high-volume sampler. See also Barrett et al. (2015) for a subset of these samples for the winter 2012/2013.

The review conducted here revealed some issues with the data contained in EBAS such as fragmentation of time series, data gaps, and duplications (i.e. several versions of the same data). Also, some time series which had been previously submitted were found to be missing from EBAS. This sparked a major revision in collaboration with the data submitter (NOAA) that was still ongoing as of early 2019.

These data are also directly available from NOAA at:

https://data.nodc.noaa.gov/cgi-bin/iso?id=gov.noaa.ncdc:C01539 and

https://www.esrl.noaa.gov/gmd/dv/data/index.php?category=aerosols

4.2 Fairbanks, Alaska (USA)

Long-term measurements of eBC, organic aerosol, and sulphate, have been collected from Fairbanks, Alaska. Data are available from William Simpson at the University of Alaska, Fairbanks. Further details are missing at the time of preparing this report.

4.3 Oliktok, Alaska (USA)

Oliktok is a military airstrip 264 kilometres (km) NE of Barrow, Alaska. Starting in August 2016, measurements of AAC by PSAP have been undertaken by the U.S. Department of Energy and are available at: https://www.archive.arm.gov/discovery.

Table 4.3. Overview of measurement instruments in use at Barrow, Alaska. Information provided by NOAA.

Instrument[1]	Wavelengths	Sizecut	Coverage
AE8	broadband wavelength	Total	24/03/1988–26/05/1991
AE16	1 wavelength (880 nm)	Total	26/05/1991–10/12/2001
AE31	7 wavelengths (370, 470, 520, 590, 660, 880 and 950 nm)	Total	18/02/2010–19/08/2016
AE33	7 wavelengths (370, 470, 520, 590, 660, 880 and 950 nm)	Total	15/08/2014–present
PSAP	1 wavelength (565 nm)[2]	1 µm/10 µm	06/10/1997–12/08/2006
PSAP	3 wavelengths (467, 530 and 660 nm)	1 µm/10 µm	12/08/2006–21/08/2014
CLAP	3 wavelengths (467, 528 and 652 nm)	1 µm/10 µm	30/08/2011–present

[1] AE: Aethalometer; CLAP: Continuous Light Absorption Photometer; PSAP: Particle Soot Absorption Photometer
[2] Reported at 550 nm due to Bond et al. (1999) correction

4.4 IMPROVE Monitoring Network, Alaska (USA)

The Interagency Monitoring of Protected Visual Environments (IMPROVE) monitoring network has collected 24-hour $PM_{2.5}$ and PM_{10} samples at three-day intervals since 1988. Monitoring sites are located primarily in rural areas throughout the United States, and over the lifetime of the network, have included nine sites in Alaska, five of which continue to collect samples today (Table 4.4). The $PM_{2.5}$ samples are analysed for aerosol composition by the thermal-optical-reflectance (TOR) method (Chow et al., 2004) to measure organic and light-absorbing carbon. In 1994, the hybrid integrating plate (HIPS) measurement was introduced to measure the transmittance and reflectance of the filter sample at a wavelength of 633 nm, from which the sample absorption is derived (White et al., 2016). The HIPS calibration methodology was modified for the data post-2003 and caution should be used when merging pre- and post-2003 data (White et al., 2016). More information about the IMPROVE monitoring network and access to the data are available at: http://vista.cira.colostate.edu/Improve. For further information about the IMPROVE observations, please contact Bret Schichtel (Bret.Schichtel@colostate.edu).

Table 4.4. List of Interagency Monitoring of Protected Visual Environments (IMPROVE) monitoring sites throughout Alaska, USA and their dates of operation.

Site	Start date	End date
Ambler	26/06/2004	27/09/2004
Denali National Park	02/03/1988	ongoing
Gates of the Arctic National Park	05/11/2008	15/10/2015
Kenai Peninsula Borough	19/08/2015	ongoing
Petersburg	02/07/2004	25/09/2009
Simeonof	31/10/2001	ongoing
Toolik Lake Field Station	08/11/2018	ongoing
Trapper Creek	13/09/2001	ongoing
Tuxedni	21/12/2001	19/12/2014

4.5 Alert (Canada)

Data in EBAS extend back to 1989 for light absorption measurements made by AE, and back to 2004 for measurements by PSAP (Tables 4.5 and 4.6). During the period 1989–2009, observations were made using an AE6 model (Magee Scientific), which calculates eBC concentrations from filter attenuation measurements using a broadband 'white light' source, with a spectrum centred at 880 nm (i.e. not specific spectral wavelengths). From 2009 and onwards, an AE31 model was used. However, there is no agreed upon method to convert the eBC data from the AE6 model to the AAC data from the AE31 model. Discussions with Environment and Climate Change Canada (ECCC) and the WMO GAW World Calibration Centre on Aerosol Physics (WCCAP) have been initiated to decide how time series dating back to the late 1980s can best be represented in EBAS. Following these discussions, the time series will be updated. Additionally, the time series submitted by Alert in the 1990s were found to contain errors that will be corrected as part of the review.

The current agreement between ECCC, WCCAP, and the World Data Centre for Aerosols (WDCA) regarding the submission of AE6 data is to use an AE31 Level 0 template to submit the initial eBC data from the AE6 instrument output. In Level 1, the EBAS team will convert the eBC data into

Table 4.5. Black carbon time series available for Alert, Canada in EBAS as of June 2019. A full revision of the data is ongoing, and thus no time series plots are shown here. AE6 data extending back to 1989 is currently in the process of being entered into EBAS and therefore is not listed.

Matrix[1]	BC reported value[2]	Instrument type[3]	Instrument reference	Start date	End date
aerosol	AAC	PSAP	CA01L_Radiance-Research_PSAP-3W_ALT	01/01/2004	18/03/2004
aerosol	AAC	PSAP	CA01L_Radiance-Research_PSAP-1W_ALT	18/03/2004	29/07/2005
aerosol	eBC/AAC	AE	CA01L_Magee_AE31_ALT	01/01/2009	01/01/2016
aerosol	eBC/AAC	AE	CA01L_Magee_AE31_ALT	01/01/2016	01/01/2018
pm1	AAC	PSAP	CA01L_Radiance-Research_PSAP-3W_ALT_pm1	11/07/2007	28/03/2017
pm1	AAC	PSAP	CA01L_Radiance-Research_PSAP-3W_ALT	11/07/2007	01/01/2008
pm1	AAC	PSAP	CA01L_Radiance-Research_PSAP-1W_ALT	31/03/2005	11/07/2007
pm1	AAC	PSAP	CA01L_Radiance-Research_PSAP-1W_ALT_pm1	31/03/2005	11/07/2007
pm1	AAC	CLAP	CA01L_GMD_CLAP-3W_ALT_pm1	28/03/2017	01/01/2018
pm10	AAC	PSAP	CA01L_Radiance-Research_PSAP-3W_ALT	11/07/2007	01/01/2008
pm10	AAC	PSAP	CA01L_Radiance-Research_PSAP-3W_ALT_pm10	11/07/2007	28/03/2017
pm10	AAC	PSAP	CA01L_Radiance-Research_PSAP-1W_ALT	31/03/2005	11/07/2007
pm10	AAC	PSAP	CA01L_Radiance-Research_PSAP-1W_ALT_pm10	31/03/2005	01/01/2007
pm10	AAC	CLAP	CA01L_GMD_CLAP-3W_ALT_pm10	28/03/2017	01/01/2018

[1] aerosol: total aerosol particle phase; pm1: aerosol particle phase in the size fraction less than 1 micrometer mean aerodynamic diameter; pm10: aerosol particle phase in the size fraction less than 10 micrometers mean aerodynamic diameter
[2] AAC: aerosol absorption coefficient; eBC: equivalent black carbon
[3] AE: Aethalometer; CLAP: Continuous Light Absorption Photometer; PSAP: Particle Soot Absorption Photometer

Table 4.6. Overview of measurement instruments in use at Alert, Canada. Information provided by Environment and Climate Change Canada (ECCC).

Instrument[1]	Wavelengths	Coverage[2]
PSAP	1 wavelength	18/03/2004–31/03/2005
AE6	1 wavelength	1/05/1989–31/12/2008
AE31	7 wavelength	27/04/2008–present
PSAP	1 wavelength	11/07/2007 (pm1 and pm10)
PSAP	3 wavelengths	11/07/2007–28/03/2017 (pm1 and pm10)
CLAP	3 wavelengths	29/08/2014–present (pm1 and pm10)

[1] AE: Aethalometer; CLAP: Continuous Light Absorption Photometer; PSAP: Particle Soot Absorption Photometer
[2] pm1: aerosol particle phase in the size fraction less than 1 micrometer mean aerodynamic diameter; pm10: aerosol particle phase in the size fraction less than 10 micrometers mean aerodynamic diameter

broadband AAC values using a MAC of 19 m^2/g and a filter loading correction factor of 3.5, which is the same for the AE6 and AE31. Level 2 data will be averaged to hourly values.

eBC time series from Alert appear in several publications covering various timespans, with the longest covering the period 1989–2012 (Stone et al., 2014; Sharma et al., 2002, 2004, 2006, 2013, 2017; Eckhardt et al., 2015; AMAP, 2015).

The deviations between the instrument metadata in Table 4.6 are still being investigated, and are expected to be fully resolved at a later stage.

EC measurements at Alert date back to October 2006 and are part of the long-term Canadian Aerosol Baseline Measurements (CABM) carried out by the Climate Chemistry Measurement and Research section in the Climate Research Division of ECCC in Toronto.

