Harmonising environmental research and monitoring of priority pollutants and impurities in the Svalbard atmosphere (HERMOSA)

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1. Introduction

Atmospheric pollution research and monitoring in Svalbard occupies a significant position in pan-Arctic research on priority pollutants (AMAP 2016, 2017), providing observations of their long-range atmospheric transport (Iversen and Joranger 1985; Hung et al 2010). Atmospheric research in Svalbard has been increasing in diversity and magnitude in recent years, with more comprehensive long-term observational efforts and numerous short-term intensive field experiments. Coordination of the research and scientific exchange in terms of common sampling and analytical protocols, joint data analysis, publications, and related planning of future research has growing potential. Coordination offers two advantages: it lowers the environmental footprint of researchers coming to Svalbard (by reducing the number of people necessary to collect samples for various impurities) and allows researchers to see a bigger, interconnected picture of environmental processes.

In this chapter, we collect information from various sources on the state of the research and monitoring of priority pollutants and other impurities in the atmosphere over Svalbard, bridging the chemical, biological and supportive physical monitoring efforts. By atmospheric impurity we mean any kind of substance that is dispersed in the atmosphere, whether in gaseous or particulate form. The definition encompasses molecules of various sizes and chemical composition, as well as biological cells and small organisms, referred to as aerial plankton. Among physical properties of the atmospheric aerosol, we mention mainly the aerosol optical depth (AOD) as a basic parameter monitored in Svalbard, however AOD is elaborated on elsewhere (e.g. Hansen et al 2023). Unfortunately, it is impossible to list every short-term dataset from campaigns conducted in Svalbard, hence we only strive for a representative overview with a focus on long-term monitoring programmes. The opportunities for harmonising several types of measurements are sought in this work, and the distribution of measurements across Svalbard is both an opportunity and a hindrance; hence, the first iteration of the problem is divided by geographical locations. Direct monitoring of atmospheric impurities is also closely connected to their deposition in precipitation. Therefore, we also mention efforts in precipitation sampling which may lead to synergy with aerosol or air sampling, though we must restrict considerations of the topic to such cases alone (excluding, for example, the literature on ice cores collected in Svalbard).

Abbreviations used in the text

AOD	aerosol optical depth
BC	black carbon
CCN	cloud condensation nuclei
CEACs	chemicals of emerging Arctic concern
CFCs	chlorofluorocarbons
eBC	equivalent black carbon
GC	gas chromatograph
NILU	Norwegian Institute for Air Research
NOAA/CMDL	US National Oceanic and Atmospheric Administration/Climate Monitoring and Diagnostics Laboratory
PAHs	polycyclic aromatic hydrocarbons
PCBs	polychlorinated biphenyls
PFAS	per- and polyfluoroalkyl substances
PM	particulate matter
POPs	persistent organic pollutants

Previous SESS Reports have included a few chapters showing a fraction of the vast topic of atmospheric impurities (Gallet et al 2019; Malard et al 2019; Petkov et al 2019; Viola et al 2019; Gilardoni et al 2020; Mazzola et al 2020; Sipilä et al 2020; Singh et al 2021; Traversi et al 2021; Petkov et al 2022). In the interest of efficient information processing, we will only refer to topics previously described in SESS reports to the extent which is necessary to understand the potential for harmonisation between the already described and other atmospheric components. The same approach is taken with the parallel chapters in this report on mineral dust (SVALDUST, Di Mauro et al 2023) and AOD measurements (LOAD-RIS, Hansen et al 2023). Due to the focus on measurement harmonisation and the best potential to do so for lower tropospheric, ground-based measurements, we will narrow our focus to these kinds of experiments and monitoring programmes.

2. Overview of existing knowledge

2.1. Existing monitoring and available datasets

2.1.1. Atmospheric impurity monitoring in Ny-Ålesund

Ny-Ålesund has an unparalleled position for atmospheric impurity monitoring in the Arctic and Svalbard, holding two main facilities with an elevation difference of 425 m (Gruvebadet Atmosphere Laboratory 'Gruvebadet' at 50 m and Zeppelin Observatory 'Zeppelin' at 475 m asl), and several facilities dispersed in its vicinity (Figure 1). It offers a unique opportunity for harmonised studies of atmospheric impurity differences with elevation (within and beyond the boundary layer) and between multiple impurities. For example, a recent study (Song et al 2022) explored the sources of atmospheric particles in Ny-Ålesund with machine learning, showing the importance of secondary aerosol in cloud condensation processes and predicting non-linear changes in aerosol composition with temperature changes (resulting from climate change).

The earliest regular monitoring work at Ny-Ålesund was conducted by the Norwegian Institute for Air Research (NILU), starting as early as 1989 (for SO_2 and SO_4^{2-} measurements), although short-term studies had been conducted there earlier, e.g. in 1980-83 on organochlorine persistent organic pollutants (POPs) by Oehme and Ottar (1984). NILU's main facility is located on top of Zeppelin (joined since by other institutions), a unique site where local contamination factors exert a much smaller influence than at any other land-based station in Svalbard due to its elevation. NILU is collecting data on a wide range of variables there, from inorganic ions and gaseous compounds (oxides of carbon, sulphur and nitrogen, also H_2 and NH_3), through various forms of mercury in atmospheric air, to metals and metalloids in precipitation. Carbon dioxide concentrations are monitored there by Stockholm University; in parallel, weekly flask samples have been analysed for trace gas concentrations by the US National Oceanic and Atmospheric Administration's Climate Monitoring and Diagnostics Laboratory (NOAA/CMDL). The monitoring programme at Zeppelin also spans organic compounds: greenhouse gases (CH_4, fluorinated gases), POPs and selected contaminants of emerging Arctic concern (CEACs) (AMAP 2011, 2016, 2017; Carlsson et al 2016; Platt et al 2022; Xie et al 2022b), saccharides, volatile organic compounds and more (ebas-data.nilu.no/; see also section 6. *Data availability*). Furthermore, selected POPs and CEACs have been detected in air samples from Ny-Ålesund (as well as Longyearbyen, Barentsburg and Hornsund) via diverse national research projects (Appendix 1 & 2). The concentrations of most POPs listed for control under the Stockholm Convention, e.g. polychlorinated biphenyls (PCBs) polybrominated diphenyl esters (PBDEs), and organochlorine pesticides, showed clearly seasonal variation and declining trends over the years from the 1990s to 2021 (AMAP 2016; Wong et al 2021). Given the advances in sampling and analytical techniques,

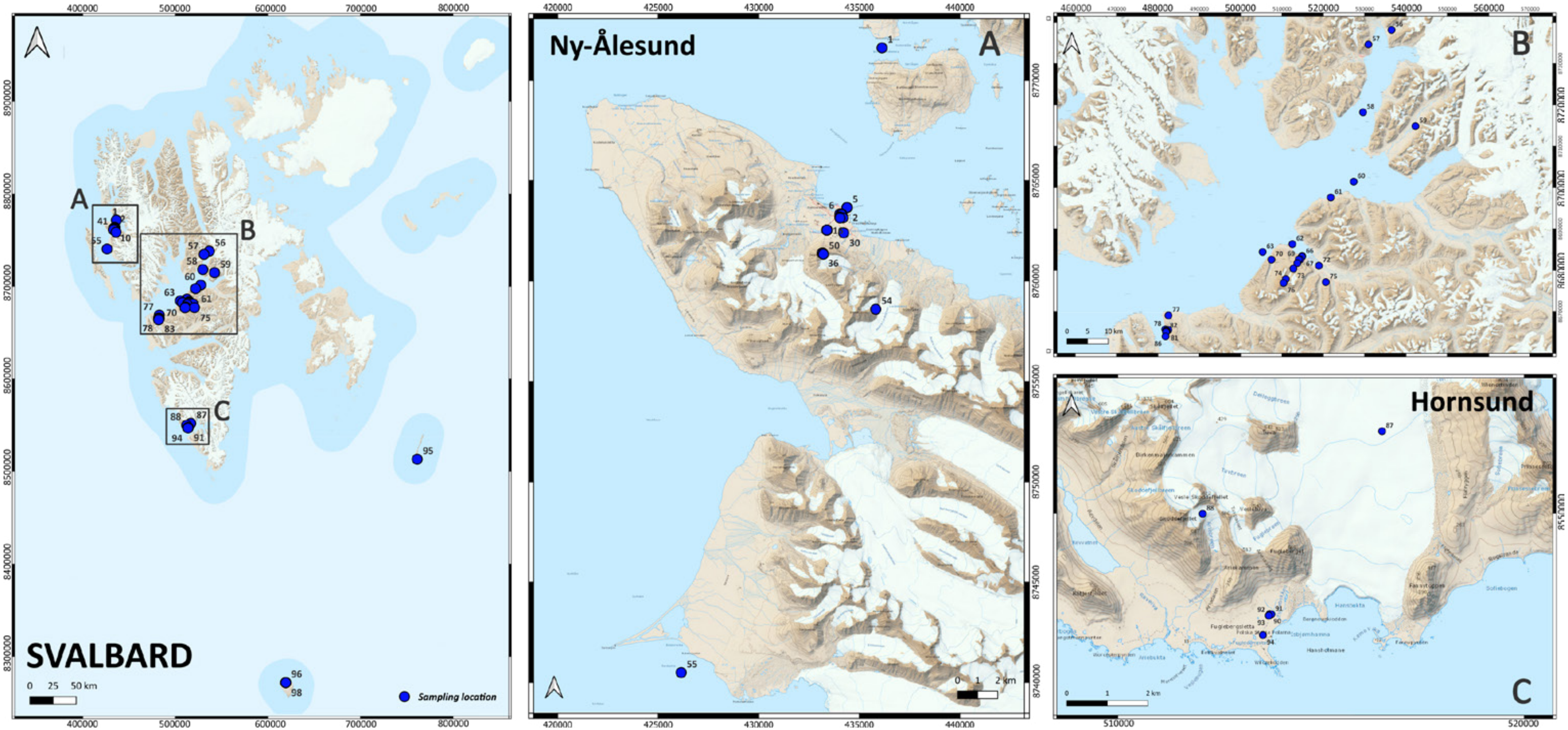

Figure 1: Distribution map, showing measurement sites relevant to the topic of atmospheric impurity monitoring and harmonisation across Svalbard. The numbered locations are described in Appendix 2. Map source: Norwegian Polar Institute, toposvalbard.npolar.no.

more and more novel CEACs have been identified and quantitatively detected in Arctic air (see Appendix 1; Xie et al 2015; Wong et al 2021). Unfortunately, the time trends of CEACs are not as clear as those for classic POPs, and the relatively high concentrations of CEACs in Arctic summer imply the impact of local sources or reemission from cryosphere (AMAP 2017; Xie et al 2022a). Studies of CEACs from Svalbard also testify to the transport, persistence, and impacts of these chemicals in the Arctic (Hao et al 2021; Li et al 2022).

