Dust in Svalbard: local sources versus long-range transported dust (SVALDUST)

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1. Introduction

1.1. What is dust

Dust particles are commonly defined according to their size, including clay-sized (<4 µm), silt-sized (4–62.5 µm) or sand-sized (62.5 µm –2 mm) material (UNCCD 2022). Giant dust particles (>75 µm in diameter) of wind-blown mineral have been observed at large (>10 000 km) distances from their source, and individual giant Saharan dust particles of up to 450 µm in diameter have been sampled in air over the Atlantic Ocean at 2 400 and 3 500 km from the west African coast (van der Does et al. 2018). The dust cycle contains sediments that travel within the atmosphere mainly by suspension, and that can be deposited on land, in lakes, or in the ocean (Bullard et al. 2016). The main source of these microscopic particles is the ground and the lifting energy is provided by the wind; thus the usual terminology for these particles is 'mineral dust' or 'aeolian dust'.

The role of aeolian dust for the radiation balance of the Earth is size-dependent. Dust has a direct cooling effect when particles of size <2 µm are transported into the high atmosphere and block incoming sunlight (e.g. Claquin et al. 2003). Mineral dust deposited and trapped on the cryosphere (cryodust; see Lewandowski et al. 2020) can impact snow and ice properties, contributing to the mass balance of glaciers, lowering their albedo (Lambert et al. 2013; Goelles et al. 2017, as well as influencing rheological properties of ice (Green and Mahajan 2005). Dust records from the ice core may illustrate potential changes in dust emissions or transportation pathways over long time scales.

Dust loading in the atmosphere has increased by 25-100% since pre-industrial time (Kok et al. 2021). There is an estimated two billion tonnes of dust travelling in the atmosphere every year, and double this mass if sand and giant particles are included (van der Does et al. 2018; Dagsson-Waldhauserova et al. 2019). Changes in the emission of high latitude dust (HLD) have not yet been estimated, but first estimates are that HLD contributes about 5% to global dust emissions (Bullard et al. 2016;

Dust types used in this chapter

High Latitude Dust – dust originating from cold arid areas of ≥ 50°N and ≥ 40°S with size up to 100 µm. Northern dust sources are in Alaska, Canada, Denmark, Greenland, Iceland, Svalbard, Sweden, and Russia and southern dust sources are in Antarctica, Patagonia and New Zealand.

Volcanic dust – dust of volcanic origin which was re-suspended/emitted from old to ancient tephra deposits in volcanic deserts often located in proximity to glaciers. Volcanic dust is mainly driven by glaciofluvial processes and by wind-recycled tephra sediment transport. It is sometimes referred to as dust from the volcaniclastic deserts in high latitudes. Volcanic dust is dark in colour and has greater radiative forcing impacts than mineral dust, especially when deposited on the cryosphere where the impacts are similar to those of black carbon.

Glacigenic dust – dust suspended during glacial periods, but also refers to contemporary dust from cold regions. This term was used before HLD was defined.

Cryodust – natural abiotic particulate matter deposited and trapped in glaciers.

Coal dust – dark dust particles from coal mines at high latitudes, usually deposited on the cryosphere that is in close proximity or downwind of the mine.

Light Absorbing Impurities / Light Absorbing Particles – the term light-absorbing impurities (LAI) refers to impurities (including also other than particles, e.g. algae) in snow and ice, while the term light absorbing particles (LAP) refers to particles in the atmosphere or in snow and ice.

Meinander et al. 2022). Sand and dust storms, including HLD, were identified as a hazard that affects 11 of the 17 Sustainable Development Goals (UNCCD 2022).

1.2. General information on dust at high latitudes

High-latitude (HL) sites and regions can be sources and receptors of dust. In the latter case, dust can be both local and long-range transported to the receptor sites.

Like desert dust around the world, HLD also consists of various parent materials. Icelandic, Alaskan, some Canadian, and some Antarctic sources are of volcanic origin with high proportion of iron oxides and low proportion of quartz compared to low latitude deserts (Bachelder et al. 2020; Baldo et al. 2020; Crusius et al. 2021). Dust from the other source areas show variable amounts of a dual component from sedimentary covers and metamorphic complexes (Moroni et al. 2016, 2018).