Prior to 2011, aerosol filter samples were collected downstream of a TSP (total suspended particles) inlet; after 2011 the aerosol cut-off size was changed to 1 µm. Weekly integrated aerosol filter samples are analysed according to the EnCan-total-900 method (e.g. Huang et al., 2006; Chan et al., 2019), which uses a thermal-only method, unlike that of the thermal-optical methods specified by IMPROVE, NIOSH 5040, and EUSAAR-2 protocols. EnCan-total-900 was originally developed for performing carbon isotope analysis on carbonaceous aerosol fractions, and thus provides both EC and corresponding carbon isotope measurements, which can be used for source apportionment of BC. Many Arctic observatories, including Alert, collect a wide suite of measurements which can be used for improved understanding of EC and aerosol sources.

An intercomparison study including EnCan-total-900 and two of the most commonly used thermal-optical programs (IMPROVE and EUSAAR-2) was submitted for publication, but not accepted; results are still available online (Karanisou et al., 2015). Additionally, the results of a long-term intercomparison study on EC and OC measurements determined by three national aerosol networks (IMPROVE, CABM, and the Canadian Air and Precipitation Monitoring Network) for a co-located site operated by ECCC were recently published (Chan et al., 2019). IMPROVE or IMPROVE-A protocols were used by the first two networks, whereas EnCan-total-900 was used by the third network. The results indicated that although there are systematic differences among the EC datasets collected by different protocols over decadal time periods, the results are highly correlated. This suggests that as long as the stability and traceability of individual instruments are ensured via calibration and rigorous QA/QC processes, individual datasets collected by different networks could provide consistent, and similar trends. However, the sampling frequency, blank corrections, and temperature protocols may still introduce differences.

The EC time series for Alert has been available in the EBAS database since July 2019, although it has not been published in its entirety. Instead, various subsets of the data have been published by different researchers. For example, Sharma et al. (2017) reported EC measurements collected at Alert over the period March 2011–December 2013, while Leaitch et al. (2018) reported EC values for the period April 2012–October 2014, and Leaitch et al. (2013) provided mean seasonal EC data for the period 2005–2010. Eckhardt et al. (2015) used EC data from 2008–2009 to validate model capabilities for simulating black carbon concentrations in the Arctic atmosphere. A trend in the annual mean of EC at Alert was included in a presentation in the IPCC Expert Meeting on Short Lived Climate Forcers in Geneva (https://www.ipcc.ch/site/assets/uploads/2019/02/31_Huang.pdf) Currently, the EC time series at Alert is being intensively used for model-observation intercomparisons in AMAP and Coupled Model Intercomparison Project Phase 6 (CMIP6) activities.

Long-term isotopic measurements of EC (and OC) can provide valuable information for tracking changes in BC source apportionment, an important discernment as both gas flaring and biomass burning are sources of BC transported to the Arctic region. It is known that carbon-13 (^{13}C) can be used to distinguish EC emitted by gas flaring from that of transportation-related diesel and gasoline combustions. Similarly, carbon-14 (^{14}C) can be used to distinguish EC originating from the burning of biomass and fossil fuels. Starting in 2003, $\delta^{13}C$ has been measured in EC from Alert, and the trend from 2003–2015 reveals changes in emission sources. Since 2014, $\delta^{14}C$ of EC has been measured as a complementary project to enhance source apportionment work. Both ^{13}C and ^{14}C measurements were carried out by an OC/EC separation using EnCan-total-900 thermal protocol, followed by Isotope Ratio Mass Spectrometry or Accelerator Mass Spectrometry analysis. These data will also be used to constrain the emission inventories via validating the climate model simulations in AMAP or CMIP6 activities.

Monthly snow samples were also collected at Alert for the period of October–May, since 2014. EC concentrations were measured using the same thermal method used for air filter EC analysis (the melt snow water was first filtrated through quartz filters and the dried filters were analysed for EC via EnCan-total-900). The filtration recovery rate has been evaluated via a BC standard (i.e. Regal Black for SP2 instrumentation), as well as via isotope analysis. A portion of snow samples have also been analysed for carbon isotopes for source apportionment.

4.6 Cambridge Bay, Nunavut (Canada)

An AE (Model AE22) was used during 2016 and 2017 (https://kpdc.kopri.re.kr/search/5a2d063d-2f5a-4108-80d8-96ccf47638d0). The responsible institution was the Korean Institute for Polar Research. Additional details are missing at

the time of writing this report. For further information please contact Young Jun Yoon (yjyoon@kopri.re.kr).

4.7 Pond Inlet (Canada)

The Resolute Bay instruments (see below) are now at Pond Inlet. The instruments were moved in July 2018, and data are not yet fully processed.

4.8 Resolute Bay (Canada)

Resolute Bay is a Canadian site influenced by local pollution from shipping and the town itself, including garbage burning activities and an operational power plant. Aerosol light absorption and scattering measurements were made from 2013–2015. Several manuscripts have been written on these data (Aliabadi et al. 2015; 2016) but they utilise very different approaches to estimate the influence of ship emissions on BC, including ship locations and back-trajectories.

4.9 Summit, Greenland (Denmark)

Aerosol absorption coefficient data at Summit Greenland are available in EBAS from 2003 onward (Table 4.7). Aerosol measurements made by AE were cited by Stohl et al. (2006), and those made by CLAP were described by Schmeisser et al. (2018). There are no long-term measurements of EC at Summit station, however a single short-term study spanning one summer, May–July 2006, is available (Hagler et al., 2007). These data are also directly available from NOAA.

Table 4.8 lists the instrument reference information in EBAS. Deviations between instrument metadata are still being investigated, and are expected to be fully resolved at a later stage. There are also some issues related to the time series in EBAS and several updates are in progress, therefore, time series plots are not shown.

4.10 Villum Research Station at Station Nord, Greenland (Denmark)

Villum Research Station in Greenland is actively reporting its data to AMAP and EMEP with respect to general air pollutants, persistent organic pollutants, and heavy metals, however, advanced aerosol observations, including BC properties, have not been reported thus far. An invitation was thus sent to Aarhus University to inquire about data reporting. They indicated that the site had undergone major upgrades in instrumentation over the last few years. A MAAP was operational from summer 2011–summer 2013, and from January 2015–May 2015 (together with an SP-AMS). An AE has been operational since summer 2017. Data will be reported to EBAS at a later stage.

Long-term sampling of aerosol filter samples for subsequent analysis of EC has been an ongoing activity since summer 2008. Aerosol filter samples are collected weekly using a high-volume sampler with a PM_{10} inlet and are analysed according to the EUSAAR-2 protocol. The time series is not publicly available, but Nguyen et al. (2014) reported EC measurements of selected aerosol filter samples from 2010, and Massling et al. (2015) reported measurements from May 2011–July 2013. Eckhardt et al. (2015) used EC data from Villum Research Station from 2008–2009 to validate model capabilities for simulating black carbon concentrations in the Arctic atmosphere. According to the person responsible for performing the OC/EC analysis of the Villum Research station aerosol filter samples, the entire data series will be published in a forthcoming paper.

4.11 Ny-Ålesund, Svalbard (Norway)

Ny-Ålesund is a research village on the west side of the Spitzbergen Island of Svalbard, Norway. Several nations have permanent research and monitoring facilities in Ny-Ålesund. In addition, visiting researchers perform observations during short term campaigns. The 'Research in Svalbard' database (https://www.researchinsvalbard.no) provides detailed

Table 4.7. Black carbon time series available for Summit, Greenland in EBAS as of June 2019.

Matrix[1]	BC Reported Value[2]	Instrument Type[3]	Instrument reference	Start date	End date
aerosol	AAC	AE	US08L_Magee_AE16_SUM	01/01/2003	01/01/2011
pm25	AAC	CLAP	US06L_GMD_CLAP-3W_SUM_pm25	08/05/2011	01/01/2019

[1] aerosol: total aerosol particle phase; pm25: aerosol particle phase in the size fraction less than 2.5 micrometers mean aerodynamic diameter
[2] AAC: aerosol absorption coefficient
[3] AE: Aethalometer; CLAP: Continuous Light Absorption Photometer

Table 4.8. Overview of measurement instruments in use at Summit, Greenland. Information provided by NOAA.