A large part of the atmospheric impurity research at Ny-Ålesund is now carried out in Gruvebadet, about 1 km away from the main settlement. Gruvebadet is dedicated to the study of the atmospheric composition and the atmosphere–cryosphere interaction. It is equipped with several instruments for aerosol studies (see positions 12-29 in Appendix 2). The accessible roof holds an installation of both sampling heads and full samplers (Figure 2). Several continuous measurements are performed at Gruvebadet to fully characterise the aerosol composition within the planetary boundary layer during the entire year, alongside dedicated experimental campaigns. Specialty areas of Gruvebadet laboratory include size-segregated chemical and optical analyses of particulate matter (PM, in this case PM10, which has a maximum diameter of 10 µm), including trace elements, water-soluble organic carbon, and forms of black carbon (BC), microplastics, additives, plasticisers and other CEACs, as well as properties of ice nucleating particles, all performed with state-of-the-art analytical techniques. Multi-decadal results on equivalent black carbon (eBC; see section 2.2) in Svalbard are available from Zeppelin; since 2010, these data have been integrated into the measurements at the Gruvebadet laboratory (cf. Gilardoni et al 2020). Continuous monitoring of the optical (scattering and absorption) and physical (dimensional distribution) properties of the in-situ aerosol is conducted using semi-automatic instrumentation (nephelometer, scanning mobility particle sizer and aerodynamic particle sizer absorption photometer) in collaboration between Italian institutions running Gruvebadet and the Alfred Wegener Institute (Germany), the Institute for Atmospheric and Earth System Research (Finland), Stockholm University (Sweden), the National Centre of Science Research 'Demokritos' (Greece) and the Korean Polar Research Institute (Republic of South Korea). Recently (in 2021), a campaign was conducted to measure particle fluxes using the eddy covariance technique, encompassing measurement of momentum flows and ultrafine particles with a sonic anemometer and a condensation particle counter. Flow measurements of dimensionally segregated particles were conducted through the use of an optical particle counter. A passive sampler for dry deposition of aerosol, and a 'Cyclone' sampler collecting spores and pollen, complement the programme at this supersite.

The Gruvebadet facility is also used to study the atmosphere–cryosphere interaction (in tune with a SESS report recommendation by Gallet et al 2019), through a parallel programme of snow monitoring (for wet and dry deposition), showing the role of snowpack as a chemical sink for emissions from rock weathering, forest fires, marine and biogenic emissions, and anthropogenic contaminants, such as BC, secondary aerosols (e.g. SOx, NOx), complex organic pollutants (e.g. POPs) and heavy metals (e.g. As, Cd, Pb). Quantifying the concentrations of those impurities in the seasonal snowpack allows us to understand the accumulation and depletion mechanisms, and consequently to assess the total load of contaminants potentially released by spring melt into the local food chain. Furthermore, air–snow exchange may significantly interfere with atmospheric concentrations of per- and polyfluoroalkyl substances (PFAS) at Ny-Ålesund, showing strong snow to air evaporation for fluorotelomer alcohol and fluorotelomer acrylates (Xie et al 2015). For atmosphere–cryosphere interaction studies, a weekly sampling of the entire snowpack has been adopted – by snow pit approach, with a vertical resolution of 10 cm. Snow is then analysed to quantify the concentration of elements and compounds of interest (at the National Research Council of Italy, Institute of Polar Sciences), the BC loading (at the Norwegian Polar Institute) and to characterise the microbial community (at Université de Lyon, Centre national de la recherche scientifique). Snow density and stratigraphy data support interpretation of the

Figure 2: Overview of the instruments placed atop the roof of Gruvebadet Atmosphere Laboratory. (Photo: Marco Casula)

chemical data, and an automated nivometric station has been working near the Gruvebadet site since 2020.

It is worth mentioning that at Gruvebadet, several measurements have been integrated into one sampling protocol, described partially in the studies using the data collected there (Scalabrin et al 2012; Zangrando et al 2013; Turetta et al 2016, 2021; Feltracco et al 2019, 2020, 2021b, a). The currently developing project BETHA-NyÅ[1] aims to further harmonise aerosol measurements at Gruvebadet and Zeppelin, as proposed by Traversi et al (2021).

2.1.2. Other land-based atmospheric impurity research in Svalbard

Besides the atmospheric measurement hub at Ny-Ålesund, the main air impurity screening sites in Svalbard are located in Longyearbyen, Barentsburg, and Hornsund; however, studies on specific topics may be encountered in other locations, such as Petuniabukta. One of the earliest monitoring sites in the Norwegian Arctic (including Svalbard) was Bjørnøya – inorganic compounds in atmospheric air and aerosol have been measured there since 1977[2] (SO_2 in atmospheric air). Important discoveries at that time were made possible by this station functioning, e.g. Iversen (1989) showing the meteorological mechanism of long-range atmospheric transport causing winter/spring pollution maxima. The measurements in Bjørnøya were phased out in 1989.

In Longyearbyen, a strong focus of atmospheric impurity research was on local and regional pollution. A fully equipped sampling observatory has been established on the roof of UNIS, with several high volume air samplers (TISCH, Cleves, OH, USA, Type TE-1000BL; US Environmental Protection Agency TO-A4, TO-9A). Further campaignbased studies were conducted at the former Aurora

1 [RiS ID 11924](RiS ID 11924)
2 http://ebas.nilu.no/

observatory in Adventdalen, and in collaboration with SvalSat on the adjacent mountain Platåfjellet. During the past years, in Longyearbyen, POPs and novel CEACs have been detected in gaseous and/or particle phase during research projects (including novel PFAS, polychlorinated biphenyls [PCBs] and polycyclic aromatic hydrocarbons [PAHs] and their major transformation products).

The research conducted in Longyearbyen has been instrumental in documenting the transition from a coal-mining-based community to a settlement relying mostly on services as an income source, with both sources contributing to local air pollution. Coal mining has been present in Longyearbyen (and Svalbard in general) since the early 1900s when John Munro Longyear established the first mining infrastuctures in Adventdalen (Westby and Amundsen 2003; Kvello 2004). Since then, five major locations across Svalbard have had large coal mining infrastructures established and in operation (Appendix 3). After the Norwegian government decided to abandon coal mining in Svalbard (in 2017), other activities such as services, municipal administration, research, education, construction and maintenance, as well as international tourism, have replaced coal mining as the main source of employment in Svalbard (Avango 2020).

Today, around 3000 inhabitants are living and working in Svalbard, mainly in Longyearbyen (2400) and Barentsburg (400). All settlements in Svalbard are isolated infrastructures: life-supporting services such as heating, electric power, water supply, and waste handling need to be provided on-site. In addition to high costs of infrastructure operation, settlements in Svalbard have a significantly higher ecological footprint per inhabitant compared to mid-latitude locations, where infrastructure is shared. An earlier report by the Norwegian Environmental Agency concluded that Svalbard's man-made CO_2 emissions (produced by ca 3000 people = 0.06% of the total population) accounted for ca 1% of the total Norwegian CO_2 emissions in 2009 (Vestreng et al 2009). Hence, it is important to control local emissions, not least to minimise the risk of exposure for local populations (e.g. to CEACs).

For two decades now, Svalbard settlements have been comprehensively investigated for local pollution. Transportation and emissions from gasoline-fuelled engines are an important local contamination source in Svalbard. Shipping, the operation of heavy vehicles that run of fossil fuels (e.g. lorries), and private transportation (cars, snowmobiles) contribute significantly to the local pollution profile. Reimann et al (2009) reported on the emission of volatile organic compounds in Longyearbyen, especially aromatics, from snowmobile exhaust. Elevated levels of aromatics were attributed to the extensive use of two-stroke engine snowmobiles between November and June. Aromatics were emitted at levels similar to those of a medium-sized European city, like Zürich (400 000 inhabitants). Also for PAHs, elevated air concentrations were confirmed to come from fossil-fuel-driven engines, both in and around Longyearbyen. A variety of local sources such as a local petrol station, the coal power plant and various municipal installations were confirmed. Unlike aromatics, PAHs are environmentally stable contaminants and hence were subsequently found in surface soil along major snowmobile tracks near Longyearbyen.

PAHs are relevant local pollutants, and coal-fired power plants both in Longyearbyen and Barentsburg are identified as their major local source. A recent comprehensive study investigated the emission profile and the rapid atmospheric transformation process for PAHs (Marquès et al 2017; Drotikova et al 2020, 2021). Air samples from three locations, at increasing distances from the source (0 to 8 km from the power plant), were investigated for PAHs and their major transformation products (oxy- and nitro-PAHs). Seasonal profiles have been described: during polar day, rapid photochemical transformation eliminates nitro-PAHs, while oxy-PAHs are less affected.

In the past years, a variety of new organic pollutants were identified as local contaminants in Svalbard (AMAP 2017; Kallenborn et al 2018). Among CEACs, PFAS were found to be directly emitted from Svalbard installations, mainly at the local airports (Longyearbyen, Ny-Ålesund, Svea – the fire fighting training locations) and local waste dumps

(Skaar et al 2019; Ali et al 2021). Elevated levels of PFAS in the local food webs were confirmed both in Ny-Ålesund and Longyearbyen. Recently, a study on surface snow revealed the presence of novel ultra-short PFAS in the vicinity of Longyearbyen (Foxfonna glacier). Here, the photochemical transformation of long-chain precursor PFAS led to elevated levels of trifluoroacetate and trifluoromethane sulphonic acid in surface snow. Trifluoroacetate was also identified in drinking water in Longyearbyen (Nödler, pers. comm.), proving the importance of PFAS emission screening.

In Barentsburg, aerosol measurements started in 2011 (Sakerin et al 2012; Golobokova et al 2013). Since 2016, systematic measurements of optical, microphysical and chemical aerosol properties have been conducted by researchers from the Russian Academy of Sciences and the Arctic and Antarctic Research Institute (Chernov et al 2016, Sakerin et al 2018; Sakerin et al 2019). AOD, and other physical properties including eBC concentration, have been measured by sun photometer (since 2015), aethalometer, integrating nephelometer and a photoelectric particle counter (Sakerin et al 2012, 2019; Chernov et al 2016). Aerosol was sampled for further measurements of chemical composition, for example the concentration of major inorganic ions and trace metals (Chernov et al 2016; Sakerin et al 2018; Golobokova et al 2020). The sampling was performed according to international guidelines (EMEP 2001; EANET 2003). Alternating daily and weekly modes, 14 to 18 m^3 of air was pumped through a four-stage filter holder at 2 m above the ground on the south side of Barentsburg Meteorological Observatory (V. Radionov, pers. comm.). Concentrations of 17 PAHs were also measured there in aerosol (Sep-Oct 2017; Golobokova et al 2020).

The chemical composition of the atmospheric boundary layer was observed daily from April to September in 2011-2015, and monthly from April 2016 to 2018. Since 2016, atmospheric gases (CO_2, CO, SO_2, H_2S, NO_x, O_3 and gaseous Hg) have been automatically monitored, maintained by the Arctic and Antarctic Research Institute, and the data were occasionally used for comparisons with other sites in Svalbard. Since 2019, aerosol is sampled weekly. The highest ion concentrations were measured in 2011-2012 during the renovation of Barentsburg. After the introduction of a filter system on Barentsburg power plant in 2012, the total ion concentrations were halved by 2016, but subsequently increased slightly (Sakerin et al 2018). Generally, ion concentrations increase in winter-spring and drop slightly in May-June, with sea spray as a main source of aerosol throughout the year and the local influence of coal mining and power plant exhaust being more prominent during the polar night (Golobokova et al 2020).