It is estimated that HLD contributes 5% to the global dust budget and active HLD sources cover >1 500 000 km^2 (Bullard et al. 2016 Meinander et al. 2022). Arctic HLD sources are estimated to contribute 1-3% of the global dust with area of >1 000 000 km^2 (Groot Zwaafting et al. 2016; Meinander et al. 2022). It is estimated that during years when dust activity in enhanced, about 5.5% of the Arctic land areas are active dust sources (>1 mil. km^2, Meinander et al. 2022). The most active research has been done in Iceland, Canada, Alaska, and Greenland (Crusius et al. 2011; Arnalds et al. 2016; Bachelder et al. 2020). Model simulations by Groot Zwaaftink et al. (2016) showed that dust surface concentrations and deposition in the Arctic are dominated by the local high-latitude sources, due to limited convection and efficiency of removal processes.

1.3. Objectives of this report

The main objectives of this report are as follows:

- to identify and characterise local and long-range dust sources in Svalbard
- to summarise available information on dust sources in Svalbard and evaluate contributions to dust load from long-range transport
- to propose for the future a plan/strategy for the collection, treatment, evaluation, and harmonisation of new data on the subject

2. Overview of existing knowledge

2.1. Dust sources over Svalbard

Local and long-range sources of dust have been recognised in Svalbard, which are quite well distinguishable from each other due to the presence of specific mineral phases and / or mineralogical assemblies. Estimated dust loads in central and southern Svalbard from different sources range from 4 g up to 4-5 kg per m^2 per year (Rymer et al. 2022). In the Hornsund region the annual aeolian accumulation rate was estimated to between 29-117 g/m^2 (Pekala 1980) and 300-400 g/m^2 (Czeppe 1968) and to 2.66-24.56 g/m^2 per snow season (Kavan et al. 2020). At lower elevations up to 300 metres above sea level, local dust is more prevalent than dust from long-distance transport.

2.2. Local sources

Svalbard has been recognised as an important HLD source with several active hotspots in northwestern, central and southern Svalbard (Meinander et al. 2022). In Ny-Ålesund local dust dominates in the summer–fall period (Moroni et al. 2016, 2018), while Hornsund reports local dust as early as late spring and throughout the melting season (Zwolinski et al. 2013; Kavan et al. 2020; Lewandowski et al. 2020; Spolaor et al. 2021). Dust storms have been reported in Longyearbyen (Dörnbrack et al. 2010; Khan et al. 2017; Kandler et al. 2020), in Pyramiden and Ebba Valley (Strzelecki and Long 2020; Kavan et al. 2020), as well as at the forefield of the Werenskioldbreen glacier (Migała and Sobik 1984). Although it has been shown that HLD sources can also be active during winter (Dagsson-Waldhauserova et al. 2019; Meinander et al. 2022), no evidence of dust emissions occurring in this season is reported for Svalbard.

Periglacial and proglacial areas are the main local dust sources in Svalbard (Zwoliński et al. 2013). These areas develop at the edge of glaciers or within glacial valleys, and they are increasing in size due to accelerated glacier ablation. These areas affect the narrow coastal or nearshore plains that border the entire archipelago. Glacial valleys, instead, develop radially from the inland to the coast. They are very extensive, quite stable in general and, thus, able to supply dust sediments more regularly than coastal plains during the year.

The mineralogical assemblage and the mineral chemistry of local dust (Moroni et al. 2016, 2018; Lewandowski et al. 2020) clearly reflect the geological features of the sites, marked by the presence of different sedimentary units overlying diverse metamorphic complexes, and small magmatic units (Dallmann 2015).

The presence and production of anthropogenically-derived dust on Svalbard is also evident from observational studies of dust collected in proximity to coal mines near Longyearbyen and Svea, which were active at the time of the studies (Aamaas et al. 2011; Khan et al. 2017). Up to 4863 ng/g of coal dust was found near Mine 7 in Longyearbyen and in Svea while the mines were active, and has been shown to reduce spectral albedo of surface snow by up to 84% directly next to the mine and up to 55% within 0.5 km downwind of the mine (Khan et al. 2017). These coal dust deposits are visible dark scars along the otherwise pristine landscape (Figure 1).

2.3. Long-range sources

Long-range transport to Spitsbergen involves dust from high- to low-latitude regions. According to global transport model simulations (Groot Zwaaftink et al. 2016; Figure 2), the largest contribution to Svalbard comes from Africa, Asia and, above all, Eurasia, while the contribution from Iceland, North America and, especially, from Greenland is much smaller. In addition, dust from remote sources shows a marked seasonal trend with highs in late winter/spring and lows in summer/autumn.