Instrument[1]	Wavelengths	Sizecut	Coverage
AE16	1 wavelength (880 nm)	Total	05/08/2003–07/07/2016
AE33	7 wavelengths (370, 470, 520, 590, 660, 880 and 950 nm)	Total	30/10/2014–10/01/2018
PSAP	1 wavelength (565 nm)[2]	2.5 µm	06/05/2011–17/08/2015
CLAP	3 wavelengths (467, 528 and 652 nm)	2.5 µm	06/05/2011–present

[1] AE: Aethalometer; CLAP: Continuous Light Absorption Photometer; PSAP: Particle Soot Absorption Photometer
[2] Reported at 550 nm due to Bond et al. (1999)

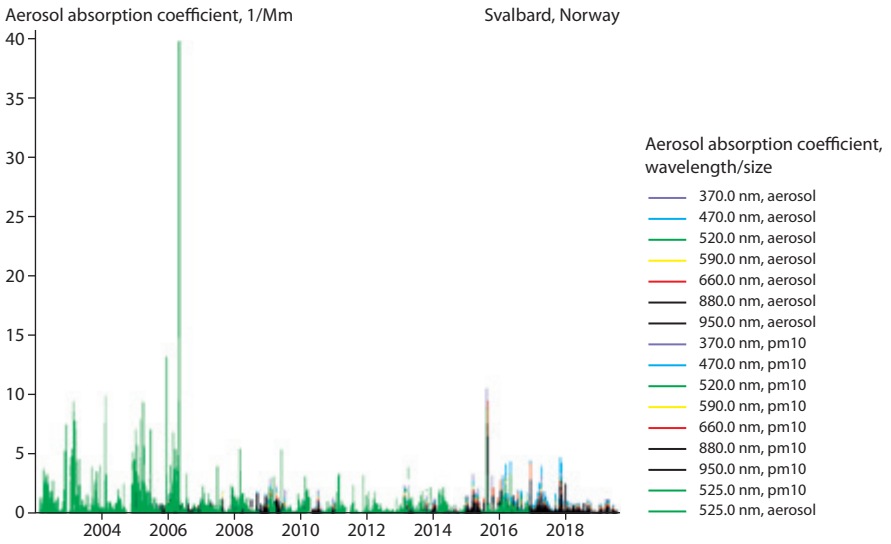

Figure 4.4. Time series of aerosol absorption coefficient (AAC) EBAS data from Zeppelin Observatory, Svalbard, Norway as of June 2019.

information on research activities and projects. Below is an introduction to the activities of the major international monitoring programs (EMEP, AMAP, GAW) at Zeppelin Observatory, and other institutions with known research activities in Ny-Ålesund, such as the National Research Council of Italy (CNR). However, it remains possible that institutions other than those discussed below may also be undertaking BC measurements in Ny-Ålesund (e.g. Korean Polar Research Institute).

4.11.1 Zeppelin Observatory at Ny-Ålesund, Svalbard (Norway)

Zeppelin Observatory is located at 472 meters above sea level on Zeppelin mountain at Ny-Ålesund. Aerosol measurements at the observatory are collected by several research institutions, including NILU, the Department of Environmental Science and Analytical Chemistry (ACES) at Stockholm University, and the Greek National Centre for Scientific Research (NCSR) Demokritos. AAC measurements by PSAP have been undertaken by ACES since 2002. NCSR Demokritos has operated an AE at Zeppelin since the 1990s (Eleftheriadis et al., 2009) and since 2016, NILU and NCSR Demokritos have commonly operated an AE33 (Table 4.9). Long-term AAC measurements for Zeppelin from 2002 to the end of 2018 are available in the EBAS database (Figure 4.4). Our review found that the AE33 data from Zeppelin were not available in EBAS, the reason being that this instrument model is currently being included as part of QA/QC efforts of international monitoring programs (ACTRIS, GAW, EMEP) and a new data-reporting template is under development. The EUA-BCA observation review gave the momentum to push this initiative to completion, and as a result, data are now in the process of being uploaded to the database.

ACES has performed long-term EC measurements at Zeppelin Observatory since at least 2008 (Hansen et al., 2014) and possibly as early as 2006 (Stohl et al., 2007). According to Hansen et al. (2014), samples are collected at weekly intervals using a low-volume aerosol filter sampler equipped with a TSP inlet. EC is quantified according to the NIOSH 5040 protocol, using transmission for charring correction. It is suspected that the analytical methodology has been changed from NIOSH 5040 to EUSAAR-2, but the time series originator has not confirmed this. The time series is not publicly available, thus its completeness is not assessed here, however, as the sampling and analytical methodology appears to be identical for samples collected in 2006 (Stohl et al., 2007), and 2008 forward (Hansen et al., 2014), the time series might extend more than a decade.

NILU has collected aerosol filter samples at Zeppelin Observatory at weekly time intervals using a high-volume sampler with a PM_{10} inlet since January 2017. EC is quantified from the filter samples with the EUSAAR-2 protocol (CEN, 2017) using transmission for charring correction as part of an ongoing project to assess the source apportionment of carbonaceous aerosols. It was recently decided that although this time series will be continued beyond 2018, it is not known for how long. Data are not currently available in EBAS but will be provided directly from NILU upon request.

Short-term EC measurements at the Zeppelin Observatory have been reported April–May 2006 (Stohl et al., 2007),

Table 4.9. Black carbon time series available for Zeppelin Observatory, Svalbard, Norway in EBAS as of June 2019.

Matrix[1]	BC reported value[2]	Instrument type[3]	Instrument reference	Start date	End date
aerosol	AAC	PSAP	SE03L_ZEP-PSAP-1	01/01/2002	01/01/2011
pm10	AAC	PSAP	SE02L_PSAP_CUSTOM_ZEP	01/01/2011	01/01/2017
aerosol	AAC	AE	GR05L_Magee31_NA01	01/01/2005	01/01/2011
pm10	AAC	AE	GR05L_Magee31_NA01	01/01/2013	01/01/2016

[1] aerosol: total aerosol particle phase; pm10: aerosol particle phase in the size fraction less than 10 micrometers mean aerodynamic diameter
[2] AAC: aerosol absorption coefficient
[3] AE: Aethalometer; PSAP: Particle Soot Absorption Photometer

March–April 2008 and November 2008–March 2009 (Yttri et al., 2014; Winiger et al., 2015). Yttri et al. (2014) determined EC on high-volume aerosol filter samples (PM_{10}) collected for 24h according to the EUSAAR-2 protocol.

4.11.2 Gruvebadet Atmospheric Station at Ny-Ålesund, Svalbard (Norway)

The CNR has collected AAC measurements at the Gruvebadet Atmospheric Laboratory on Svalbard since 2010. The measurement location is about 500 m from the Ny-Ålesund village. Measurements are made using a three wavelength PSAP (467, 530, and 660 nm; Radiance Research), typically from March to September each year when the station is staffed. Data are recorded continuously and are available upon request to the data owner. Quicklook plots are available at: http://www.isac.cnr.it/~radiclim/CCTower/?Data:Aerosol.

The University of Florence and Italian National Institute for Nuclear Physics have collected quartz fibre filter samples at the Gruvebadet Atmospheric Laboratory for subsequent analysis of EC since 2011. The samples are analysed using the NIOSH 5040 method.

Measurements of eBC at the Gruvebadet Observatory have also been reported (Gogoi et al., 2016). Continuous measurements of airborne particulate eBC mass concentrations were collected over four years, from 2010–2013. A 7-channel AE (Model AE-30; Magee Scientific) was used to sample ambient air at a flow rate of 5 litres per minute (LPM) from a height of 3 m above ground at 30-minute measurement intervals.

4.12 Abisko (Sweden)

The authors are not aware of any long-term EC measurements at the Abisko Research Station located in northern Sweden. Winiger et al. (2016) reported a short-term study covering the period September 2011 to March 2013. Aerosol filter sampling was performed using parallel high-volume samplers with $PM_{2.5}$ and TSP inlets, and the filters were subsequently analysed according to the NIOSH 5040 method.

4.13 Kevo (Finland)

Kevo is located in northern Finland. An eBC time series for this site spanning 1965–2010, was reported by Dutkiewicz et al. (2014). To our knowledge, this temporal dataset is the longest record of eBC measurements anywhere in the Arctic. Aerosol filter samples were collected at weekly intervals using a high-volume sampler with a TSP inlet. The filter samples were analysed for eBC using an Optical Transmissometer (Model OT21, Magee Scientific). A sub-section of the cellulose filter samples were digested, allowing the transfer of aerosol particles to a quartz fibre filter for thermal-optical analysis according to the NIOSH 5040 method. This dual approach connects the data obtained by the optical analytical method with those from the thermal-optical protocols commonly used at other Arctic observatories.

4.14 Pallas (Finland)

Pallas is part of the Pallas-Sodankylä GAW station located in northern Finland. A detailed description of this measurement site was published by Lohila et al. (2015). The Finnish Meteorological Institute (FMI) has continuously measured absorption data using filter-based methods at Pallas since 2015 (Table 4.10; Figure 4.5) (Hyvärinen et al., 2011; Collaud Coen et al., 2013; Lihavainen et al., 2015; Schmeisser et al., 2018).

Additionally, residual BC in individual particles and the BC mixing state have been measured campaign-wise in Pallas since 2011 (Raatikainen et al., 2015), however, due to the large volume of data produced by these analyses, the data are not currently publicly available.

By the end of 2018, FMI will have performed five years of EC measurements at Pallas, with analyses dating back to fall 2013. At this site, measurements are performed according to the

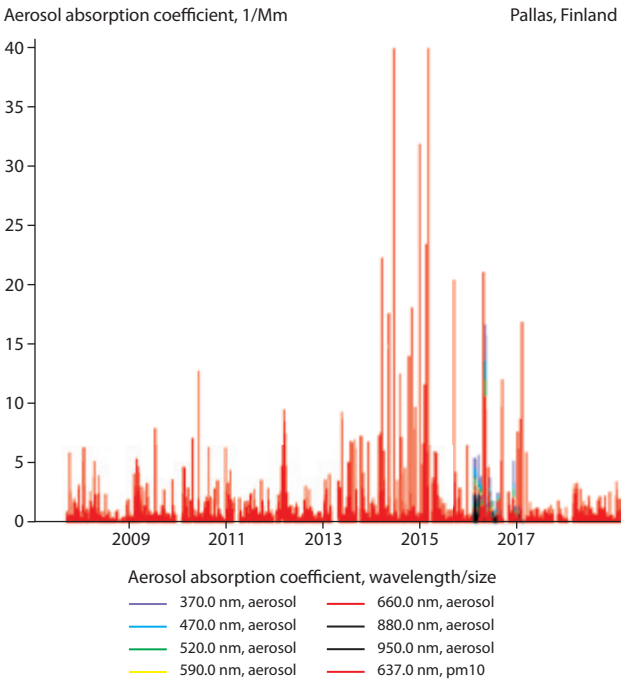

Figure 4.5. Time series of aerosol absorption coefficient (AAC) EBAS data at from Pallas, Finland as of June 2019.