The ground-based monitoring programme Northwest branch of RPA 'Typhoon' (Saint Petersburg) includes the analysis of atmospheric aerosol for 16 PAHs, PCBs and trace metals, since 2002 (Demin et al 2011). Apart from direct measurements, method development and intercalibration exercises with NILU were conducted. Samples have been collected twice a year in spring (March) and late summer (August) with a multichannel low-volume sampler simultaneously on three AFA-HA-20 filters (acetate cellulose fibrous material with electrostatic effect, 20 cm^2) at three sites in Barentsburg and outside the settlement (Demin et al 2011; E. Yaeski, pers. comm.). The methods of sampling and analysis remained unaltered for the whole observation period.

The Governor of Svalbard, in collaboration with the Norwegian Environmental Protection Agency (Miljødirektoratet), commissioned a Svalbard-wide survey on potential local sources of PCBs in 2007 (Lundkvist et al 2008). In virtually all settlements in Svalbard, elevated PCB concentrations were found in the local environment; decommissioned and defective technical equipment (like transformers) was identified and removed for proper destruction. This first survey noted the paucity of information on PCB contamination from Russian settlements and hence a dedicated campaign for mapping PCB contamination in Barentsburg and Pyramiden was initiated (Evenset and Ottesen 2009). The latter authors concluded that although local emissions could be considered high, the majority of PCB pollution in Svalbard stems from decades of long-range atmospheric transport.

In southern Spitsbergen, long-term monitoring of several atmospheric pollution parameters is carried out at the Polish Polar Station in Hornsund. This station is the site that has been operating longest in the AERONET network in Svalbard, among other things providing continuous cloud-screened observations of spectral AOD since 2004. Aerosol studies have been complemented with ceilometer data since 2017. Extended measurements of aerosols in the atmosphere were conducted there in the years 2009-2015, when Raman lidar was operational (Pietruczuk and Karasiński 2010), detecting the impact of volcanic ash (Karasiński et al 2013) or wildfires (Markowicz et al 2016) on the atmosphere of Svalbard. In the spring of 2021, more detailed data on the concentration of the aerosol and its size distribution were collected using OPS 3330 and NanoScan SMPS 3910 TSI spectrometers.

The chemical composition of aerosol is also monitored at the Polish Polar Station in Hornsund, albeit less comprehensively. This is one of the northernmost continuous monitoring sites for radionuclides in the ground-level atmosphere since 2002 (Mysłek-Laurikainen et al 2006) and was recently expanded to include an EcoGamma environmental gamma radiation monitor. This monitoring additionally provides information on the concentration of dust deposited on Petrianov filters in an AZA-1000 high-volume air sampler, which are replaced at weekly intervals (Burakowska et al 2021). The measurements have confirmed an influx of radioactive isotopes into Svalbard after the Fukushima nuclear power plant disaster (Burakowska et al 2021), which was visible also in Ny-Ålesund (Paatero et al 2012). Besides this ongoing programme, recent measurements have been made in Hornsund within the scope of short-term projects (Sea-snow POPs[3] and HiLDA[4]) since 2019, to determine the concentration of organic compounds in the atmosphere at Hornsund and to characterise mineral and anthropogenic compounds in atmospheric particulate matter.

Since 2004, monitoring of the chemical composition of precipitation (rain and snow) has been carried out in Hornsund (Figure1, see also Appendix 2). Samples are collected: a) ~500 m north of the station (from a high-density polyethylene precipitation collector), after each rain or snowfall; b) on glaciers (Hansbreen until 2019; Ariebreen since then) after each snowfall near the ablation poles (into polyethylene bags); c) in an elevation transect from the seashore to the summit of Fugleberget, irregularly (into polyethylene bags). All physico-chemical analyses are carried out in the station's chemical laboratory. After pH, conductivity and HCO_3^- titration measurements, samples are filtered (on 0.45 µm cellulose membrane filters) and analysed for the major ion composition using ion chromatography (now a Methrom 930 Compact chromatograph). The data on precipitation composition collected at Hornsund, before and after 2004, allows characterisation of the origin of rain and snow (e.g. Pulina 1991; Głowacki and Leszkiewicz 1994; Głowacki and Pulina, 2000; Burzyk et al 2001; Krawczyk et al 2002; Krawczyk and Skręt 2005; Kozak et al 2015), spatial differences in precipitation chemistry (e.g. Krawczyk et al 2008), and the impact of wildfires and long-range transport (e.g. Bryś 2002; Głowacki and Krawczyk 2002; Ruman et al 2014; Kozak et al 2015; Nawrot et al 2016).

2.1.3. Specific study topics with atypical or sparse spatial representation

Aeolian dust studies in Svalbard, which recently started again after lying dormant since the 1980s (e.g. Pękala 1980; Åkerman 1983; Gębica and Szczęsny 1988), are limited to a few sites. Direct observational data exist only for Ny-Ålesund (Moroni et al 2015, 2016, 2018; Gallet et al 2018; Conca et al 2019; Jacobi et al 2019), Hornsund (Migała and Sobik 1984; Kavan et al 2020; Lewandowski et al 2020; Spolaor et al 2021), and Longyearbyen (e.g. Khan et al 2017; Kandler et al 2020). Apart from that, there are only two studies from Petuniabukta area in central Svalbard (Kavan et al 2020; Rymer et al 2022). The studies at Ny-Ålesund were conducted using ground level active filtering (Conca et al 2019), or vertical profiling (Moroni et al 2015, 2016); the

3 RiS ID 11108
4 RiS ID 11195

detailed mineralogical and chemical composition of the aerosol was reported by Moroni et al (2018). Aeolian processes are also monitored as the deposition of material on snow (Khan et al 2017; Gallet et al 2018; Jacobi et al 2019; Kavan et al 2020; Lewandowski et al 2020; Spolaor et al 2021). The only direct deposition of dust was observed by Rymer et al (2022) using passive samplers in central Spitsbergen. Quantifying mineral dust deposition remains a challenge due to its large spatial and temporal variability – the measured deposition rates vary, are site-specific, and depend on the method used.

Another type of measurement sparsely distributed across Svalbard is aerobiological sampling. Aerobiology research is a relatively nascent field in Svalbard; few studies have been published from the archipelago on aerial microbiology and aerial plankton, or on the transport of pollen and eukaryotic spores, both of local and distant origin (cf. Figure 1). Johansen and Hafsten (1988) detected pollen, bryophyte and fungal spores in Bürkard traps at Ny-Ålesund, most of them of local origin. However, Polunin (1955) found mostly exotic pollen species for Svalbard including *Pinus* pollen, highlighting the role of long-range transport. In a study on bacterial diversity in the air over Svalbard (Cuthbertson et al 2017), biodiversity was found to be similar to that in other environments, both polar and non-polar. The identification of viable bacteria suggests that living bacteria are ubiquitous in the air around Svalbard. In a six-month study on the composition of the bacterial community in the atmosphere at NyÅlesund, community structure exhibited seasonal dynamics that mimicked the different stages of bacterial colonisation of algal blooms in the surrounding fjords. This highlights the importance of open water as a source of airborne microorganisms (Feltracco et al 2021a). In a cultivation-dependent study (likely to underestimate the number of live airborne microorganisms), fifteen fungal taxa were isolated from the air of Longyearbyen (Pusz and Urbaniak 2021). Currently, no long-term monitoring programmes focus on aeromicrobiology in Svalbard, although the project ArcticBioAir[5] is generating pilot data to determine the potential of such monitoring. Finally, even though microinvertebrates predominate in the faunal diversity of polar regions and play a pivotal role in matter flow, the majority of studies investigate microinvertebrate transport only by migratory birds, humans or imported soils (Coulson et al 2013; Pilskog et al 2014). Few studies discuss passive transport of invertebrates by wind at all (Hodkinson et al 2001; Coulson et al 2002, 2003; Coulson 2015), and among them, only two test aerial transport empirically (Coulson et al 2002, 2003).

2.1.4. Atmospheric impurities research from the seas surrounding Svalbard

A complementary element of atmospheric impurity monitoring in Svalbard is that it is also done in the seas around the archipelago. While the sampling techniques and protocols match those used on land, the research done at sea is tied geographically to cruise routes and thus repeated measurements concern a wider area rather than an exact location. Challenging atmospheric conditions at sea introduce potential obstacles to measurement, e.g. dense fog, strong winds and breaking waves.

Since 2004, AOD instruments have been deployed periodically on various ships navigating around Svalbard: *RV Oceania* (2007, 2009-2020, e.g. Leck et al 2001; Tjernström et al 2014; Heintzenberg et al 2015), the Swedish icebreaker *Oden* (2008; ASCOS campaign – Chang et al 2011; Sierau et al 2014), *RV Polarstern* (2012, 2015, 2017, 2020), *RV Jan Mayen* (2009); *RV Akademik Mstislav Keldysh* (2016; Terpugova et al 2018) and *RV Alliance* (2021). *RV Oceania*, owned by the Institute of Oceanology, Polish Academy of Sciences, participates in the Maritime Aerosol Network, a component of the AERONET network, and has been providing AOD measurements from the Norwegian and Greenland Seas since 2007. Since 1987, the Institute of Oceanology has been conducting a regular, annual AREX Arctic Expedition (Węsławski and Sagan 2020), performing meteorological surveys, measuring aerosol fluxes, and the physical and optical properties of aerosols right from the

5 RiS ID 11752

start. The cruises are conducted year by year with almost the same research plan, with continuity and repeatability both in time and space, covering about 90 days in the Arctic each summer (Ferrero et al 2019; Pakszys et al 2020). The annual summer cruise of *RV Oceania* cruise is one of the longest monitoring programmes conducted in the Svalbard seas. Recently, in collaboration with the University of Mila Bicocca, PAHs, n-alkanes, organic matter and trace elements have occasionally been included in the monitoring.

The German research icebreaker *RV Polarstern* (of the Alfred Wegener Institute) has a longer Arctic history than *RV Oceania*, starting in 1991, continuing between 2001 and 2021 (2009, 2012, 2015, 2017, 2020, 2021), and crowned with the longest expedition across the ArcticOcean: the MOSAiC cruise, which lasted over a year. This was the first year-round expedition into the central Arctic to explore the Arctic climate system, drifting with the sea ice across the central Arctic from September 2019 to October 2020, launching radiosondes along the way. The Institute's polar research aircraft and UAVs played an important part in atmospheric investigations throughout MOSAiC (Mazzola et al 2020; Griesche et al 2020).

Air quality monitoring at sea is especially important in the context of sea–air exchange phenomena. Substantial evidence from observations and modelling shows the impact of climate change on the biogeochemical cycle of POPs and CEACs in the Arctic, pertinent to both the seas and the atmosphere (Ma et al 2016). For instance, many legacy POPs have revolatilised into air from water, snow or ice as a consequence of sea ice retreat and rising temperatures (Ma et al 2011). Besides, many CEACs were likely transported with ocean currents and waves from the low and medium latitudes to the High Arctic. The warm Atlantic seawater may bring CEACs such as ionic PFAS, organophosphate esters, and compounds from pharmaceuticals and personal care products into the waters surrounding Svalbard and influence their atmospheric levels through air–water gas exchange or sea spray (Li et al 2017; Sha et al 2022). Both ship-based and stationary observations in Svalbard have shown that gas exchange between air and water/snow alters the atmospheric concentrations of chemicals (Yu et al 2019; Araujo et al 2022; Dastoor et al 2022).