Results from field observations confirm some of the model results. In particular, Crocchianti et al. (2021)

Figure 1. Mine 7 near Longyearbyen (Breinosa mountain). Note the dark coal dust deposits on surface snow. Photo: Alia Khan

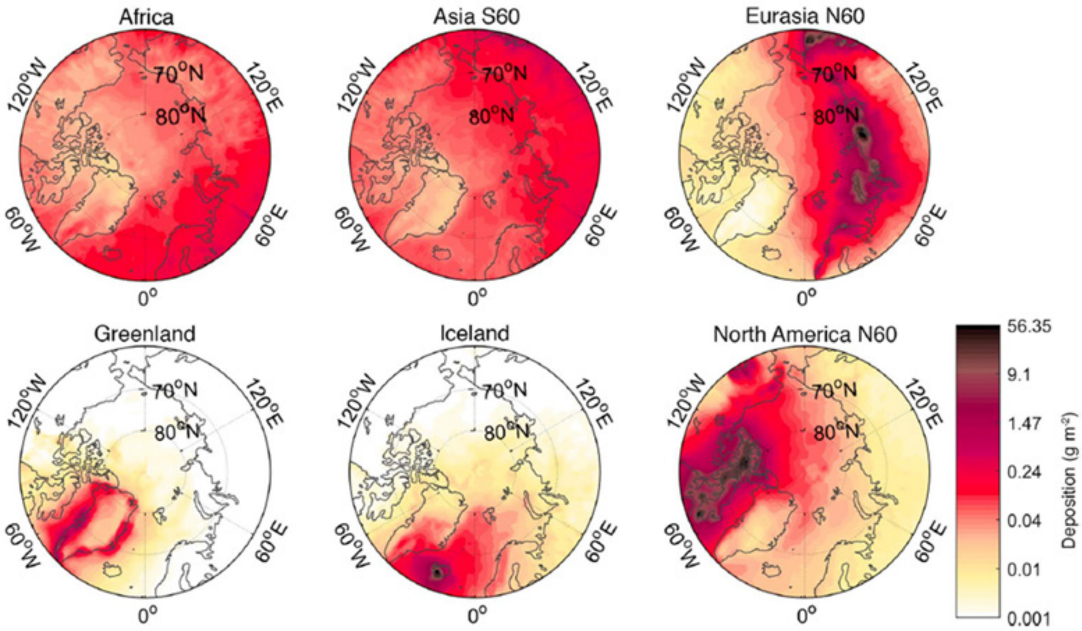

Figure 2. Simulated annual wet and dry deposition of dust (g/m^2) in the Arctic originating from different source regions averaged for the period 2010-2012. Reprinted from Groot Zwaafting et al. 2016, with permission of the authors.

have identified HL sources for the dust reaching Ny-Ålesund to be Eurasia, Greenland, Arctic-Alaska and Iceland. In addition, the mineralogy and the mineral chemistry of dust with respect to the parent soils made it possible to distinguish the local dust fraction from those of Iceland, Siberia and Alaska (Moroni et al. 2016, 2018, 2020). The presence of Saharan dust, including giant quartz particles, and Asian dust is documented over the Arctic (Groot Zwaafting et al. 2016; Varga et al. 2021), but not directly in Svalbard. In a study comparing dust deposition at Pyramiden and Hornsund, Kavan et al. (2020) showed that dust deposited at high altitudes is dominated by long-range transport.