Table 4.10. Black carbon time series available for Pallas, Finland in EBAS as of June 2019. In addition, a MAAP instrument has been in use at the station but these data have not been reported to EBAS.

Matrix[1]	BC reported value[2]	Instrument type[3]	Instrument reference	Start date	End date
pm10	eBC/AAC	MAAP	FI01L_Thermo_5012_PAL	01/01/2007	01/01/2019
aerosol	eBC/AAC	AE	FI01L_Magee_AE31	01/01/2016	01/01/2017

[1] aerosol: total aerosol particle phase; pm10: aerosol particle phase in the size fraction less than 10 micrometers mean aerodynamic diameter
[2] AAC: aerosol absorption coefficient; eBC: equivalent black carbon
[3] AE: Aethalometer; MAAP: Multi-angle Absorption Photometer

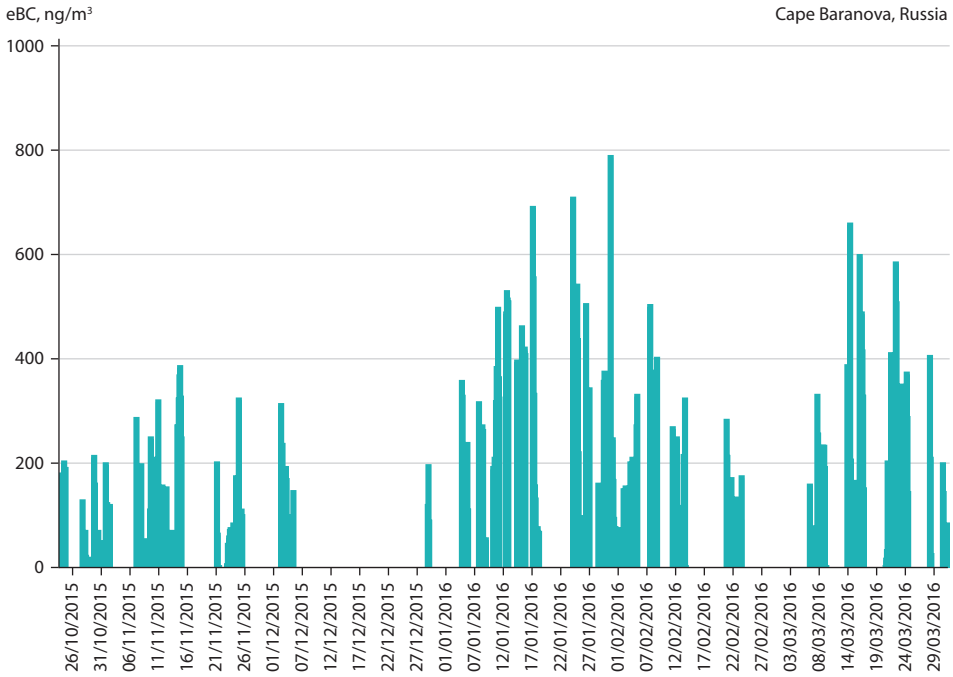

Figure 4.6. Time series of equivalent black carbon (eBC) in mass concentration measurements at Ice Base Cape Baranova, Russia from October 2015 to April 2016. Data from: https://iccpa2019.univie.ac.at/fileadmin/user_upload/k_iccpa2019/2019/AbstractBook_ICCPA_2019_Website.pdf.

EUSAAR-2 protocol using a semi-continuous monitor with a sampling line including a $PM_{2.5}$ inlet and a denuder. These data have been reported to the European Environmental Agency (EEA) database (http://aqportal.discomap.eea.europa.eu), however, it should be noted that the data are reported as two different BC values; eBC is measured from the semi-continuous monitor along with EC, and this variable was first reported to the EEA database instead of EC (Aurela, pers. comm.).

4.15 Cape Baranova (Russia)

The Ice Base Cape Baranova research station is located on Bolshevik Island of the Severnaya Zemlya Archipelago, and is operated by the Russian Arctic and Antarctic Research Institute (AARI). The research station initially opened in the 1980s, but recently reopened in 2013 after an almost 10-year temporal close.

Moscow State University, in collaboration with AARI and NCSR Demokritos, installed a portable AE and sampling system at a remote site away from the base station for long-term monitoring of Arctic aerosol characteristics, which has been on-going since October 2015 (Table 4.11; Figures 4.6 and 4.7). Data are directly available from Olga Popovicheva (olga.popovicheva@gmail.com).

In collaboration with FMI, AARI started monitoring greenhouse gas and aerosol observations in October 2015 using a specifically equipped container (Laurila et al., 2016; Ivakhov et al., 2019). AAC is measured by MAAP (Model 5012, Thermo Scientific) operated with a PM_{10} inlet and a flow rate of 11 LPM. Data is available from Eija Asmi (eija.asmi@fmi.fi).

The National Institute of Polar Research of Japan and the University of Tokyo, Japan recently engaged in eBC measurements at Ice Base Cape Baranova during 2017 (https://blog.arcs-pro.jp/en/2018/09/ice-base-cape-baranova.html). They installed a COSMOS instrument at Baranova to measure eBC concentrations on a filter tape after volatilization (Miyazaki et al., 2008).

Table 4.11. Measurements at the Ice Base Cape Baranova station, Russia.

Instrument[1]	Size cut	Coverage
MAAP	10 µm	10/2015–06/2016; 09/2018–present
COSMOS	1 µm	10/2017–present
AE	Total	10/2015–04/2016
Sampling system	10 µm	Spring 2015; 10/2015–12/2016

[1]AE: Aethalometer; COSMOS: Continuous Soot Monitoring System; MAAP: Multi-angle Absorption Photometers

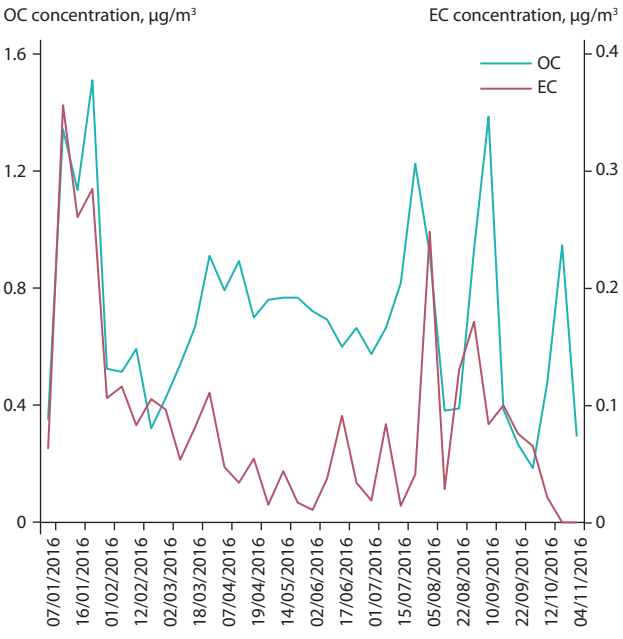

Figure 4.7. Time series of elemental carbon (EC) and organic carbon (OC) mass concentrations from Ice Base Cape Baranova, Russia, during 2016. Data from: https://iccpa2019.univie.ac.at/fileadmin/user_upload/k_iccpa2019/2019/AbstractBook_ICCPA_2019_Website.pdf.

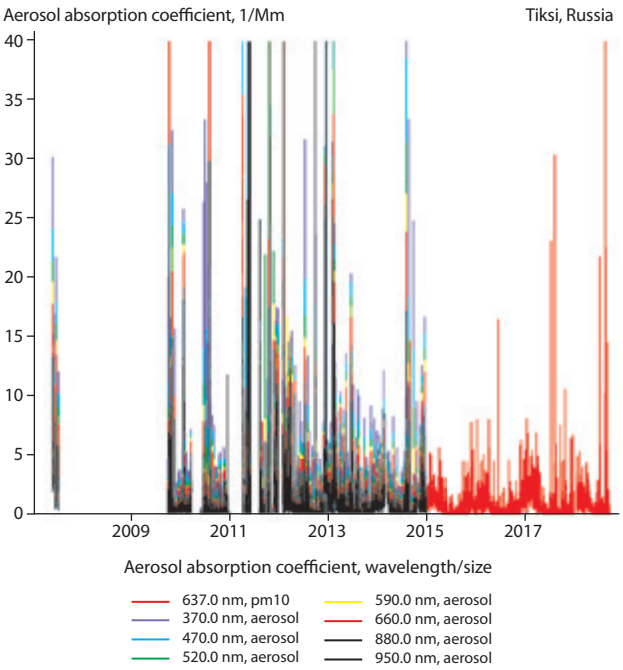

Figure 4.8. Time series of aerosol absorption coefficient (AAC) EBAS data from Tiksi, Russia as of June 2019.