2.2. Sampling techniques and data collection protocols

The liquids and solids dispersed in the atmospheric air (e.g. aerosols, PM) encompass both iorganic and organic chemicals, frequently in mixed particles, particles with specific optical properties, such as BC, and more complex and larger airborne impurities, such as pollen, microplastics, and small living organisms. Some of these substances have closely related aerosol and gaseous forms, e.g. sulphate in aerosol which comes from the dissolution of gaseous SO_2. With such a variety of analytes, a suite of analytical approaches need to be employed for their qualitative and quantitative characterisation. However, since the mode of transport is similar for multiple species of similar molecular or particle size, similar sample collection approaches can be used, which allows for harmonisation of several measurement types in one monitoring protocol. In harmonisation attempts, key variables to consider are the types of sampling consumables required (e.g. filter material or pore size), exposure time (or sampled air volume), and the analytical steps leading to final results.

The first group of chemicals with harmonised sampling regimes in the Svalbard monitoring includes gaseous constituents measured online, such as the greenhouse gases (CH_4, CO_2, hydrofluorocarbons, SF_6), O_3, and several ozone-depleting chemicals (chlorofluorocarbons [CFCs], hydrochlorofluorocarbons [HCFCs], halones, and other halogenated organic gases). The online measurements offer quick access to analytical results and high sampling frequencies, e.g. NILU monitors 23 gases at Zeppelin at least once per 4 hours (every 5 minutes for O_3). Most of these measurements are provided by automated gas chromatography (GC) systems with different detectors: flame ionisation for methane, MgO-UV for carbon monoxide, and mass spectrometry for halogenated compounds (Myhre et al 2010). CH_4 concentrations may also be measured with cavity ring-down spectroscopy (ebas-data.nilu.no/). For longer-term averages, weekly flask sampling has also been used for trace gas analysis by NOAA CMDL.

Inorganic ionic species in atmospheric aerosol play an important role as source indices (Giardi et al 2016; Udisti et al 2016; Amore et al 2022): for example, sodium and chloride typically originate from sea salt; bromide and iodide depend on the sea ice extent (Spolaor et al 2013). Some of them also play a role in climate forcing (Toon and Pollack 1980; Satheesh and Krishnamoorthy 2005), exerting a cooling effect by light reflection and forming reflective clouds (especially sulphate). Their role as cloud condensation nuclei (CCN) is also important (Merikanto et al 2009). Since it is relatively easy to determine the concentration of ions, they form a basis for further analyses and have been monitored in Svalbard for a long time. The traditional method of sample collection for the analysis of inorganic ions in air and aerosol includes a combination of denuders (glass and alkaline-carbon-coated) and filters (Beine et al 2001). The filter pack captures both fine and coarse particulate matter (a Teflon filter, 1-µm pore size) and acids evaporated from the front filter (a Nylon filter, 1-µm pore size). The analytical technique best suited for the determination of inorganic ions collected by both denuders and filters is ion chromatography. Collection times applied by Beine et al (2001) were between 12 and 24 hours. Nowadays, sampling and analysis of inorganic ions remains similar, yet with a large variety of modified protocols. For example, Teinilä et al (2003) used polycarbonate films and a sequence of membrane filters with two types of impactors in their NICE campaign (at Ny-Ålesund). In Barentsburg, samples were collected on a four-stage filter pack. The direct accumulation of aerosol took place at the first polytetrafluoroethylene filter (0.8 µm pore size; Golobokova et al 2013; Chernov et al 2016). Three other filters, chemically pre-treated (EANET 2003), collected gases (filter 2: nitric acid, filter 3: sulphur dioxide, hydrochloric acid, filter 4: ammonia). Similarly, Park et al (2017), Becagli et al (2019) and Jang et al (2021) used quartz filters to analyse sulphate and methandsulphonic acid concentration (at Gruvebadet). All the above studies used a variation of 18 MΩ water extraction and ion chromatography as determination technique. The variety of employed filter materials harmonisation of ion analysis with a different particulate impurity monitoring, using filter papers dedicated to that purpose.

Alternatively, copper grids coated with carbon film may be used, combined with a later analysis by electron microscopy (as at the Chinese Yellow River). Nanoscale secondary ion mass spectrometry may the be used to analyse the composition of individual aerosol particles (Chi et al 2015). At Gruvebadet, the equivalent of this approach is using nucleopore polycarbonate membrane filters with a 12-stage low volume impactor and analysis by scanning electron microscopy (see also section 2.1.1), which is also a way to study mineral dust composition.

For mineral dust quantification, most sampling protocols are rather individual and depend on the device used (for active sampling procedures). The passive sampling in Rymer et al (2022) used the standard Marble Dust Collector traps (Hall and Upton 1988). An alternative sample collection strategy involves sampling of snow cover as a substrate for mineral dust deposition. Usually only the upper layer of snow is sampled to avoid contamination from the ground surface.

Sampling for determination of metals and metalloids is very similar to sampling for determination of ions, and sometimes different parts of the same filter are used for both determinations (Zhan et al 2014; Golobokova et al 2020), which is an excellent harmonisation example. Analytical methods, invasive and non-invasive, are used to determine the content of metals and metalloids. The invasive method requires wet digestion of the sample, using e.g. nitric acid and microwaves as an energy source. Subsequently, the content determination is performed using inductively coupled plasma mass spectrometry (Berg et al 2004; Demin et al 2011; Zhan et al 2014; Bazzano et al 2016; Conca et al 2019, 2021; Golobokova et al 2020; Turetta et al 2021). This method can also be used to determine the isotope content of e.g. lead (Bazzano et al 2016). It is also possible to determine the content of the radioisotope ^{210}Pb using the automatic alpha/beta analyser (Paatero et al 2003). A non-invasive method is to use X-ray fluorescence spectroscopy (Anderson et al 1992; Shpartko et al 2021).

Among metals, mercury is of special importance due to its toxic effects. Hg is determined in the air in three forms: gaseous elemental, gaseous reactive and associated with particulates (Gauchard et al 2005). The most popular device for determining gaseous elemental Hg is a Tekran gas-phase mercury vapor analyser, which uses cold vapour atomic fluorescence spectrometry: atmospheric air is passed through a gold trap, the gold forms an amalgam with mercury, and after a specified sample enrichment time, thermal mercury desorption and final detection as HgO by atomic fluorescence spectrometry is performed. The other two types of mercury must first be isolated from the air stream: for gaseous reactive Hg, a KCl-coated annular denuder or soda lime trap is used, and for Hg on particulates, quartz filters are used. The enriched samples can then be analysed using the same spectrometric technique (Ferrari et al 2005; Osterwalder et al 2021). A detailed description of the repeatability of the method is presented by Aspmo et al (2005).

BC particles have a unique combination of properties, including strong visible light absorption, being refractory with an aggregate morphology, and insoluble in water and common organic solvents (Gilardoni et al 2020). BC mass concentrations are measured directly by incandescent and thermal techniques or indirectly from absorption measurements using appropriate mass absorption cross-section values as the conversion factor (Petzold et al 2013). Different terms are used for black carbon depending on the property being measured. While rBC refers to incandescent measurements, EC is used for thermal techniques and eBC is the term for optical or photoacoustic techniques. The results obtained with different techniques agree within a factor of two. The principal measurement technique for BC is based on single-particle soot photometers, using an online laser-induced incandescent method to determine the size distribution of rBC. Total mass concentrations and information on the mixing state of BC (a ratio of BC to total particle diameters) can also be derived (Schwarz et al 2010; Kondo et al 2011). Long-term monitoring of BC in the atmosphere is based on two other techniques. The first is the thermal-optical methods, which measure elemental and organic carbon at the same time (Caiazzo et al 2021). Active research networks have adopted different protocols to quantify elemental carbon (see WMO/GAW [2016] for details). Elemental carbon measurements may differ by up to a factor of two due to differences in protocols, instruments, laser signals, and corrections for the chemical character of organic carbon (Karanasiou et al 2015). Filter-based optical methods are another approach taken for long-term BC monitoring, providing outputs as eBC. Instrumentation available in Svalbard includes particle soot- and multi-angle absorption photometers and aethalometers (Petzold and Schönlinner 2004). Uncertainties in the filter-based absorption techniques are caused by non-BC aerosol compounds, which can either absorb or scatter the light when deposited on the filter, and by light scattering of the filter itself. Correction schemes have been developed for the Arctic to account for the effects mentioned above in the aethalometer absorption conversion (Backman et al 2017).

Atmospheric POPs monitoring at Zeppelin is a key component of the Arctic Monitoring and Assessment Programme (e.g., AMAP 2016), and its collection and analysis method are therefore well established. In order to generate high quality data and comparable results, a standard operation protocol for air sampling and analysis has been harmonised through the analytical laboratories working within the Programme for classic POPs including PCBs, PBDEs, OCPs and PFAS. Standard operating procedures have been created for both active and passive air sampling for POPs monitoring. Newer studies of POPs aspire to match the standard techniques closely, e.g. at Barentsburg, PAHs and PCBs were determined in particulate matter collected on glass fibre filters (14 m^3 of air collected in 24 hours) (Golobokova et al 2020). The concentrations of PAHs were measured by a GC-MS (GC with mass spectrometric detection) Triple Quadrupole system. In the RPA 'Typhoon' programme, less typically, 16 PAH concentrations were determined with high-performance liquid chromatography with fluorescence and diode array detectors. PCB analysis was performed with a GC with electron capture detection (Demin et al 2011, E. Yaeski, pers. comm.).

A challenging topic for the sampling and analysis techniques is CEACs, due to variety of the encountered substances, new substances being added to the catalogue, and their relatively low concentration levels. As the concentrations of CEACs in Arctic air are usually at picogrammes to nanogrammes per cubic metre (pg/m^3 to ng/m^3), suitable sampling and pre-concentration techniques are essential to match the sensitivity of the analytical instruments. Active air sampling is performed with a high-volume sampler equipped with glass- or quartz-fibre filters for collecting atmospheric particles (cutoff points vary), and solid adsorbents, e.g. Amberlite XAD-2 resin, polyurethane foam alone in combination with XAD-2 resin combination for the gaseous phase (Röhler et al 2020, 2021). Cellulose nitrate membrane filters (pore size: 1-5 µm) are used to trap microplastics in the air. The sampling of CEACs is typically compatible with the POPs collecting programmes.

Passive samplers (PAS) have been also deployed to monitor the background level and annual trends of POPs and CEACs in Svalbard (Li et al 2022). Sampling media include polyurethane foam discs, XAD-2 resin and semi-permeable membrane devices. PASs are cost-effective, simple in operation, and could be deployed anywhere, e.g. on a glacier or in remote sites without power supply, thus providing data from more locations.

Many other organic compounds are also screened in Svalbard by NILU, as can be ascertained from the EBAS database[6]. Such compounds are collected with a high-volume air sampler (besides selected POPs, including PFAS, also carbohydrates such as levoglucosan, mannitol and sucrose, and other substances, e.g. bisphenol A and triclosan; also total organic carbon), passive airsampler with a polyurethane foam plug (PAHs, PCBs, and organochlorine pesticides – a campaign in 2006), steel canister (chosen alkanes and alkenes), glass flask (selected alkanes), and adsorbent tube (selected aldehydes and ketones).