2.4. Dust impact on the atmosphere

Dust is an important air pollutant with severe impacts on human health, visibility, and traffic safety (Querol et al. 2019; Monteiro et al. 2022). It can cause extreme particulate matter concentrations (PM10) up to 50 000 µg/m^3 (1000x higher the health limit) as measured for example in Iceland and elsewhere (Querol et al. 2019). PM10 concentrations >1 000 µg/m^3 have been reported during dust storms from several locations in high latitudes, including populated areas (Arnalds et al. 2016; Bachelder et al. 2020; Butwin et al. 2020). Aeolian transport of 11 tonnes of dust over a one-metre transect was measured during an extreme wind erosion event in Iceland in 2010 and evaluated as one of the most extreme wind erosion events measured on Earth (Arnalds et al. 2013). Experiments and observations have shown that HLD such as that from Iceland has impacts on atmospheric chemistry (Urupina et al. 2019; Romanias et al. 2020). HLD uptake of gases (both greenhouse gases with their precursors and gases controlling global warming) has been investigated in the laboratory and during in situ observations. Icelandic dust particles efficiently scavenge SO_2 and NO_2 to form sulphites/sulphates and nitrous acid. Dust is also an important agent in cloud formation as dust particles serve as ice nucleating particles (INPs) and cloud condensation nuclei, allowing ice and liquid droplet formation. HLD and particularly Icelandic and Svalbard dusts are efficient INPs and significant INP contributors in the Arctic, having impact on the mid- to high-latitude mixed phase clouds (Sanchez-Marroquin et al. 2020; Tobo et al. 2019; Meinander et al. 2022; Rinaldi et al. 2021). Th high ice nucleating ability of HLD is likely due to its origin in glacial valleys rich in primary minerals (olivenes, pyroxenes, feldspars, and amphiboles) and less rich in clays compared to low latitude dust. Increased INP concentrations can lead to a reduction in supercooled water and a decrease in shortwave reflectivity of clouds to produce a positive climate feedback.

2.5. Dust impact on the cryosphere

The cryosphere is an important part of the climate system and small changes in surface properties can have large radiative impacts. Dust deposition has a great effect on the cryosphere because it lowers the surface albedo and therefore influences the surface energy balance and melt rates. A mainly local source of HLD is fine sediment from glacier forefields. Glaciers produce this glacial flour which gets airborne due to katabatic winds in areas with limited vegetation cover. Due to glacier retreat, more land surface is exposed to wind and therefore dust emissions are likely to increase (Bullard 2013). Light-absorbing HLD particles can induce snow optical characteristics that impact Arctic amplification and cryosphere melt via radiative feedback (Boy et al. 2019; Meinander et al. 2022).

Snow and ice darkening due to the deposition of light-absorbing particles is a global phenomenon with regional characteristics (Di Mauro et al. 2021). The impact of dust on the optical properties of snow and ice strongly depends on the nature and size of mineral particles (Skiles et al. 2018; Shi et al. 2022) and also snow and ice properties, such as grain size and snow age (Warren and Wiscombe 1980). Most of the radiative impact of dust on snow occurs at wavelengths below 600 nm, and it is possible to analyse this effect by measuring the spectral reflectance of snow and ice (Di Mauro et al. 2015, 2017; Khan et al. 2017). Black carbon has instead a rather flat absorption spectrum.

3. Methods

The methods reported here are part of long-term monitoring activities continuously performed in observatory labs (e.g. Gruvebadet, Zeppelin, Hornsund), and during short-term fieldwork campaigns (e.g. balloon experiments, snow/ice sampling on glaciers). Sampling, sample treatment and analysis appear to be quite varied and heterogeneous, and this has often made data integration and comparison quite complex.

3.1. Sample collection and treatment

Dust sampling is part of both long-term and short-term monitoring activities. Dust sampling has been performed in air, ice/firn and snow. Dust sources such as bare soils and sedimentary deposits have been also sampled in some cases. Sampling site locations are presented in Figure 3, while aerosol, snow and ice/firn sampling techniques commonly employed in Svalbard are reported in appendix 1.

3.2. Continuous measurements

Long-term HLD atmospheric observations (ground and balloon-borne) have been conducted in Iceland, Canada and Antarctica (Thorsteinsson_et al. 2011; Dagsson-Waldhauserova et al. 2014a,b; Arnalds et al. 2016; Kavan et al. 2020; Bachelder et al. 2020; Butwin et al. 2020). The analysis of aerosol chemical composition is a useful approach to quantify aerosol dust. Sharma et al. (2019) studied dust variability at Alert through the analysis of aluminium and calcium aerosol concentration from 1980 until 2013. Higher dust contributions were observed in late summer – early fall and during spring. The most common instruments to measure dust in situ are particle counters, able to measure particle number concentration in specific size ranges. Examples of particle counters are Optical Particle Counter (OPC 3330, EDM365, 22 or 31 size bins PM0.25–32), Dusttrak DRX 8533EP (4 size bins PM1-10), Light Aerosol Optical Counter (LOAC, 19 size bins PM0.2–100), and Thermo EMS Andersen FH 62 I-R instrument and Grimm EDM 365. Dust concentration is generally derived as the concentration of particle number or mass in the coarse size range (above 1 or 2.5 micrometers). Song et al. (2021) investigated dust occurrence in Svalbard through cluster analysis of particle size distribution and aerosol bulk chemical composition