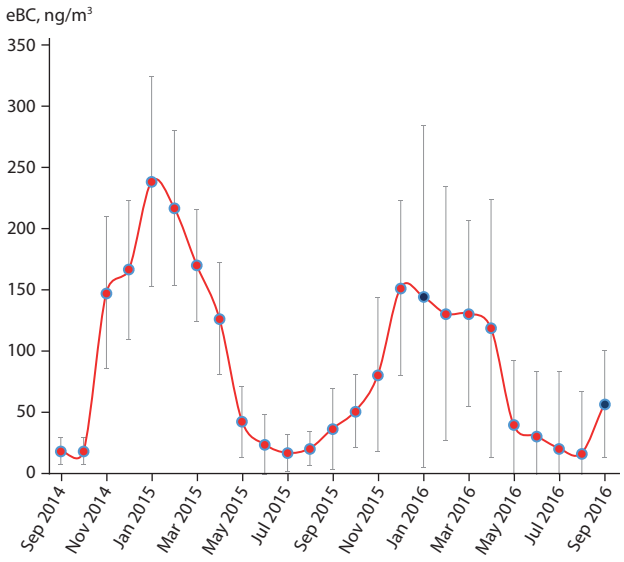

Figure 4.9. Monthly equivalent black carbon (eBC) measurements at Tiksi, Russia from September 2014 to September 2016 (Popovicheva et al., 2019). Monthly means and standard deviations are represented by points and bars, respectively. Large standard deviation values for January and September 2016 (indicated in blue) have been reduced by a factor of three for display on the on the plot.

4.16 Tiksi (Russia)

The Hydrometeorological Observatory at Tiksi, located on the coast of the Laptev sea in Northern Siberia, Russia is closer to the BC source regions of high-latitude Eurasia than other Arctic stations. AAC measurements at this site extend back to 2005 (Lihavainen et al., 2015), however, only data from NOAA's Earth System Research Laboratory spanning 2007–2014 are available in EBAS (Table 4.12; Figure 4.8). Measurements are ongoing and more recent data are available from NOAA upon request. An investigation of the time series showed that the data capture was low to start and improved from late 2009 onward. FMI has also been operating a MAAP at Tiksi since 2013.

In addition, AE and MAAP data collected between 2012–2014, was published by Backman et al. (2017) and is available in EBAS (https://doi.org/10.21336/gen.1). eBC data measured over these two years at Tiksi has been compared to that from other Arctic observatories (Backman et al., 2017; Schmeisser et al., 2018).

Seasonal trends of eBC at Tiksi were examined for the period 2014–2016 (Popovicheva et al., 2019). Over this time period, monthly eBC concentrations showed seasonal variation with the highest concentrations observed from January to March (up to 450 ng/m^3) and lowest levels measured in June and September (about 20 ng/m^3) (Figure 4.9).

Short-term EC measurements collected between April 2012 and March 2014 have been described by Winiger et al. (2017). Aerosol filter samples were collected using a high-volume filter sampler with a TSP inlet and analysed using the NIOSH 5040 protocol.

Aerosol sampling and analysis for OC and EC was also performed during seven time periods over the autumn, winter–spring, and early summer from September 2014 to September 2016. Low-volume filter samples were collected downstream of a TSP inlet and analysed according to the EUSAAR-2 method (Popovicheva et al., 2019).

4.17 Other sites with in-situ black carbon data

In an effort to identify additional BC datasets, the following resources were queried as part of this review, however, no additional data were found:

- WMO Global Atmosphere Watch Station Information System (GAWSIS): https://gawsis.meteoswiss.ch/GAWSIS//index.html
- International Arctic Systems For Observing The Atmosphere (IASOA): https://www.esrl.noaa.gov/psd/iasoa/home2

Table 4.12. Black carbon time series available for Tiksi, Russia in EBAS as of June 2019.

Matrix[1]	BC reported value[2]	Instrument type[3]	Instrument reference	Start date	End date
aerosol	eBC/AAC	AE	US06L_Magee_AE31_TIK	01/01/2007	01/01/2015
pm10	eBC/AAC	MAAP	FI01L_Thermo_5012_TIK	01/01/2015	01/01/2019

[1] aerosol: total aerosol particle phase; pm10: aerosol particle phase in the size fraction less than 10 micrometers mean aerodynamic diameter
[2] AAC: aerosol absorption coefficient; eBC: equivalent black carbon
[3] AE: Aethalometer; MAAP: Multi-angle Absorption Photometer

Figure 4.10. Locations of major research stations in the Arctic. Most sites depicted focus on research fields other than atmospheric composition. Credit: Hugo Ahlenius, UNEP/GRID-Arendal: http://www.grida.no/resources/7141

- EU-PolarNet: https://www.eu-polarnet.eu
- Sustaining Arctic Observing Network (SAON): https://www.arcticobserving.org
- International Arctic Science Committee (IASC): https://iasc.info
- Svalbard Integrated Observing System (SIOS): https://sios-svalbard.org
- Individual Arctic-Based Research Stations (Figure 4.10): https://en.wikipedia.org/wiki/List_of_research_stations_in_the_Arctic

4.18 Conclusions

We have assessed the availability of ambient aerosol BC measurements in the Arctic with a focus on data submitted to EBAS and a primary goal of identifying long-term time series with public availability. Thus, this review has allowed gaps in monitoring capacity and geographical coverage to be identified.

BC observations in air can include AAC measurements that originate from on-line aerosol absorption photometers or EC measurements from sampling of aerosol filter samples and subsequent off-line analysis by thermal-optical or thermal analysis. Isotopic information (e.g. radiocarbon and stable carbon isotopes) provided by off-line analysis of EC, can also provide valuable information on BC source attribution and apportionment.

Data from international monitoring efforts are generally open and freely-accessible. Although data documentation and reporting has improved significantly over time, in the course of this review, it was discovered that early data sets, in particular those prior to 2010, lacked proper attention to data reporting requirements. Since this discovery, a large number of improvements have been made to major monitoring databases, including the correction of erroneous data, and revisions to the user-interface of the EBAS database. Through the efforts of NOAA, WMO-GAW, and ACTRIS, observations are now of good quality, although some challenges remain in the documentation of metadata and consistency of time series over time. A full review of historic time series is still ongoing at the time of writing this report.

Only a few Arctic sites have long-term AAC datasets available (Table 4.1). Similarly, only a few long-term EC time series exist. There are no apparent reasons why long-term EC measurements should be of less relevance to the Arctic compared to those of rural and urban environments. Still, such measurements appear less common than optical AAC measurements, and this may be explained by cost and logistical challenges. Low Arctic EC levels and challenges associated with collection of aerosol filter samples (e.g. destruction of filter samples by harsh weather conditions) provide EC time series with a poorer time

resolution and possibly less data capture than for AAC. In the future, the suitability of on-line approaches to determine EC in the Arctic ought to be explored, and compared to the off-line approach.

Long-term EC observations mainly stem from the western part of the Arctic. When including short-term studies, this spatial coverage extends eastward, but most BC observations come from western Arctic observatories. Notably, none of the identified eastern Arctic long-term EC time series are publicly available in their full length, although there are plans for doing so in 2019 for at least one of them. The data owners of these long-term time series should be encouraged to make them publicly available. Our overview is not complete, but the majority of long-term time series are likely accounted for, assuming they are associated with the major atmospheric observatories in the Arctic. Unanswered requests to Russia regarding EC measurements could change this geographical pattern, both for long- and short-term measurements. Based on this review, we find it unlikely that the current number of long-term time series identified in the Arctic by this survey is sufficient to cover the actual variability of BC for this vast area.

Short-term studies reporting EC have mainly been documented in scientific journals. Sampling approaches and analytical methodologies differ amongst sites, both for long-term and short-term datasets. All current datasets are based on the off-line analysis of aerosol particle filter samples, with the exception of one (Pallas), which is obtained using a semi-continuous instrument. Thermal-optical analysis operated according to the NIOSH 5040, IMPROVE, or the EUSAAR-2 thermal program protocols is used at all but one site (Alert). For the sake of measurement comparability across the Arctic, analytical approaches ought to be harmonised, but this could prove challenging, as some of the long- and short-term measurements of isotopes (i.e. ^{13}C and ^{14}C of EC) depend on particular protocols for source apportionment of the carbonaceous aerosol. Preferably, sampling ought to be harmonised as well, but this is more crucial for OC, which is obtained by thermal-optical or thermal analysis along with EC. Further, laboratories responsible for analysing aerosol filter samples for EC should regularly participate in interlaboratory comparison exercises to ensure the stability of the measurements and to minimise the impact of analytical and sampling methodologies on the observed trends of EC. As long as the stability and traceability of individual instruments are ensured via calibration and rigorous QA/QC, the annual trends in different datasets should be compatible within a specific uncertainty range, despite differences in sampling and analytical protocols.

5. Aircraft, ship, satellite-based and snow observations of black carbon

The present review primarily focuses on long-term observations of BC in air at Arctic sites. However, the following are other relevant resources discovered during the reviewing effort.

5.1 Aircraft-based observations

Airborne observations, either by manned aircraft or UAS, offer the potential to provide atmospheric BC measurements along vertical and horizontal transects. In particular, the vertical distribution of BC is of major interest since this information supports transport studies and provides information on climate forcing. In the Arctic region, only discrete aircraft-based sampling campaigns have been conducted (i.e. no regular, on-route measurements by planes are operational). The data are thus, due to operational aspects and costs, only available in special cases:

A special issue of Atmospheric Chemistry and Physics offers detailed information about the data available from the International Polar Year's Polar Study using Aircraft, Remote Sensing, Surface Measurements and Models of Climate, Chemistry, Aerosols, and Transport (POLARCAT) project (Stohl et al., 2015).