Given the diverse techniques and configurations developed for monitoring POPs and CEACs in Arctic air, sampling artefacts often occur related to the technical design, sampling material, or air-sampling interval, in particular: breakthrough, microbial or photo degradation, and equilibrium or non-equilibrium states regarding passive sampling (Bohlin-Nizzetto et al 2020; Li and Wania 2021; Hao et al 2021). The concentrations of certain POPs and CEACs could be underestimated by 30-95% (Melymuk et al 2014), which might override their seasonal variations and mislead the assessment of their environmental fate and related risk. Therefore, the current challenge is to validate sampling approaches with a focus on POPs and CEACs through interlaboratory comparison to achieve comparability of air impurity measurements in the Arctic. Detailed information on methodologies for air sampling, chemical analysis, data management and quality assurance/quality control is provided in the literature and annual reports (NILU 2021).

A distinct set of methods is dedicated to aerobiology, even though the basic collection mechanism resembles that for other particulates (Feltracco et al 2021a). Aerobiological sampling methods involve impaction, impingement, membrane filtration (Figure 3) or drop plate mechanisms, which have been extensively reviewed in Griffin et al (2011). Although efforts have been made to establish standard methodologies (Pearce et al 2016; Dommergue et al 2019; Jensen et al 2022), no single ideal method exists. For example, microinvertebrates passively transported by wind are still collected by classical techniques, unchanged for decades. Each methodology has advantages and disadvantages (Table 1) – selecting the right one will depend on the research question. Recent developments in this regard include work by Ferguson et al (2019), who evaluated airborne recovery efficiencies using filtration and liquid impingement and found filtration using polycarbonate filters to give the best recovery, with impingement recommended for shorter duration

6 http://ebas-data.nilu.no

of sampling. Luhung et al (2021) investigated DNA extraction efficiencies from filters and found that direct extraction (by placing sampling filter into extraction kit) underestimated total cell numbers. Instead, they suggested a two-stage approach: first removing biomass from the filter, then re-filtering onto a smaller, thinner membrane. Total bacterial count can be measured by growing cells on agar and counting the total number of colony-forming units and using fluorescence microscopy on filters (combined with staining via a universal DNA stain such as DAPI, or a 16S-rRNA-specific probe such as EUB338) and molecular methods (Mayol et al 2014; Cuthbertson et al 2017). With the development of molecular sequencing methods (PCR, Sanger or Illumina sequencing), and improvements in microscopy, cell culture, and sampling methodology, along with modern sensitive sensors detecting changes in air composition, new possibilities opened up for quantifying the abundance, diversity, and composition of several biological constituents in the air.

Table 1: Typical aerobiology sampling methods.

Method	Advantages	Disadvantages
Membrane filtration	Low cost, easy to use, high capture rate, possibility of combining biological and chemical analysis	Desiccation of microorganisms on the filter surface, filter size can impact particle loading, inefficient extraction of nucleic acids
Impingement	Efficient for culture- and non-culture-based analyses, the liquid matrix can be split for various analyses	Low capture rates, loss of collection fluid to evaporation and violent bubbling, loss of viability, liquid incompatible with chemical analysis
Impaction	Cell death from impaction is insignificant, efficient means of obtaining total counts of fungal spores, ease of use, portability, assessment of culturable populations of bacteria and fungi per volume of air	Restricted use in the analysis of other microbial types (bacteria and viruses), loss of viability due to impact stress, loss of recovery efficiency, small sample volumes due to low flow rates
Sticky traps	Low cost, easy to use and install, perfect for counting of animals and plants directly on the trap.	Dedicated to invertebrates and plant particles, often destroy invertebrate specimens; cannot be used for quantifying bacteria and fungi

3. Contributions to interdisciplinarity

An integral part of this chapter is connecting the chemical, biological and supportive physical measures of atmospheric impurity loading, and certainly more work at this interface is warranted. The analysis of geographical distribution of atmospheric impurity measurements in Svalbard shows the most likely location for interdisciplinary studies is the Ny-Ålesund hub, as co-siting multiple measurements offers vast opportunities for improved understanding of the Arctic environment as a whole. The internal harmoniation of measurements at Ny-Ålesund is already underway. Emerging disciplines, such as aerobiology and CEACs are likely to be enhanced there in the future. However, other locations also offer opportunities for interdisciplinary studies. For example, Longyearbyen could be a site to screen for changes in human impact as mining ceases to be the predominant activity in the area. Furthermore, climate-induced changes in spatial patterns and seasonality of parameters related to atmospheric impurities need to be studied at more than one site to be comprehensively understood, and the Arctic is likely to face multiple non-linear changes (e.g. Song et al 2022). Air impurity interactions with climate are likely to be at the forefront of interdisciplinary issues in Svalbard since multiple components of the atmospheric aerosol – of various origins, and both chemical and biological – can act as CCN and ice-nucleating particles (Varutbangkul et al 2006; Möhler et al 2008; King et al 2012; Abbatt et al 2019). Furthermore, both direct and indirect

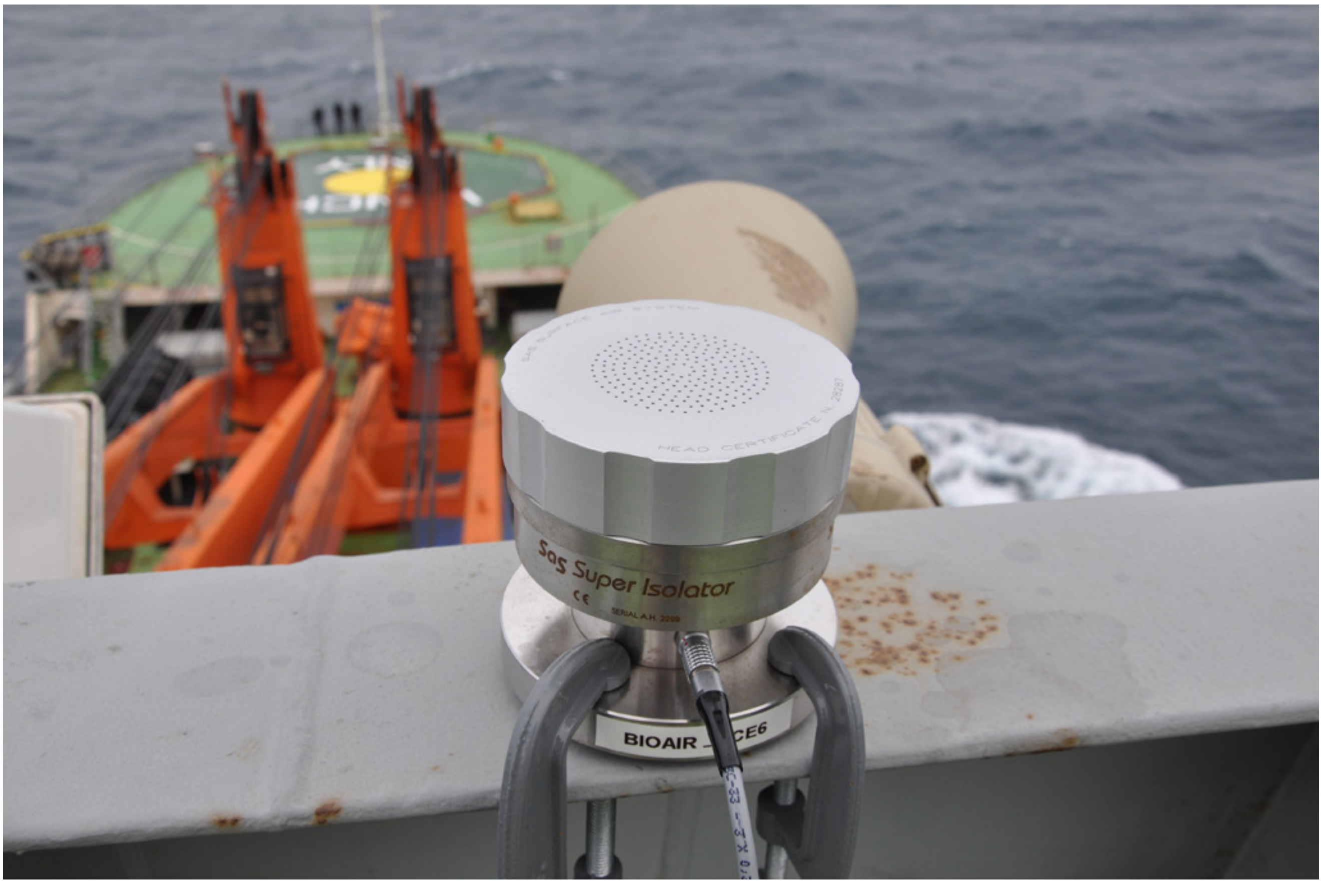

Figure 3: For air sampling for microorganisms, a number of commercial options are available. Key considerations are: a) direct collection or a filter size of 0.2 µm to capture bacteria, b) maximum flow rates for DNA yield, c) ability to withstand the Arctic environment, d) a convenient power source (battery or generator) to enable long sample runs and e) preferably many users to provide data for comparison elsewhere. Pictured is one such example, the SAS Air Sampler as deployed in the field. (Photo: David Pearce)

impacts of aerosol upon radiation and precipitation components of climate have been noted (Toon and Pollack 1980; Satheesh and Krishnamoorthy 2005; Merikanto et al 2009; Burgos et al 2020; Allen et al 2020), and the climate properties change air quality. Interdisciplinary aspects, such as impacts on cryosphere and ecosystems, are inherent in atmospheric impurity studies (Boy et al 2019), as are the well-known connections to human health, social science and economy (IPCC 2021, 2022a, b).

4. Unanswered questions

Within each field of atmospheric impurity research, there remain unanswered questions. For example, researchers investigating mineral dust still ponder the origin of the deposited material, especially whether it is local or long-range transported (e.g. Moroni et al 2016, 2018; Conca et al 2019; Kavan et al 2020; Lewandowski et al 2020). Shrinking glaciers are expected to expose more mineral dust sources locally (Zawierucha et al 2019; Schuler et al 2020; Geyman et al 2022; Rymer et al 2022). Altitude effects on mineral dust deposition are also of concern, as are seasonal changes. Other atmospheric impurities are in principle subject to the same concerns and open questionsrelated to changing origin (what is the proportion of local to long-range sources?), changing seasonality (how do seasonal patterns in impurity concentrations change?), and unknown effects of altitude. An additional concern is the question of how atmospheric impurities impact climate in such changed conditions, through light scattering in the atmosphere, precipitation changes and albedo (surface reflectivity) effects. In aerobiology, rising temperatures in the Arctic along with an increasing number of tourists spur a question about invasion of Svalbard by non-native pollen and spores. Specifically for CEACs, questions arise about their degradation products and their environmental fate. We believe that the parallel monitoring of multiple impurities would accelerate research progress towards solving such questions, since information provided by various impurity contents will be more comprehensive and thus more likely conclusive.

5. Recommendations for the future

For a harmonised picture of spatial distribution of key atmospheric impurities across Svalbard, we recommend establishing regular measurements of a basic set of variables at ground-based stations, which are logistically available and represent a different level of local human impact (proposed here: Longyearbyen, as the main settlement, and Hornsund, as a relatively remote site with year-round staff). These are also AERONET sites, already measuring AOD. The proposed set of key impurities includes: BC (due to its climate impacts and a large uncertainty in deposition patterns; cf. Zdanowicz et al 2021); CH_4 (due to climate effects and potential local sources), inorganic ions (simple aerosol source markers), pollen (to track the colonisation of Svalbard by new plants), and selected CEACs (e.g. PFAS due to known sources in Svalbard). Such measurements should be performed with consistent methods and be subject to interlaboratory checks. Co-timing of measurements (and matching their time resolutions) at these stations will also be necessary. Regular measurements will also allow detection of changes in **seasonal phenomena** due to climate change.