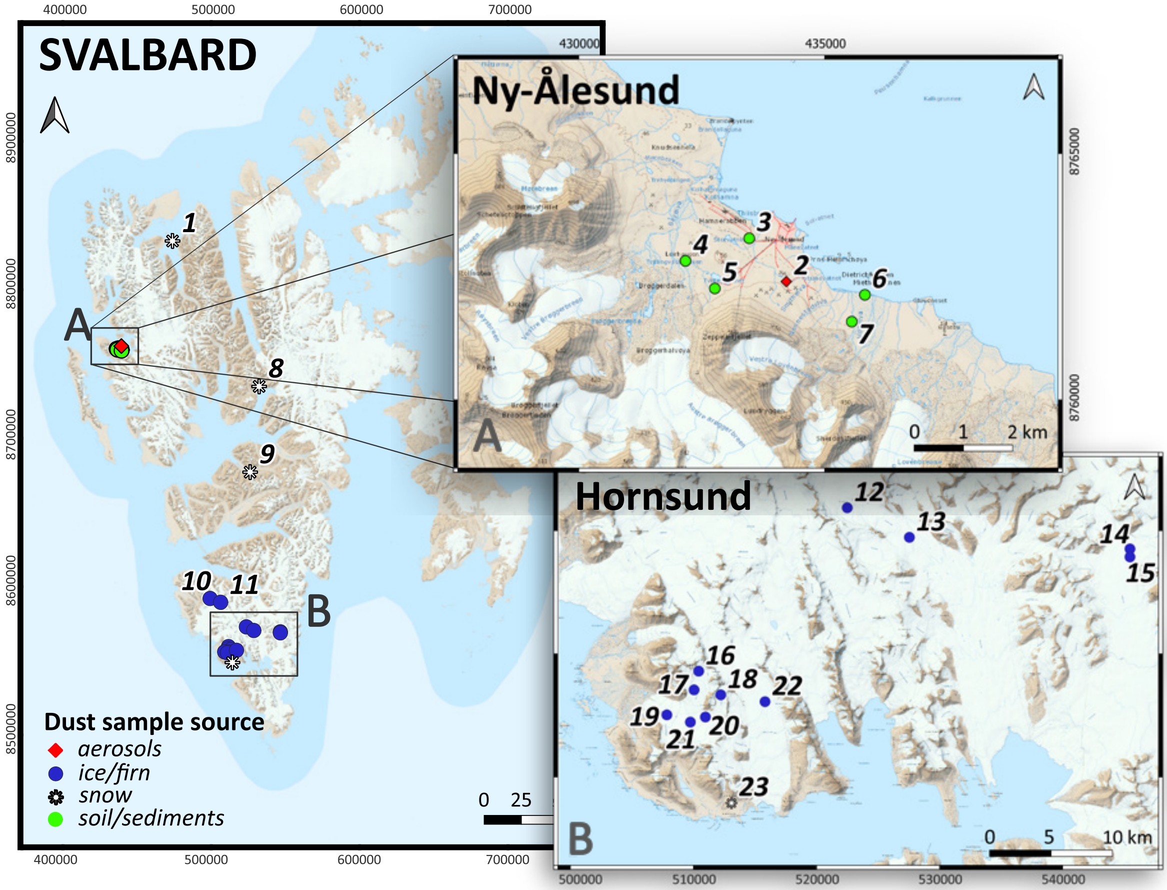

Figure 3. Sampling site locations: 1 – Woodfjorden; 2 – Gruvebadet; 3-7 – Ny-Ålesund; 8 – Pyramiden; 9 – Breinosa; 10-11 – Recherchebreen; 12-13 – Storbreen; 14-15 – Hornbreen; 16-21 – Werenskioldbreen; 22 – Hansbreen; 23 – Ariekammen. Coordinate Reference System: WGS84 / UTM 33N. Map made based on the NPI S100 Topographic Raster Data for Svalbard. © Norwegian Polar Institute.

at Gruvebadet. Dust-dominated aerosol was characterised by coarse particles (volume size distribution peaking at 3 µm and 12-14 µm) and an average calcium to sodium ion ratio of 1.8. Dust was observed mainly from June to October. Finally, the analysis of aerosol optical properties allows the identification of dust transport episodes, because dust particles are generally characterised by small scattering Angstrom exponents and might show large absorption Angstrom exponents (Russell et al. 2010; Costabile et al. 2013).