Airborne measurements of refractory black carbon (rBC) have been conducted in the Arctic by the Alfred Wegener Institute (AWI) since 2009 with almost yearly frequency. Observations cover the European Arctic, Greenland, Canadian Arctic, and Arctic Ocean and were organised within long-term projects such as the Polar Airborne Measurements and Arctic Regional Climate Model Simulation Project (PAMARCMIP; Herber et. al, 2012), the Network on Climate and Aerosols: Addressing Key Uncertainties in Remote Canadian Environments (NETCARE; https://www.netcare-project.ca), and the Arctic Amplification (AC)^3 Transregional Collaborative Research Centre (http://www.ac3-tr.de; Wendisch et al., 2019) projects. Two aircraft campaigns are planned to take place in spring and autumn 2020 within the framework of the Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAIC) project (https://www.mosaic-expedition.org).

Within the framework of the Airborne Extensive Regional Observations in Siberia (YAK-AEROSIB) experiments, BC measurements were collected over eastern and western Siberia onboard the Optik Tu-134 aircraft laboratory (Konovalov et al., 2018; Antokhin et al., 2018). In 2012, the YAK-AEROSIB measurement campaign was carried out July 31–August 1 (Antokhin et al., 2018). On July 31, the aircraft departed from Novosibirsk (54°9'N, 85°2' E) and arrived in Yakutsk (61°9' N, 128°5' E), with an intermediate landing in Tomsk (56°2' N, 84°7' E). On August 1, the aircraft returned, departing from Yakutsk and landing in Novosibirsk. During the flights, the aircraft performed several ascents and descents within 1–8 km of altitude and crossed several major smoke plumes originating from fires in Siberia. Further information regarding the 2012 YAK-AEROSIB campaign flight tracks can be found elsewhere (Antokhin et al., 2018) and the BC measurement data obtained by this study is available on the YAK-AEROSIB project website (https://yak.aeris-data.fr).

Other Arctic airborne campaigns and resources include:

- Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS) Field Campaign: https://espo.nasa.gov/arctas
- Aerosol, Radiation, and Cloud Processes affecting Arctic Climate (ARCPAC) Program: https://www.esrl.noaa.gov/csd/projects/arcpac
- European Facility for Arctic Research (EUFAR): http://www.eufar.net
- Facility for Airborne Atmospheric Measurements (FAAM): https://www.faam.ac.uk
- HIAPER Pole-to-Pole Observations (HIPPO) Project: https://www.eol.ucar.edu/field_projects/hippo
- International Consortium for Atmospheric Research on Transport and Transformation (ICARTT): https://www.esrl.noaa.gov/csd/projects/icartt
- Multidisciplinary Drifting Observatory for the Study of Arctic Climate (MOSAIC): https://www.mosaic-expedition.org/
- Network on Climate and Aerosols: Addressing Key Uncertainties in Remote Canadian Environments (NETCARE): http://www.netcare-project.ca/campaigns
- Polar Airborne Measurements and Arctic Regional Climate Model Simulation Project (PAMARCMIP): http://www.ac3-tr.de/news/pamarcmip-campaign

5.2 Ship-based observations

Ship-based campaigns offer the potential to collect data over horizontal transects through the Arctic Ocean, and thus can yield data from regions without facilities or fixed sites. However, a major challenge associated with ship-based measurements is the potential influence of the ship's own emissions on BC data as illustrated by the direct sampling of ship exhaust (Figure 5.1).

To date, only a few ship-based BC time series have been identified:

Taketani et al. (2016) describe shipborne observations of atmospheric BC aerosol particles over the Arctic Ocean, Bering Sea, and North Pacific Ocean collected during September 2014.

Aerosol instrumentation was installed onboard the 'Akademik Trechnikov' research vessel during the AARI marine expedition from Arkhangelsk to the Severnaya Zemlya archipelago October 6–26, 2015 (Popovicheva et al., 2017). On-line measurements of aerosol and BC concentrations, as well as aerosol sampling, were performed at two sites for the assessment of clean-air and ship exhaust aerosols (http://www.sinp.msu.ru/en/post/24443).

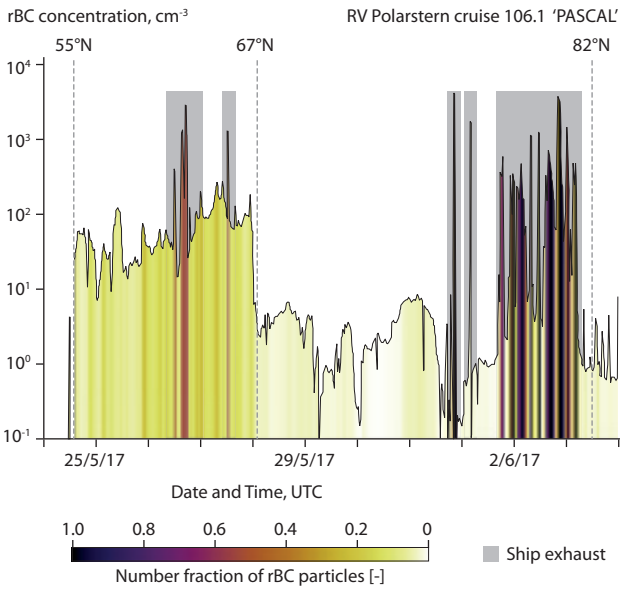

Figure 5.1. Time series of refractory black carbon (rBC) concentrations and particle fractions from the RV Polarstern northward transect of the 106.1 Pascal cruise (Fram Strait and Svalbard). Levels of rBC measured in ship exhaust are indicated by grey shadows.

For access to data, please contact Olga Popovicheva (olga.popovicheva@gmail.com).

Arctic Ocean 2018, a joint expedition of the Swedish Polar Research Secretariat and US National Science Foundation, included the Microbiology Ocean Cloud Coupling in the High Arctic (MOCCHA) project. Between July 31–September 21, 2018, measurements were made en route from Longyearbyen to the North Pole and back (Figure 5.2). During the expedition, eBC was measured about 20 meters above sea surface using an AE (Model AE33) and MAAP. Data processing is in progress and expected to be finalised by summer 2020. For access to preliminary data, please contact the data originators (Julia Schmale, schmale@psi.ch for AE33 data; Paul Zieger, zieger@aces.su.se for MAAP data). Additional information about the expedition can be found on the Arctic Ocean 2018 website: (https://polarforskningsportalen.se/en/arctic/expeditions/arctic-ocean-2018).

Figure 5.2. Ship track of the Arctic Ocean 2018 campaign.

As part of the MOSAIC expedition spearheaded by AWI, a German research icebreaker vessel will depart from Tromsø, Norway in September 2019 and spend the next year drifting through the Arctic Ocean trapped in ice. Six hundred people from 17 countries will participate in the expedition, and several times that number of researchers will subsequently use the data gathered for climate and ecosystem research. The measurement program will include BC observations by means of an SP-2 and another absorption-based photometer on the ship. Additional information regarding the expedition can be found on the MOSAIC website: (https://www.mosaic-expedition.org).

5.3 Satellite-based observations

Satellite-based remote sensing uses ultraviolet (UV) light, visible light, and infrared sensors onboard polar-orbiting satellites or geostationary platforms to provide data on atmospheric composition, although the latter do not cover high latitude regions. A large number of satellite sensors are dedicated to aerosol studies or provide aerosol information as by-products (Table 5.1).

Optical satellite-based instruments (e.g. radiometers, imaging or scanning spectrometers, and lidars), measure characteristics of atmospheric radiation, and specific retrievals are needed to convert signals to aerosol characteristics (e.g. total amounts). The conversion is based on radiative transfer theory and takes into account multiple surface reflectance and light scattering effects, including molecular- and aerosol-scattering and absorption. Aerosol retrieval in the Arctic is challenging due to the very low concentrations of aerosol found in Arctic air masses combined with the high albedo of snow- and ice-covered surfaces. This makes it difficult to separate the contributions of surface reflectance, aerosol scattering, and aerosol absorption to satellite-measured radiance.

In general, it is difficult to unambiguously distinguish between different aerosol types with the passive instruments currently in space. Multi-wavelength measurements and measurements of polarization can give an estimate of factors such as fine-mode fractions, effective particle radius, and aerosol shape. The most common aerosol quantity measured from space is the Aerosol Optical Depth (AOD), which is the integrated aerosol extinction over a vertical atmospheric column. Aerosol layer heights are seen with active instruments (e.g. lidar) or can be retrieved from dual-view passive remote sensing instruments (e.g. Advanced Along-Track Scanning Radiometers (AATSRs) or Sea and Land Surface Temperature Radiometers (SLSTRs)). For the latter passive instrumentation, the vertical resolution is crude (km) compared with that from active sensors (tens to hundreds of meters). Aerosol absorption optical depth (AAOD) retrieval, representing the absorbing part of aerosols, can be retrieved from the Ozone Monitoring Instrument (OMI) onboard the EOS-Aura satellite (Torres et al., 2007; 2013). BC, as well as dust, organic carbon aerosols, and volcanic ash can contribute to the absorbing aerosol signal. AAOD is an altitude-dependent quantity, therefore aerosol layer height and climatology based on Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP) sensor data and real-time carbon monoxide observations collected by the

Table 5.1. Examples of recent satellite sensors and their respective satellites used for aerosol data retrieval.