For several atmospheric impurities, three sites across Svalbard are insufficient to **detect the spatial differences**, especially in bulk atmospheric deposition, which is both more varied and more relevant to the impact on the terrestrial system than pure atmospheric concentrations. For such variables, field campaigns can be used to supplement the existing data, be it with the use of passive air samplers or snow as a natural deposition medium. Impurities we recommend here are: mineral dust, CEACs with an established negative impact on the terrestrial ecosystem, BC and aerobiological parameters (the deposition of pollen, and DNA studies of microbial communities).

The altitudinal transect in Ny-Ålesund between Zeppelin and Gruvebadet should remain in operation, if possible with unified protocols – consistent with SESS report recommendations by Sipilä et al (2020) and Traversi et al (2021); shorter-term experiments on altitude differences in impurity concentrations in the atmosphere and their deposition would be beneficial elsewhere (Viola et al 2019).

Unified or highly comparable measurement methods are desired, which has already been postulated for BC (Gilardoni et al 2020) and microplastics (Singh et al 2021), or harmonised Svalbard-wide sampling strategies (consistent with the conclusions of Petkov et al 2022). Therefore, a long-term experiment involving parallel collection with different sampling protocols at one site is proposed here.

A sample bank should be designed for CEACs, in the form of non-targeted chemical analysis recording (with high-resolution gas- or liquid chromatography and mass spectrometric techniques). It is possible that a future re-analysis of such data from past samples would detect CEACs that have not yet been discovered. This would make it possible to study their temporal trends, testifying to the changing human impact in the Arctic, resulting e.g. from the diversion of shipping routes or increased tourism.

Broadening the spectrum of measured properties also applies as a prospective research area **in aerobiology** as more in-depth characterisation of the gene pool in the aerial microbiome becomes possible. Functional links with the environment are also an important concern for future aerobiology studies (new recommendations compared to Malard et al 2019).

Finally, the breadth of existing data, not all of which is fully available (FAIR-compliant), drives the last recommendation to **make the existing and future datasets findable, accessible, interoperable and reusable** to facilitate solving complex scientific problems connected to atmospheric impurities through collaboration.

6. Data availability

Data availability is shown in Appendix 2.

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Appendix 1: Details of the POPs and CEACs monitoring in the atmospheric air at Ny-Ålesund.

Monitoring efforts for POPs and CEACs in the Svalbard atmosphere, undertaken at the Ny-Ålesund (NyÅ) hub, in chronological order (except Gruvebadet - see Appendix 2 for all Gruvebadet datasets). All data by NILU are available at EBAS[1] , and all data by Z. Xie (Hereon) are available at PANGAEA[2] .

Organic species	Sampling method	Location within NyÅ	Period of sampling	Research unit	Contact person
OCPs, PCNs	HVS	Zeppelin	1993-present	NILU	P. Bohlin-Nizzetto (pbn@nilu.no)
PAHs	HVS	Zeppelin	1994-present	NILU	P. Bohlin-Nizzetto
PCBs	HVS	Zeppelin	2001-present	NILU	P. Bohlin-Nizzetto
PBDEs, PFAS (ionic)	HVS	Zeppelin	2006-present	NILU	P. Bohlin-Nizzetto
OCPs, PCBs, PBDEs, OPEs	PAS (Gas phase)	Ny-Ålesund	2011-2018	RCEES	Q. Zhang (qhzhang@rcees.ac.cn)
PFAS (volatile)	HVS	Zeppelin	2011-present	Hereon	Z. Xie (zhiyong.xie@hereon.de)
OCPs, PBDEs, HCBD, CUPs, novel BFRs, CFRs	HVS	Ny-Ålesund	2012-Present	Hereon	Z. Xie
cVMS	HVS (Gas phase)	Zeppelin	2013-present	NILU	P. Bohlin-Nizzetto
Chlorinated paraffins	HVS	Zeppelin	2013-present	NILU	P. Bohlin-Nizzetto
Phthalate esters, fragrance material, UV-filters, OPEs	HVS	Ny-Ålesund	2014-present	Hereon	Z. Xie
cVMS	HVS (Gas phase)	Ny-Ålesund	2015-Present	Hereon	Z. Xie
Chlorinated paraffins	HVS	Ny-Ålesund	2015-Present	Hereon	Z. Xie
HCBD	HVS	Zeppelin	2020-present	NILU	P. Bohlin-Nizzetto
Novel BFRs	HVS	Zeppelin	2017-present	NILU	P. Bohlin-Nizzetto
CFRs	HVS	Zeppelin	2019-present	NILU	P. Bohlin-Nizzetto
PFAS (volatile)	HVS (Gas phase)	Zeppelin	2017-present	NILU	P. Bohlin-Nizzetto
PFAS (ionic)	HVS (Particle phase)	Ny-Ålesund	2017-Present	Hereon	Z. Xie
OPEs, phthalate esters	HVS	Zeppelin	2017-present	NILU	P. Bohlin-Nizzetto
Alkylphenol	HVS	Ny-Ålesund	2018-Present	Hereon	Z. Xie
Microplastics	HVS (Particle phase)	Ny-Ålesund	2019-Present	Hereon	Z. Xie
Volatile fluorinated substances	HVS (Gas phase)	Zeppelin	2020-present	NILU	P. Bohlin-Nizzetto

Abbreviations

BFRs – brominated flame retardants, CFRs – chlorinated flame retardants, CUPs – current use pesticides, cVMS – cyclic volatile methyl siloxanes, **HCBD** – hexachlorobutadiene, HVS – high-volume air sampling, OCPs – organochlorine pesticides, **OPEs** – organophosphate esters, PAHs – polycyclic aromatic hydrocarbons, PAS – passive sampling, **PBDEs** – polybrominated diphenyl ethers, PCBs – polychlorinated biphenyls, PCNs – polychlorinated naphthalenes, PFAS – per- and polyfluoroalkyl substances.

1 http://ebas-data.nilu.no
2 https://pangaea.de

Appendix 2: Data availability

To access the links, please use the pdf-file of the chapter: https://doi.org/10.5281/zenodo.7406842

Abbreviations used in the table:

Dataset impurity types and methods

AAS = atomic absorption spectrometry; **AOD** = aerosol optical depth; **BC** = black carbon; **CCN** = cloud condensation nuclei; **CEACs** = chemicals of emerging Arctic concern; **CFCs** = chlorofluorocarbons; **COSMOS** = continuous soot monitoring system; **CRDS** = cavity ring-down spectroscopy; **eBC** = equivalent black carbon; **EC** = elemental carbon; **FID** = flame ionisation detector; flue gas **CEM** (continuous emission monitoring); **FTIR spectroscopy** = Fourier-transform infrared spectroscopy; **GC** = gas chromatograph; **HCFCs** = hydrochlorofluorocarbons; **HFCs** = hydrofluorocarbons; **H-NMR** (proton nuclear magnetic resonance); **HR-TOF-AMS** (High-Resolution Time-of-Flight Aerosol Mass Spectrometer); **HVS** = high-volume air sampler; **ICP-MS** (inductively coupled plasma – mass spectrometry); **INP** = Ice Nucleating Particles; LVS (low-volume sampler); **MAX-DOAS** = Multi-AXis Differential Optical Absorption Spectroscopy; **OC** = organic carbon; PAHs = polycyclic aromatic hydrocarbons; **PCBs** = polychlorinated biphenyls; **PFAS** = per- and polyfluoroalkyl substances; **PIXE** = Proton Induced X-ray Emission; **PM** = particulate matter; **POPs** = persistent organic pollutants; **PSAP** = particle soot absorption photometer; **PUF** = polyurethane foam; **SEM** = scanning electron microscope; Skypost (a Sequential Tecora® Skypost low volume sampler with automatic filter change, with PM10 sampling head); **SMPS** = Scanning Mobility Particle Sizer; **SP2** = single-particle soot photometers; ; **TEM grids** = Transmission electron microscopy grids; **TOC** (total organic carbon); **TSP** = total suspended particulate matter; **VOCs** = volatile organic compounds; **WSOC** = water-soluble organic carbon

Parameters

A = Air/aerosol; **P** = Snow/rain

Locations

BAR = Barentsburg; **GVB** = Gruvebadet Atmosphere Laboratory; **HRN** = Hornsund; **LYR** = Longyearbyen; **NyÅ** = Ny-Ålesund; **ZEP** = Zeppelin Observatory

Dataset providers

AARI = Arctic and Antarctic Research Institute; **AWI** = Alfred Wegener Institute; **ISP-CNR** = National Research Council of Italy, Institute of Polar Sciences; **IRET- CNR** = National Research Council of Italy, Institute of Research on Terrestrial Ecosystems; **ISAC-CNR** = National Research Council of Italy, Institute of Atmospheric Sciences and Climate; **HEREON** = Helmholtz-Zentrum Hereon; **IG PAS** = Institute of Geophysics, Polish Academy of Sciences; **INFN** = National Institute for Nuclear Physics (Italy); **KOPRI** = Korean Polar Research Institute; **NILU** = Norwegian Institute for Air Research; **NIPR** = National Institute for Polar Research (Japan); **RAS** = Russian Academy of Sciences; **RPA 'Typhoon'** = Research and Production Association 'Typhoon' (Russia); **AMU** = Adam Mickiewicz University of in Poznan; **UniFI** = University of Florence; **UniTO** = University of Turin; **UniGE** = University of Genoa; **UniMib** = University of Milan Bicocca; **UNIS** = University Centre in Svalbard

No. on the map (Fig. A1)	Dataset (impurity type + method in brief)	Parameter and temporal resolution of measurement (if known)	Period	Location	Metadata access (URL)	Dataset provider
1	POPs (mainly organochlorine pesticides and PCBs) by high-volume sampler	**A**	1980-1983	NyÅ	(Oehme and Ottar 1984)	NILU
2	Black carbon by aethalometer	**A**; every 5 or 10 mins (two devices)	2011	NyÅ, Chinese Yellow River, and three other locations	(Zhan and Gao 2014)	J. Zhan & Y. Gao (Rutgers University)
3	Black carbon by aethalometer	**A**, every 10 mins	2005-2008	NyÅ, Chinese Yellow River	(Chen et al. 2016)	L. Chen (State Oceanic Administration, Xiamen, China) et al
4	Trace gases (O_4, BrO, OClO, NO_2) by MAX-DOAS	**A**, continuous (every 2000 ms)	2017	NyÅ, Chinese Yellow River	(Chen et al. 2022)	D. Chen (Chinese Academy of Sciences, Hefei) et al
5	Mineral dust by copper TEM grids coated with carbon film	**A**, 20 min - 2 h	2012	NyÅ, Chinese Yellow River	(Chi et al. 2015; Yu et al. 2019)	J. W. Chi (Shandong University, Jinan) et al; H. Yu (Hangzhou Normal University) et al
6	Inorganic ions, conductivity (EC) and pH by bulk sampler	**P**, daily in 1980-83, then weekly	1980-2021, EC only in 1984-85, gaps for particular parameters	Ny-Ålesund	LINK	NILU
7	Inorganic ions by filter pack	**A**, weekly	2019-2021	NyÅ, Transfor-matorbua	LINK	NILU
8	Inorganic ions by filter pack	**A**, daily or weekly, depending on the period	Mid-2008-2018	NyÅ, Nord-polhotellet	LINK	NILU
9	Trace gases (e.g. CO, CH_4, O_3) by FTIR spectroscopy			NyÅ, AWIPEV	Data not directly available	project website: https://www.iup.uni-bremen.de/ftir/cms/
10	Pollen	**A**, weekly	1986	NyÅ	(Johansen and Hafsten 1988)	S. Johansen & U. Hafsten
11	Atmospheric optical depth (AOD) / water vapour in the air column / inversion aerosol products	**A**, depending on cloud cover	Since 2017 (& March-April 2006)	NyÅ	LINK LINK	C. Ritter (AWI), AERONET
12	Bacteria	**A**	2018	NyÅ, GVB	(Feltracco et al. 2021a)	M. Fetracco (ISP-CNR)
13	WSOC, phenolic compounds, trace elements and rare earths; in 6 dimensional classes of aerosol \ Andersen High volume cascade impactor	**A**, weekly	Since 2010	NyÅ, GVB	LINK (Zangrando et al. 2013; Turetta et al. 2016, 2021; Feltracco et al. 2019, 2020, 2021b, a)	E. Barbaro (ISP-CNR, UNIVE)