Long term measurements of aerosol chemical composition, particle size distribution, and aerosol optical properties have been routinely performed at the Zeppelin Observatory (78.9071 N - 11.8867 E, 474 m a.s.l.) and at the Gruvebadet Atmospheric Laboratory (78.918 N - 11.895 E, 61 m a.s.l.) since 2010. A complete list of analytical techniques used to characterise and quantify dust in the aerosol phase is reported in the chapter 'HERMOSA' of this report (Koziol et al. 2023).

The Polish Polar Station in Hornsund, together with NASA, has been conducting Aerosol Optical Depth (AOD) monitoring since 2004. A CE318 (Cimel's Sun Sky Multispectral Photometer) is used for this purpose. Automatic measurements are taken during the polar day, usually from April to September. Later, the device is sent to NASA for review and calibration. The data obtained goes to the AERONET (Aerosol Robotic Network) database maintained by NASA.

From October 2009 to 2017, measurements were made with a ground-based bistatic lidar system with multilevel elastic and Raman scattering. It allowed regular vertical soundings of the troposphere and lower stratosphere over the Polish Polar Station in Hornsund (77.00°N, 15.55°E, 10 m above sea level; Karasiński et al. 2014). The Nd:YAG laser generated three wavelengths simultaneously, i.e. 1064 nm;

532 nm and 355 nm. Automatic measurements of PM10 and PM2.5 particulate matter are planned to be launched in Hornsund in the near future.

3.3. Field campaigns

Field spectral reflectance measurements of dust deposited on snow, such as with field spectrometers, are necessary to quantify the impacts of dust on snow albedo, as well as to develop indices that can be used to map dust on snow from space (Khan et al. 2017; Di Mauro et al. 2015). More research is needed to continue to develop indices specific to the dust sources found in Svalbard beyond the local coal dust, which absorbs broadly in the visible wavelengths (Khan et al. 2017), as well as to monitor dust impacts on the local cryosphere.

Dust measurement campaigns in the Hornsund area have so far taken place irregularly. Measurements have been conducted in late June/early July (Kavan et al. 2020) or in spring (Lewandowski et al. 2020). In the first case, snow was taken in the vertical profile of the Ariekammen slope to determine the amount and mineral composition of dust. In the second case, the focus was on shallow firn-ice cores. In both cases, efforts were made to determine the impact of local and long-distance transport on dust delivery to the Svalbard archipelago. Different analytical methods were used. The results obtained confirmed the greater contribution of dust of local origin. Attention was drawn to the need for further research to confirm the results obtained.

Other studies conducted seasonally in the Hornsund area include AOD measurements using solar photometers. Since the focus of this chapter is on mineral dust, we refer the reader to Koziol et al. 2023.

3.4. Source identification: analytical methods

An inventory of solid phases in ice or snow can be indicative for localisation of source rocks, at least for their most general classification. The dating of radioactive minerals found in dust further constrains sourcing area to orogens formed at the given time. For instance, Lewandowski et al. (2020) used the Electron MicroProbe (EMP) for U-Th-Pb chemical dating of monazite grains, and magnetic methods for identification of magnetically active minerals, found in an ice core from southern Spitsbergen.

To distinguish between different HLD sources the geochemical features of HLD can be treated by means of potential source contribution function analysis (Crocchianti et al. 2021). Soil dust from potential source areas can also be used in resuspension chambers to segregate the aeolian part (less than 10 µm) onto filters for successive analysis (Bertinetti et al. 2022).

3.5. Source identification: Back-trajectories modelling and sand/dust forecast

Atmospheric dust in the Arctic originates from resuspension of soil dust from high latitude local sources, as well as from long-range transport events. The origin of aerosol particles in the Arctic has been investigated by tracing back air mass origin using Lagrangian back trajectory models, including HYSPLIT and LAGRANTO models (Stohl 2006).

Based on HYSPLIT back trajectories, Tobo et al. (2019) observed that air masses that spent a relatively long time over the Svalbard region in summer 2016 were enriched in larger mineral particles, indicating a significant contribution of local sources to the observed atmospheric dust. The contribution of local and long distance dust sources to the Svalbard aerosol loading was reported by Crocchianti et al. (2021) in spring and summer 2015, as well.