Sensor	Satellite
Polarization and Directionality of the Earth's Reflectances (POLDER)	PARASOL
Advanced Along-Track Scanning Radiometer (AATSR)	ENVISAT
Multi-angle Imaging Spectroradiometer (MISR)	Terra
Moderate Resolution Imaging Spectroradiometer (MODIS)	Terra; Aqua
Infrared Atmospheric Sounding Interferometer (IASI)	MetOp-A; MetOp-B; MetOp-C
Cloud-Aerosol Lidar with Orthogonal Polarization (CALIOP)	CALIPSO
Sea and Land Surface Temperature Radiometer (SLSTR)	SENTINEL-3
Tropospheric Monitoring Instrument (TROPOMI)	SENTINEL-5P
Atmospheric Lidar (ATLID); Multi-Spectral Imager (MSI)	EarthCARE[1]
SENTINEL-5	MetOp-SG[1]

[1]Launch forthcoming in 2021/2022

Atmospheric Infrared Sounder instrument onboard the Aqua satellite can help distinguish between dust and smoke aerosol types. In principle, the wavelength dependence of the aerosol single-scattering albedo (i.e. the aerosol absorption Ångstrøm exponent) can give indications related to aerosol composition (presence of black versus organic carbon). Konovalov et al. (2018) present the OMI AAOD in combination with other types of BC property observations, and demonstrate that such data are useful at lower latitudes and in situations with high particle concentrations.

Most instruments used for aerosol retrievals are based on UV- or visible-light observations, which are limited to day-time and cloud-free conditions. Cloud cover is one of the main challenges in satellite aerosol data retrieval. Active instruments such as CALIOP work better at night and have reduced sensitivity in the daytime, when the signal-to-noise ratio is higher. However, we are not aware of any Arctic studies using CALIOP for BC measurement. For optically thinner aerosol layers in the boundary layer with limited horizontal scale (e.g. compared to the dust layer), satellite sensors such as OMI with 13×24 km^2 pixel size are susceptible to sub-pixel cloud contamination on the one side and to potential underestimation from non-full pixel filling of the aerosol layer under cloud-free conditions on the other. In this case, sensors with a higher spatial resolution, such as AATSRs or Moderate Resolution Imaging Spectroradiometers (MODIS) are more useful.

Satellite observation of atmospheric BC at high latitudes is presently not a mature source of information. Currently, satellite data is primarily used to support studies of discrete synoptic-scale events with transport to the Arctic region. For such events, absorption data are important, but aerosol metrics (e.g. scattering properties) and other data on gaseous species can provide additional information, in a similar manner as ground-based stations that integrate in-situ data from multiple instruments into a single assessment. For example, Li et al. (2017) use satellite-retrieved carbon monoxide, tropospheric nitrogen dioxide, and AOD data over the North Pacific as a satellite-based approximation of column BC measurements.

For access to model-based products, refer to the Copernicus Atmospheric Monitoring Service: https://atmosphere.copernicus.eu/catalogue.

5.4 Snow observations

Measurements of BC in snow are important for understanding the effect of BC on light absorption by snow and ice and quantifying the atmospheric deposition of BC from air. Quantification is especially important for distinguishing between the influences of BC and other factors (i.e. mineral dust, snow morphology) on light absorption and reflectivity. However, satellite-based remote sensing cannot be used to estimate the BC content of snow, nor the reduction of albedo by BC, with the potential exception of highly polluted industrial regions (Warren, 2013).

There are no international standards for the sampling and analysis of snow impurities, thus comparability between studies may be limited by the analytical methods used. Two main types of sample treatment and analysis methodologies can be identified: melting and filtration of the sample followed by off-line analysis, and melting and nebulisation of the sample followed by on-line analysis. Off-line BC quantification is performed by means of thermal-optical analysis (thus named EC; Hagler et al., 2007) or by transmittance spectrophotometry (thus named eBC; Doherty et al., 2010). On the contrary, online measurements are performed by SP2 (thus named rBC; Katich et al., 2017) or photoacoustic technique (thus named AAC; Petzold et al., 2013). The use of several different BC measuring techniques combined with the variability imparted by the use of sample filtration or nebulisation treatment reduces the comparability of BC measurements in snow. For example, in an intercomparison exercise, off-line filtration measurements of EC and online measurements of rBC were, on average, shown to vary by a factor of two, depending on the sample type (Lim et al., 2014).

Dou and Xiao (2016) also highlight the discrepancy of BC concentrations measured by different methods. During thermal-optical analysis, charring of OC forms pyrolytic carbon, which is not easily distinguished from the sample's initial content of EC (Chow et al., 2004). However, thermal-optical analysis can operate according to various temperature programs, and the separation of OC and pyrolytic carbon from EC can be monitored both by reflectance (Huntzicker et al., 1982) and transmission (Birch and Cary, 1996). Comparisons of different temperature programs show that EC concentrations can differ by more than an order of magnitude (Schmid et al., 2001). For the SP2 method, the measurement of BC in snow has a higher uncertainty (60%) than the measurement of BC in atmospheric aerosol (10–25%) for the Arctic, which is due to uncertainties related to the aerosol nebulisation from snow melt and the larger size of BC particles in snow than in aerosols (Wendl et al., 2014).

Beyond differences in analytical methodologies, several other sources of uncertainty can complicate the cross-comparison of BC data from separate field campaigns and

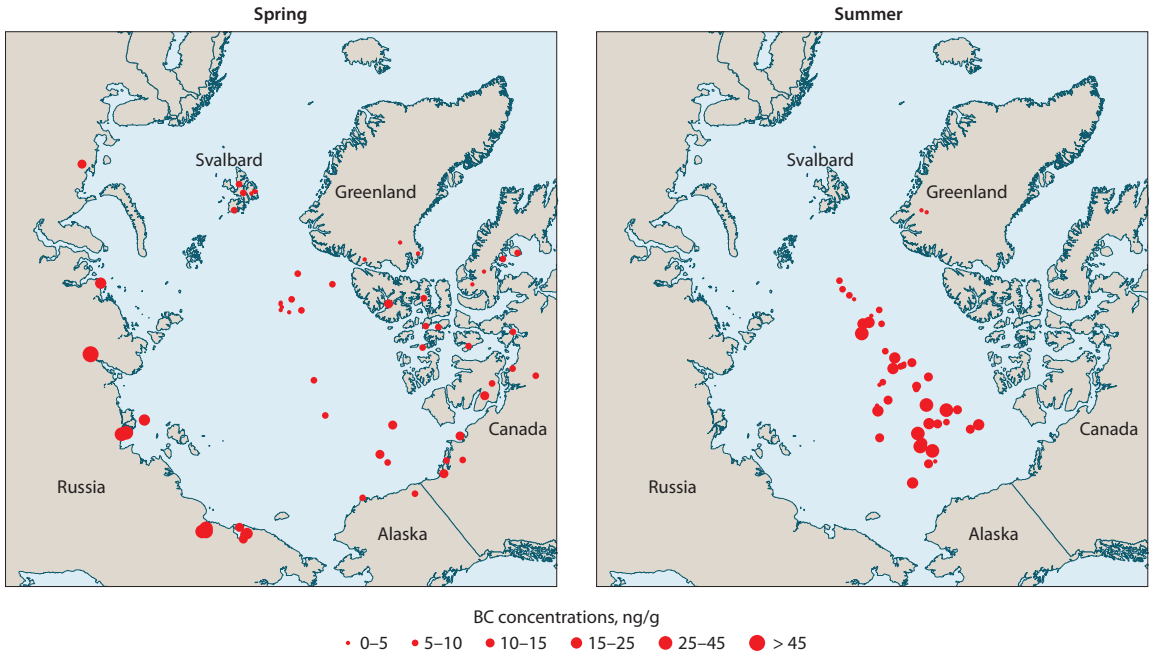

Figure 5.3. Locations and concentrations of BC snow observations collected from Arctic campaigns between 2005–2010. Reprinted from Dou and Xio (2016).

studies; determinations of BC in snow have involved various campaigns over different time periods, snow samples have been gathered at different snow depths, and in some regions, very few measurements have been conducted, such as in the Eastern Russian Arctic (Dou and Xiao, 2016). Additionally, Svensson et al. (2013) observed meter-scale horizontal variability of EC in surface snow. They found significant differences, up to a ratio of two, between samples taken 5 meters apart.

Although a standard operating procedure for the sampling, treatment, and quantification of BC in snow samples is highly needed, a number of scientific studies with relevant data have are available (with data access generally described within respective publications):

Studies reporting BC data in snow from Arctic field campaigns were reviewed by Dou and Xiao (2016) (Figure 5.3). The earliest available campaign data comes from the western Arctic in the 1980s (Clarke and Noone, 1985). Later, snow samples were gathered across the Arctic Ocean for composition analysis including BC during the Surface Heat Budget of the Arctic Ocean (SHEBA) experiment in 1998 (Grenfell et al., 2002). Measurements of BC in snow and ice greatly expanded during 2005–2009 to include sites in the Russian Arctic, the Arctic Ocean, the Canadian and Alaskan Arctic, as well as a few sites in Greenland (Doherty et al., 2010). Additionally, snow samples obtained at 36 sites across Alaska, Canada, Greenland, Russia, and the Arctic Ocean in early 2007 were analysed for light-absorbing aerosol concentrations along with a suite of associated chemical species (Hegg et al., 2009). Another campaign measured BC in Scandinavia and European Arctic snowpacks from 2007–2009 (Forsström et al., 2013). In summer 2010, a dozen snow samples were gathered from the Canada Basin and Arctic Ocean centre, improving measurement density over the Arctic Ocean in summer (Dou et al., 2012). Sampling of snow for BC quantification will be performed along the entire MOSAIC expedition from 2019–2020, including at the Polarstern location, and at Villum, Alert, and Ny-Ålesund stations.