No. on the map (Fig. A1)	Dataset (impurity type + method in brief)	Parameter and temporal resolution of measurement (if known)	Period	Location	Metadata access (URL)	Dataset provider
14	EC/OC Tecora® LVS	**A**, weekly	Since 2010	NyÅ, GVB	(Caiazzo et al. 2021)	R. Traversi (UniFI) & G. Calzolai (INFN)
15	PM10 for elementary composition (PIXE) \ Skypost	**A**, weekly	Since 2010	NyÅ, GVB	Upon request to R. Traversi	R. Traversi (UniFI)
16	PM10 sampling for ionic compounds determination \ Skypost	**A**, weekly	Since 2010	NyÅ, GVB	(Udisti et al. 2016; Becagli et al. 2019; Traversi et al. 2021; Amore et al. 2022)	R. Traversi (UniFI)
17	Sampling of PM10 - determination of trace elements and lead isotopes \ Tecora® HVS	**A**, four days - now weekly	Since 2010	NyÅ, GVB	(Ardini et al. 2020; Bazzano et al. 2021; Conca et al. 2021)	M. Malandrino (UniTO) & M. Grotti (UniGE)
18	Aerosol sampling in 4 dimensional classes for distribution of ions \ Dekati 4-stage impactor	**A**, weekly	From 2010 to 2018	NyÅ, GVB	(Giardi et al. 2016)	R. Traversi (UniFI)
19	Spore and pollen sampling \ Cyclone	**A**, weekly	From 2018	NyÅ, GVB	Upon request	L. P. D'Acqui (IRET-CNR)
20	Ice Nucleating Particles (INP) \ Tecora® PM10/ PM1	**A**, campaign based	From 2018 to 2020	NyÅ, GVB	(Rinaldi et al. 2021)	M. Rinaldi et al
21	Characterisation of WSOC in sub-micrometric aerosol with H-NMR & HR-TOF-AMS (all offline) \ Tecora® Echo HVS PM1	**A**, weekly	From 2018 - ongoing	NyÅ, GVB	LINK	M. Rinaldi, M. Paglione (ISAC-CNR)
22	Microplastics, CEACs, PAHs \ TSP Tisch HVS	**A**, weekly	From 2021 - ongoing	NyÅ, GVB	upon request	F. Corami, M. Vecchiato (ISP-CNR)
23	Optical properties of the aerosol \ Nephelometer, Radiance Res.	**A**, weekly	From 2010 - ongoing	NyÅ, GVB	upon request	M. Mazzola (ISP-CNR)
24	Optical properties of the aerosol (including eBC) \ Radiance Res. (PSAP)	**A**, daily to weekly	From 2010 - ongoing	NyÅ, GVB	LINK	M. Mazzola, S. Gilardoni (ISP-CNR)
25	Optical properties of the aerosol and BC \ Aethalometer	**A**, daily to weekly	From 2021 - ongoing	NyÅ, GVB	upon request	M. Mazzola, S. Gilardoni (ISP-CNR)
26	Aerosol size distribution, 523 nm-20 µm range \ Aerodynamic Particle Sizer	**A**, daily to weekly	From 2010 to 2020	NyÅ, GVB	(Rader et al. 2021)	M. Mazzola (ISP-CNR); R. Traversi (UniFI)
27	Aerosol size distribution, 10-487 nm range \ SMPS	**A**, daily to weekly	From 2010 - ongoing	NyÅ, GVB	upon request	M. Mazzola (ISP-CNR); R. Traversi (UniFI)
28	Passive sampler for dry deposition – SEM analysis (dimensional & chemical particle characterisation) \ Sigma-2	**A**, month	From 2020 - ongoing	NyÅ, GVB	upon request	P. Ielpo (ISAC-CNR); F. Scoto (ISAC-CNR)

No. on the map (Fig. A1)	Dataset (impurity type + method in brief)	Parameter and temporal resolution of measurement (if known)	Period	Location	Metadata access (URL)	Dataset provider
29	Multiparametric optical characterisation of airborne dust with single particle extinction and scattering	**A**, days	From 2022 - ongoing	NyÅ, GVB	upon request	Marco Potenza (UniMib)
30	CO_2, CH_4, N_2O, SF_6 and O_2/N_2 ratio and stable isotope ratio of CO_2	**A**, weekly	03/2015-03/2019	NyÅ	LINK	D. Goto (NIPR) et al
31	Inorganic ions by filter pack	**A**, daily	1989-2021, with breaks	NyÅ, ZEP	LINK	NILU
32	“Heavy metals” (As, Cd, Co, Cr, Cu, Fe, Pb, Mn, Ni, Ti, V, Zn) by high volume sampler	**A**, weekly	1994-2021, with breaks	NyÅ, ZEP	LINK	NILU
33	Cloud condensation nuclei (CCN) number concentration by a CCN counter	**A**, hourly	2007-2015; 2018-2019	NyÅ, ZEP	LINK	KOPRI
34	Ozone by UV absorption	**A**, hourly	1989-2022	NyÅ, ZEP	LINK	NILU
35	Mercury by Tekran (flue gas CEM), a gold trap denuder, high-volume sampler or mini-trap	**A**, hourly (in 2021 - every 3 hours)	1994-2016; 2021	NyÅ, ZEP	LINK	NILU
36	Halogenated greenhouse gases (CFCs; halons, HCFCs, HFCs, SF_6 and other halogenated compounds) by an online gas chromatograph (GC)	**A**, daily; since 2010 every 2 hours	2001-2021	NyÅ, ZEP	LINK	NILU
37	H_2 by GC-HgO	**A**, every 2 h	2006-2009	NyÅ, ZEP	LINK	
38	CO (carbon monoxide) by GC-HgO	**A**, at least daily (every 2 h 2006-2008; hourly 2009-2012)	2001-2012	NyÅ, ZEP	LINK	NILU
39	CO (carbon monoxide) by online CRDS	**A**, hourly (daily in 2013)	2013-2022	NyÅ, ZEP	LINK	NILU
40	CO_2 and CH_4, N_2O by online CRDS	**A**, hourly	2012-2022	NyÅ, ZEP	LINK	NILU
41	PAHs by high-volume sampler	**A**, weekly	2008	NyÅ, ZEP	LINK	
42	POPs (mainly organochlorine pesticides and PCBs) by passive PUF samplers	**A**, single sample	2006	NyÅ, ZEP	LINK	
43	POPs (mainly organochlorine pesticides and PCBs) by high-volume sampler	**A**, weekly samples, representing 48-72 h	Pesticides regularly since 1994, PCBs since 1998; early measurements in 1984	NyÅ, ZEP	(Hung et al. 2016); 1984 data in (Oehme 1991)	NILU
44	PFAS by high-volume sampler	**A**, weekly samples, representing 48 h	2006-2014	NyÅ, ZEP	(Wong et al. 2018)	P. Bohlin-Nizzetto (NILU)

No. on the map (Fig. A1)	Dataset (impurity type + method in brief)	Parameter and temporal resolution of measurement (if known)	Period	Location	Metadata access (URL)	Dataset provider
45	OC/EC (organic carbon/ elemental carbon) by high-volume sampler (in PM10)	**A**, weekly	2017-2021	NyÅ, ZEP	LINK	NILU
46	Saccharides by high-volume sampler	**A**, weekly	2017-2021	NyÅ, ZEP	LINK	NILU
47	VOCs (volatile organic compounds) by adsorbent tube	**A**, daily	1994-1998	NyÅ, ZEP	LINK	
48	Alkanes by glass flask	**A**, weekly	2003-2016	NyÅ, ZEP	LINK	
49	Organic gaseous compounds by steel canister	**A**, daily	1989-1999 (various periods for various gases)	NyÅ, ZEP	Soon available through the SIOS data access portal	NILU
50	Black carbon, number and mass concentrations by SP2	**P**, daily	09/2012-03/2018	NyÅ	LINK	K. Goto-Azuma (NIPR) et al
51	Black carbon, mass concentration, by SP2	**A**, hourly	03/2017	NyÅ	LINK	S. Ohata (Univ. of Nagoya) et al
52	POPs and CEACs by high-volume sampler	**A**, weekly	2011	NyÅ, AWIPE-V(HERE-ON)	(Xie et al. 2015)	HEREON (Z. Xie)
53	Black carbon, mass concentration, by COSMOS	**A**, hourly (at least the first link, which is a dataset starting in 10/2012)	04/2009-10/2019	NyÅ	LINK	M. Koike (Univ. of Tokyo) et al
54	Microfauna	**A**, weekly	2000, 2001	NyÅ	(Coulson et al. 2003)	S. Coulson (UNIS) et al
55	Pollen, bryophyte spores	**A**, daily	1950	Sarsbukta	(Polunin 1955)	N. Polunin
56	Dust deposition	**A+P**, yearly	2012-2022	Petunia-bukta	(Rymer et al. 2022)	Krzysztof G. Rymer (AMU)
57	Dust deposition	**P**, campaign based	2019	Petunia-bukta	LINK	J. Kavan (Uni. Wroclaw & Masaryk University, Czech Rep.)
58	Bacteria	**A**, once	2015	Billefjorden	(Cuthbertson et al. 2017)	L. Cuthbertson (University of Northumbria at Newcastle) et al
59	Bacteria	**A**, once	2015	Gipsdalen	(Cuthbertson et al. 2017)	L. Cuthbertson (University of Northumbria at Newcastle) et al
60	Bacteria	**A**, once	2015	Sassen-fjorden	(Cuthbertson et al. 2017)	L. Cuthbertson (University of Northumbria at Newcastle) et al
61	Bacteria	**A**, once	2015	Deltaneset	(Cuthbertson et al. 2017)	L. Cuthbertson (University of Northumbria at Newcastle) et al