Young et al. (2016) studied dust particles over the European Arctic in spring 2013 during the ACCACIA campaign. Local snow excluded the impact of local dust sources and the HYSPLIT back trajectories indicated that air masses passed over North America and northern Europe at high altitudes before reaching Svalbard. Such observations suggested that dust originated from lower latitudes, potentially Asia, and was transported through the free troposphere with weak cloud scavenging.

4. Contributions to interdisciplinarity

The study of dust is intrinsically interdisciplinarity. In fact, dust is produced in the lithosphere, travels in the atmosphere and it can be deposited on the cryosphere and biosphere, and it can alter the hydrosphere. Our chapter helps in putting the role of dust in Svalbard in the right perspective. We hereafter discuss possible interactions among spheres that involve dust transport and impact.

By accelerating the melt of snow and ice, dust is potentially able to change the surface hydrology of glaciers and snowfields in Svalbard. These particular interactions have not been explored in detail, neither with observational data nor with modelling. Snow dynamical models such as Crocus are able to assimilate dust flux from the atmosphere and estimate the reduction of snow season length due to dust (Di Mauro et al. 2019). Furthermore, dust can be involved in complex interactions on the surface of melting glaciers. For example, it can enhance the development of organic material on ice and further induce surface melting of the glaciers (Di Mauro et al. 2021).

The contribution from bioaerosols (e.g. Conen et al. 2016; Baloh et al. 2021) on the ice nucleating ability of windblown dust and on cryoconite state and development has been recognised. Bioaerosol includes bacteria, fungi, pollen and terrestrial/ marine organics amongst others (Kanji et al. 2017). The source(s) and nature of such particles are at present poorly studied and understood, and this is a point to call for interdisciplinarity in the characterisation of bioparticles and their interaction with both the atmosphere and the cryosphere. Combined bio-geochemical bio-physical characterisation of aerosol and dust in Svalbard may be the starting point for widespread activity (as for disciplines and research groups involved) regarding both the cryosphere and the atmosphere in their interaction with bioparticles and bioaerosols.

To investigate and understand the life cycle of dust, measurements can be coupled with modelling approaches on emission, long-range transport and deposition. Models can also have capacity to indicate where more direct observations are needed (Meinander et al. 2022). The World Meteorological Organisation Sand and Dust Storm Warning Advisory and Assessment System (WMO SDS-WAS) monitors and predicts dust storms from the world's major deserts[1,2]. High latitude sources have recently been included in the SDS-WAS dust forecasts for the first time. Svalbard dust sources have been identified also in the SDS Source Base-Map developed by the secretariat of the United Nations Convention to Combat Desertification, in collaboration with UN Environment Programme and the WMO[3]. Models could be developed to predict albedo changes due to dust deposition from northern circumpolar dust sources.

1 https://community.wmo.int/activity-areas/gaw/science-for-services/sds-was
2 https://dust.aemet.es/
3 https://maps.unccd.int/sds/

5. Unanswered questions

Hereafter we list a series of unanswered questions that arose during the writing of this SVALDUST Chapter.

1. What is the impact of dust on the cryosphere in Svalbard? And how does dust influence the melting of Svalbard's glaciers?

2. Is dust able to trigger a bio-albedo feedback, mediated by dark photosynthetic organisms?

3. What are the interactions between black carbon and dust both in the atmosphere and the cryosphere?

4. Are radionuclides present in the aeolian dust, and, if so, what is their concentration?

5. Can dust be a vector/medium transporting micro/nanobiotic organisms on a cross-regional scale?

6. Recommendations for the future

1. Identify and characterise new dust sources in Svalbard, e.g. those caused by permafrost thaw or related to human activities (e.g. road dust).

2. Intensify and/or regularise (=make systematic) the observation and remote detection of dust emission/uplift and dust storm events in Svalbard by means of adequate monitoring systems (such as those already in use in other HL dust sources/regions such as Iceland), installed at different sites, starting from the localities (such as Adventdalen valley near Longyearbyen) where these phenomena have already been observed.

3. Further investigation, by continuous/direct measurements and devoted campaigns, of the influence of local sources in the lower troposphere and long-range transport at higher altitudes.

4. Establish an inventory of the long-range dust sources by source profiling in order to cooperate with the modellers for quantification of the dust load from different sources.