Regional sampling can also yield important data. In Canada, a coordinated snow study between ECCC and University of Toronto was conducted from September 2014 to June 2015 at Alert, Canada under NETCARE. Fallen snow samples were collected on Teflon tables and results highlighted the deposition rates of aerosol constituents and their source attributions determined using a positive matrix factorization technique (Macdonald et al., 2017; 2018). Since 2014, ECCC has also collected snow events occurring between October and May for EC and EC isotope analysis. Data will be presented in a forthcoming paper.

AWI has collected snow samples from the Fram Strait in summer 2017 and Villum Research Station in spring 2018, however, samples have not been analysed yet.

In Norway, Forsstrøm et al. (2009) measured the EC distribution in Svalbard snow in spring 2007. They reported systematic regional differences from east to west, and after combination with air mass transport data, found that concentrations were two and a half times higher after the arrival of air masses originating from an easterly sector. Jacobi et al. (2019) combined atmospheric and snowpack observations with simulations to derive information about BC deposition between November 2011 and April 2012 to the Arctic snowpack at two locations near Ny-Ålesund, Svalbard. Measurements of eBC in snow collected from the Gruvebadet Observatory on Svalbard have also been reported (Gogoi et al., 2016). Arctic snow sampling was carried out in April 2012, during which snowpack reached near its maximum depth before the onset of melting.

Meinander et al. (2013) report measurements of albedo and BC concentrations in snow at Sodankylä in northern Finland, during an intensive melt period in April 2009. Also, in Finland, Svensson et al. (2018) collected and analysed EC and dust concentrations in snow at Pallas during spring 2015 and 2016. They also included samples collected since 2009 at Sodankylä. EC concentrations ranged from 6.2–102 µg/L. The data are available upon request from the authors.

In Russia, fresh snow samples were collected along a north–south transect between Tomsk and the Yamal coast in February–March 2014, the Kindo peninsula and near the port of Arkhangelsk in the White Sea in March 2015, and on the Kindo peninsula, in Arkhangelsk, and between Tomsk and Yamal in February–May 2016 (Evangeliou et al., 2018).

Other publications with Arctic snow BC data include Peters et al. (1995), Masclet et al. (2000), and Aamaas et al. (2011).

5.5 Conclusions

Observations made from ships or aircraft (mostly associated with research monitoring campaigns) play a fundamental role in facilitating the interpretation of distinct episodes of long-range transport. A large number of research studies reporting BC observations from short-term campaigns via ship or aircraft and measurements in snow are reported in the scientific literature, typically in combination with results of applied atmospheric transport models and/or use of satellite remote-sensing data. Aircraft-based BC observations are constrained to intensive field campaigns that are extremely expensive and mostly performed within the framework of specific projects. Ship-based observations are few, and presently no observations are performed regularly. However, the MOSAIC campaign will provide more data in the upcoming years. Availability of airborne- and shipborne- data remains limited to project-specific databases. Satellite remote sensing cannot yet directly measure black carbon in the atmosphere or in Arctic snow, but has many applications (e.g. investigating climatic and ecosystem impacts).

Assuring the comparability and quality of data collected during the course of individual studies can be challenging, and long-term archiving is not always secured. Different datasets may be comparable if the stability and traceability of individual instruments are ensured via calibration and rigorous QA/QC.

In contrast to observations collected by major Arctic observatories, access to data from research activities is best achieved by direct communication with the individual research teams/institutions responsible for the studies.

6. Synthesis, knowledge gaps, and recommendations

Measurements play an integral role in assessing spatial and temporal trends associated with the sources, atmospheric transport, and changes in BC emissions. Although it is not within the scope of this report to give subjective recommendations of specific data needs, as these must be defined by data users and the scientific or policy questions to be answered, some general recommendations originating from the review can be provided:

Publicly-available Arctic BC time series spanning several years or longer are few and generally based on optical measurements. Temporal trends based on thermal-optical and thermal-only methods are also available, but these are relatively shorter in extension. Some datasets can be openly accessed in international databases, while others can be accessed through direct contact with institutions or data originators.

Overall, there are few BC monitoring sites in the Arctic region, and even fewer with multi-decadal time series. Large areas of the Arctic, in particular the Russian Arctic region, are not involved in the collection of BC measurements. Therefore, an increase in the number of long-term monitoring sites, especially along the rim of Arctic, would be beneficial for closing geographical data gaps. Moreover, only three sites – Alert (Canada), Villum Research Station (Greenland/Denmark) and Zeppelin (Svalbard/Norway) currently have multi-decadal time series for BC measurements. Thus, it is extremely important to maintain high-precision data collection at these existing sites to continue long-term data series. WMO-GAW, NOAA, EMEP and ACTRIS should be involved in the harmonization of methods between sites to ensure data quality, comparability, and dissemination.

To be useful in the context of the available measurements described in this report, new sites would need to follow the guidance of WMO-GAW with respect to instrumentation and methods, and also provide a broad range of atmospheric variables as defined by the WMO-GAW implementation plan (https://public.wmo.int/en/resources/library/wmo-global-atmosphere-watch-gaw-implementation-plan-2016-2023). We also recommend additional measurements of EC and OC by standardised thermal-optical or thermal analysis. Complementary measurements of macro-tracers, including isotopic (^{14}C) analysis on filter samples collected for EC/OC analysis, can improve source apportionment studies and will allow for the study of the transport and impacts of BC in the Arctic. On-line instruments, such as multi-wavelength AEs and aerosol mass spectrometers, have proven highly successful for source apportionment purposes (Winiger et al., 2015), and their applicability for the Arctic environment should be explored. To ensure the comparability and compatibility among datasets collected at different sites and time periods, it is recommended that several homogeneous reference materials be established for use in regular data intercomparison activities of BC measurements.

Reporting of BC data to international databases was found to be only partly successful. Data providers generally demonstrate good documentation, and data documentation and reporting has improved significantly over time. However, data reporting is generally based on informal obligations without the provision of resources to support these efforts. We assume that the lack of strong incentives and associated funding is the major factor limiting the availability of data from existing efforts. It is thus recommended to consider strengthening the resources available to support data collection and review efforts in the Arctic region.

Interactions between data originators and data centres are time-consuming and the potential for errors to be introduced during the exchange of data exists. During the course of this review, numerous corrections and improvements to international monitoring databases were identified, and at the time of completion, several updates still remain. Therefore, we recommend that bilateral annual reviews between data providers and data centres be conducted to identify and correct errors in data, thus improving the ability to accurately track trends in Arctic BC.

Personal Communications

Aurela, M. Finnish Meteorological Institute, Helsinki. Finland.

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Acronyms and Abbreviations

AAC	Aerosol absorption coefficient
AAOD	Aerosol absorption optical depth
AARI	Arctic and Antarctic Research Institute
AATSR	Advanced Along-Track Scanning Radiometer
ACES	Department of Environmental Science and Analytical Chemistry at Stockholm University
ACTRIS	Aerosol, Clouds and Trace Gases Research Infrastructure
AE	Aethalometer
AMAP	Arctic Monitoring and Assessment Programme
AOD	Aerosol optical depth
AWI	Alfred Wegener Institute
BC	Black carbon
CABM	Canadian Aerosol Baseline Measurements
CALIOP	Cloud-Aerosol Lidar with Orthogonal Polarization sensor
CLRTAP	Convention on Long-Range Transboundary Air Pollution
CLAP	Continuous light absorption photometer
CMIP6	Coupled Model Intercomparison Project Phase 6
CNR	National Research Council (Italy)
CO_2	Carbon dioxide
eBC	Equivalent black carbon
EC	Elemental carbon
ECCC	Environment and Climate Change Canada
EEA	European Environmental Agency
EMEP	European Monitoring and Evaluation Programme
EUA-BCA	European Union Action for Black Carbon in the Arctic
EUSAAR	European Supersites for Atmospheric Aerosol Research
FMI	Finnish Meteorological Institute
GAW	Global Atmosphere Watch
HIPS	Hybrid integrating plate
IMPROVE	Interagency Monitoring of Protected Visual Environments
IPCC	Intergovernmental Panel on Climate Change
LII	Laser-induced incandescence
LPM	Litres per minute
MAC	Mass-specific absorption cross-section
MAAP	Multi-angle absorption photometer
MOSAIC	Multidisciplinary Drifting Observatory for the Study of Arctic Climate
MISR	Multi-angle imaging spectroradiometer
MSI	Multi-spectral imager
NCSR	National Centre for Scientific Research (Greece)
NETCARE	Network on Climate and Aerosols: Addressing Key Uncertainties in Remote Canadian Environments
NILU	Norwegian Institute for Air Research
NIOSH	National Institute for Occupational Safety and Health
NOAA	National Oceanic and Atmospheric Administration
OC	Organic carbon
OMI	Ozone Monitoring Instrument
PARMACMIP	Polar Airborne Measurements and Arctic Regional Climate Model Simulation Project
PM	Particulate matter
PSAP	Particle soot absorption photometer
QA/QC	Quality assurance/quality control
rBC	Refractory black carbon
SP2	Single particle soot photometer
SP-AMS	Soot particle-aerosol mass spectrometer
TOR	Thermal optical reflectance
TSP	Total suspended particles
UNECE	United Nations Economic Commission for Europe
UAS	Unmanned aerial system
UV	Ultraviolet
WMO	World Meteorological Organization
WCCAP	World Calibration Centre on Aerosol Physics
YAK-AEROSIB	Airborne Extensive Regional Observations in Siberia

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