No. on the map (Fig. A1)	Dataset (impurity type + method in brief)	Parameter and temporal resolution of measurement (if known)	Period	Location	Metadata access (URL)	Dataset provider
62	Bacteria	**A**, once	2015	Advent-fjorden	(Cuthbertson et al. 2017)	L. Cuthbertson (University of Northumbria at Newcastle) et al
63	Bacteria	**A**, once	2015	Isfjorden	(Cuthbertson et al. 2017)	L. Cuthbertson (University of Northumbria at Newcastle) et al
64	Fungi	**A**, daily	2019	Area of LYB	(Pusz and Urbaniak 2021)	W. Pusz & J. Urbaniak
65	Aerosol optical depth (AOD) / water vapour in the air column / inversion aerosol products	**A**, depending on cloud cover	2003-2004; 2018	LYB	LINK	B. Holben (NASA), AERONET
66	PAHs, oxy- and nitro-PAHs, by high-volume sampler	**A**, on days with predicted NW wind direction	28 August - 28 September 2018	LYB (UNIS roof)	(Drotikova et al. 2020)	T. Drotikova (UNIS) et al
67	PAHs, oxy- and nitro-PAHs, by high-volume sampler	**A**, 31 samples in total, 24 h each (~weekly)	Nov 2017 - Jun 2018	LYB (UNIS roof)	(Drotikova et al. 2021)	T. Drotikova (UNIS) et al
68	Aromatic VOCs by GC-FID	**A**, every 15 mins	2007	LYB	(Reimann et al. 2009)	S. Reimann (Empa, Switzerland) et al
69	Bacteria	**A**, four	2015	LYB	(Cuthbertson et al. 2017)	L. Cuthbertson (University of Northumbria at Newcastle) et al
70	Bacteria	**A**, once	2015	Bjørndalen	(Cuthbertson et al. 2017)	L. Cuthbertson (University of Northumbria at Newcastle) et al
71	Fungi	**A**, daily	2019	Area of LYB	(Pusz and Urbaniak 2021)	W. Pusz & J. Urbaniak
72	PAHs, oxy- and nitro-PAHs, by high-volume sampler	**A**, on days with predicted NW wind direction	28 August - 28 September 2018	LYB (Auro-ra station Advent-dalen)	(Drotikova et al. 2020)	T. Drotikova (UNIS) et al
73	Fungi	**A**, daily	2019	Area of LYB	(Pusz and Urbaniak 2021)	W. Pusz & J. Urbaniak
74	Fungi	**A**, daily	2019	Area of LYB	(Pusz and Urbaniak 2021)	W. Pusz & J. Urbaniak
75	Bacteria	**A**, once	2015	Mine (Gruve) 7	(Cuthbertson et al. 2017)	L. Cuthbertson (University of Northumbria at Newcastle) et al
76	Fungi	**A**, daily	2019	Area of LYB	(Pusz and Urbaniak 2021)	W. Pusz & J. Urbaniak
77	Pollen by sticky trap	**A**, weekly	2022	BAR CALM site	data available by request; RiS projects 11316 and 10855	AARI paleo reconstruction group
78	PAHs, PCBs and trace metals, by multichannel sampler PU-4EP	**A**, twice a year	Since 2002	BAR	data available by request at RPA 'Typhoon', North-West branch	RPA 'Typhoon'

No. on the map (Fig. A1)	Dataset (impurity type + method in brief)	Parameter and temporal resolution of measurement (if known)	Period	Location	Metadata access (URL)	Dataset provider
79	Trace gases (NO_x, NO_2, NO, NH_3, SO_2, H_2S, CO_2, CO, O_3) + PM10 + mercury by Lumex AAS	**A**, continuous, 10 min (Hg)	2017-2021	BAR mountain	data stored at AARI, currently not online; RiS ID 10863	AARI
80	Pollen by sticky trap	**A**, weekly	2017-2019; 2022	BAR	data available by request; RiS projects 11316 and 10855	AARI paleo reconstruction group
81	Pollen by sticky trap	**A**, weekly	2017-2019; 2022	BAR	data available by request; RiS projects 11316 and 10855	AARI paleo reconstruction group
82	Trace gases (NO_x, NO_2, NO, NH_3, SO_2, H_2S, CO_2, CO, O_3) + PM10 + mercury by Lumex AAS	**A**, continuous, 10 min (Hg)	2017-2022	BAR town	data stored at AARI, currently not online; RiS ID 10863	AARI
83	AOD, water vapour content, aerosol concentration and size distribution, BC concentration by sun photometer, photoelectric particle counter, aethalometer	**A**, continuous	2011-2022	BAR	(Chernov et al. 2016; Sakerin et al. 2019)	D. G. Chernov (V.E. Zuev Institute of Atmospheric Optics, Siberian Branch RAS, Tomsk) et al; S. Sakerin et al
84	Inorganic ions (ion chromatography) and dissolved trace metals (ICP-MS) by low-volume sampler	**A**, weekly	2011-2022	BAR	(Golobokova et al. 2015; 2020)	L. P. Golobokova (Limnology Institute, Siberian Branch, RAS) et al
85	PAHs by GC/MS TripleQuad, low volume samler	**A**, campaign based	2017	BAR	(Golobokova et al. 2020)	L. P. Golobokova (Limnology Institute, Siberian Branch, RAS) et al
86	Pollen by sticky trap	**A**, weekly	2017-2019; 2022	BAR	data available by request; RiS projects 11316 and 10855	AARI paleo reconstruction group
87	Fresh snow chemical composition: major ions, HCO_3^-, pH, conductivity	**P**, every fresh snow episode > 5 mm	2005 - 2019	Hansbreen glacier (HRN)	LINK	IG PAS (A. Nawrot)
88	Fresh snow chemical composition: major ions, HCO_3^-, pH, conductivity	**P**, every fresh snow episode > 5 mm	Since 2020 - ongoing	Ariebreen glacier (HRN)	LINK	IG PAS (A. Nawrot)
89	Metals and metalloids in precipitation, by ICP-MS, and TOC by a Shimadzu TOC Analyser	**P**, every event	2010-2012	HRN pre-cipitation gauge	(Kozak et al. 2015)	K. Kozak (Gdansk Tech) et al
90	POPs (organochlorine pesticides and PCBs) in snow	**P**, every event during 1 month; weekly surface snow at environmental chamber	2019	HRN area	LINK (Pawlak et al. 2022)	K. Koziol (Gdansk Tech)
91	Precipitation chemistry: major ions, HCO_3^-, pH, conductivity; sum of the precipitation	**P**, daily	Since 2005 - ongoing	HRN	LINK	IG PAS (A. Nawrot)

No. on the map (Fig. A1)	Dataset (impurity type + method in brief)	Parameter and temporal resolution of measurement (if known)	Period	Location	Metadata access (URL)	Dataset provider
92	Aerosol concentration, and size distribution (0.01-10 µm)	**A**, 1 min (concentration); 10 min (size distribution)	2021	HRN	LINK; LINK; LINK[3]	D. Kępski, M. Posyniak (IG PAS)
92	Aerosol concentration and size distribution in a vertical distribution	**A**, 1 min (concentration); 10 min (size distribution)	2021	HRN	LINK; LINK	D. Kępski, M. Posyniak (IG PAS)
93	Radionuclides: Concentration of: ^{7}Be, ^{210}Pb, ^{40}K, ^{137}Cs, ^{134}Cs [µBq/m^3] PM (dust) [µg/m^3]	**A**, weekly	Since 2002	HRN	(Burakowska et al. 2021)	A. Burakowska, M. Kubicki (IG PAS)
94	Aerosol optical depth (AOD) / water vapour in the air column / inversion aerosol products	**A**, depending on cloud cover	Since March 2005	HRN	LINK	P. Sobolewski (IG PAS), AERONET network
95	POPs (mainly organochlorine pesticides and PCBs) by high-volume sampler	**A**	1980-1983	Hopen	(Oehme and Ottar 1984)	NILU
96	Sulphate and sulphur dioxide concentrations by a filter pack	**A**, daily	1978-1989	Bjørnøya	LINK	NILU
97	Metal concentrations (Cd, Pb, Zn) by bulk sampler	**P**, monthly	1980-1987	Bjørnøya	LINK	NILU
98	Ion concentrations (NH_4^+, Ca^{2+}, Cl^-, Mg^{2+}, K^+, Na^+, NO_3^-, SO_4^{2-}) by bulk sampler; conductivity and pH	**P**, daily	1977-1985 (various periods within that timespan)	Bjørnøya	LINK	NILU
99	POPs (mainly organochlorine pesticides and PCBs) by high-volume sampler	**A**	1980-1983	Bjornoya	(Oehme and Ottar 1984)	NILU
100	POPs (mainly organochlorine pesticides and PCBs) by high-volume sampler	**A**	1980-1983	Jan Mayen	(Oehme and Ottar 1984)	NILU

3 Entire dataset available on the project subpage https://dataportal.igf.edu.pl/group/avseefi; registration on the website is required to download the data; field data were collected inside a polygon defined by the coordinates in Fig. 1; basic measurements in a fixed position are continued with the SPS30 micro sensor

No. on the map (Fig. A1)	Dataset (impurity type + method in brief)	Parameter and temporal resolution of measurement (if known)	Period	Location	Metadata access (URL)	Dataset provider
No marker on the map	AOD	Depending on cloud cover (only during polar day)	RV Oceania 2007	Arctic maritime aerosol optical properties (Arctic circle)	LINK	Project MAN & AERONET
			RV Oceania 2009		LINK	
			RV Oceania 2010		LINK	
			RV Oceania 2011		LINK	
			RV Oceania 2012		LINK	
			RV Oceania 2013		LINK	
			RV Oceania 2014		LINK	
			RV Oceania 2015		LINK	
			RV Oceania 2016		LINK	
			RV Oceania 2017		LINK	
			RV Oceania 2018		LINK	
			RV Oceania 2019		LINK	
			RV Oceania 2020		LINK	
			RV Polarstern 2009		LINK	
			RV Polarstern 2012		LINK	
			RV Polarstern 2015		LINK	
			RV Polarstern 2017		LINK	
			RV Polarstern 2020		LINK	
			RV Polarstern 2021		LINK	
			RV Jan Mayen 2009		LINK	
			RV Akademik Fedorov 2013		LINK	
			USCGC Healy 2011		LINK	
			USCGC Healy 2015		LINK	
			RV Oden 2014		LINK	
			RV Araon 2020		LINK	
			RV Araon 2020-21		LINK	
			RV Araon 2021		LINK	
			RV Alliance 2021		LINK	

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Appendix 3: Coal mining in Svalbard as the long-term main source of local atmospheric pollution.

Site	Description of mining history	References
Longyearbyen	1906-2018 – seven mines (Mine 1-7) established and operated by the Norwegian company Store Norske Spitsbergen Kulkompani (SNSK); 2028 - planned date to close the last one	(Westby and Amundsen 2003; Kvello 2004; Vågerö et al 2021)
Barentsburg	1939 - mining operation in Grønnfjorden officially taken over by the USSR (from a Dutch operating company); currently, the mine is operated by the Russian governmental agency Trust Artikugol	(Pashkevich 2018)
Grumant/ Colesbay	1912-1961 - operated by the Soviet Union	(Samoĭlovich and Adadurov 1927; Kulikov 1964; Portselʹ 2011)
Pyramiden	1926 - mine facilities bought by the Soviet Union; in the 1960s-1970s it was the largest mine in Svalbard; in 1998 - closed and abandoned	(Andreassen et al 2010)
Ny-Ålesund	1916 - coal mining established by the Kings Bay mining company (Kings Bay Kulkompani); 1962 - a tragic mining accident led to the close of mine operations, after which the facility gradually transformed into an international research station	(Paglia 2020)

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