5. Disentangle the relative contribution of black carbon and dust on snow and ice albedo reduction in Svalbard. Furthermore, a detailed study on the possible mechanism promoting bio-albedo feedbacks (i.e. biological reduction of snow/ice albedo) should be conducted in Svalbard, and then results should be compared with those presented for the so called 'dark zone' of the Greenland Ice Sheet.

7. Data availability

Data availability is presented in appendix 2.

8. Acknowledgements

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Appendix 1: Aerosol, snow and ice/firn sampling techniques commonly employed in Svalbard

Aerosol	
Time resolution	From a few hours up to 7 days, depending on the analytical technique employed
Size fractionation	Bulk aerosol samples (PM10 and TSP -Total Suspended Particulate matter sampling head) or size segregated samples (impactors)
Sampling substrate	Different filter substrates according to specific analytical needs (i.e. quartz for organics, teflon for trace elements, polycarbonate for Scanning Electron Microscopy (SEM), cellulose for microbial population)
Snow and ice/firn	
Sampling depth	Surface snow layer up to 10 cm; snow in a vertical profile (snow pits, snow cores) to the ground or to the glacier ice; shallow ice/firn cores (1-2 m).
Sampling techniques	Bulk samples collected manually or with ice core drilling equipment. Samples should be collected according to the protocol given by Gallet et al. (2018)
Sample preparation	Mineral fractions in the ice and snow samples are extracted by filtering the meltwater. Filters with mineral residuum are dried and divided into parts, each part being subjected to different analytical methods.

Reference:

Gallet J-C, Björkman MP, Larose C, Luks B, Martma T, Zdanowicz C (2018) Protocols and recommendations for the measurement of snow physical properties, and sampling of snow for black carbon, water isotopes, major ions and microorganisms. Norwegian Polar Institute Brief Report 046, 27 pp. http://hdl.handle.net/11250/2486183

Appendix 2: Availability of data referenced in this chapter

Dataset	Parameter	Period	Location	Metadata access (URL)	Dataset provider
High Latitude Dust deposited on snow	Sediment concentration	June-July 2019	Ariekammen and Pyramiden	https://doi.org/10.5281/zenodo.6790469	Jan Kavan (Masaryk University), jan.kavan.cb@gmail.com
Aerosol chemical speciation	Concentration of Na+, Cl-, NH4+, nssK, nssSO4, C org, EC and BC	July 2015	Gruvebadet, Ny-Ålesund	https://doi.org/10.1594/PANGAEA.908250	Beatrice Moroni, University of Perugia, Italy (UNIPG), b.moroni@tiscali.it
Aerosol chemical speciation	concentration of metals	July 2015	Gruvebadet, Ny-Ålesund	https://doi.org/10.1594/PANGAEA.908251	Beatrice Moroni, University of Perugia, Italy (UNIPG), b.moroni@tiscali.it
Percent mass fraction of aerosol particles from SEM observations	mass fraction of aerosol particles	July 2015	Gruvebadet, Ny-Ålesund	https://doi.org/10.1594/PANGAEA.908276	Beatrice Moroni, University of Perugia, Italy (UNIPG), b.moroni@tiscali.it
Aerosol optical properties	aerosol optical properties	July 2015	Gruvebadet, Ny-Ålesund	https://doi.org/10.1594/PANGAEA.908239	David Cappelletti, niversity of Perugia, Italy (UNIPG), david.cappelletti@unipg.it
Aerosol size distribution	aerosol size distribution	July 2015	Gruvebadet, Ny-Ålesund	https://doi.org/10.1594/PANGAEA.90818	Beatrice Moroni, University of Perugia, Italy (UNIPG), b.moroni@tiscali.it
Aerosol size distribution	aerosol size distribution	July 2015	Zeppelin Observatory, Ny-Ålesund	https://doi.org/10.1594/PANGAEA.908186	Beatrice Moroni, University of Perugia, Italy (UNIPG), b.moroni@tiscali.it
Results of the geochemical and magnetic studies on cryodust from glacial cores of southern Spitsbergen (Svalbard, Norway)	Sample specification; Chemical dating; Magnetic slope correction; Magnetic susceptibillity	April 2018	Recherchebreen, Hornbreen (Flatbreen), Storbreen, Werenskiold-breen, Hansbreen	https://doi.org/10.5281/zenodo.6801558	Adam Nawrot, Institute of Geophysics, Polish Academy of Sciences (IG PAS), anawrot@igf.edu.pl