SIOS

SVALBARD INTEGRATED ARCTIC
EARTH OBSERVING SYSTEM

An agenda for the future of snow research in Svalbard - a multidomain approach

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Foreword

On 1-5 February 2021, Svalbard Integrated Arctic Earth Observing System (SIOS) held a multidisciplinary workshop on snow research in Svalbard with more than 100 participants. This agenda paper is a result of consultations during and after the workshop and builds on the combined expertise of researchers and scientists from various disciplines (glaciology, biology, climatology, etc.), all of whom share a common interest and concerns with the present state and the future of snow-covered environments in the Arctic.

The agenda is intended to serve as a goal-setting, supporting reference document that can be used and cited by researchers, stakeholders and organisations planning snow-related research activities on Svalbard. It can, among other uses, be referred to when preparing applications for research funding by individuals, teams or consortia.

1. Introduction

1.1 Scope and purpose of this document

Next to the ocean, snow is the second largest interface between the atmosphere and Earth's surface during winter. In Svalbard, the seasonal snowpack (including glaciers) covers ~60 to 100 % of the land surface in winter and summer, respectively. Changes in Arctic snow cover extent or snowpack properties have occurred in recent decades in response to high-latitude warming, and will likely continue in the future. This has important anticipated effects on different aspects of the Svalbard environment, including the mass budget of glaciers, surface hydrology, permafrost and terrestrial ecosystems. Snow avalanches, slush flows, landslides and seasonal floods are all relevant geohazards in Svalbard, where snow dynamics play an important role. Managing the risk of these hazards in changing climate is challenging. In addition, tourism activities do rely on snow cover for outdoor activities, as do local communities for recreational purposes (Gallet et al. 2019). For these reasons, snow-related research will remain an important vehicle for monitoring and analysing the rate and effects of climate change in Svalbard.

This document proposes an agenda for research focussed on snow and snow-covered environments in Svalbard. Its purpose is to guide and prioritise future research efforts, based on recommendations from a multi-national community of experts. The agenda identifies important knowledge gaps and makes specific research recommendations pertaining to seasonal snow cover in relation to (1) glacier mass balance; (2) permafrost, hydrology, and terrestrial ecology; (3) the cycling and fate of atmospheric contaminants; (4) remote sensing of the snow cover, and (5) the snow modelling and dynamics of snow-atmosphere interactions. Most knowledge gaps and recommendations for any of these themes have relevance for other themes, e.g. improving predictions of the seasonal snow cover evolution in Svalbard under a future, warmer climate is needed to better forecast freshwater runoff, the winter surface balance of glaciers, the fate of airborne contaminants deposited in snow, rates of permafrost thaw, and changes in the surface radiative energy balance. The agenda paper also discusses research needs that could help develop snow-related risk assessment tools for Svalbard communities, as well as needs in terms of new technologies (e.g., cold-adapted sensors) and data management structures that can both further and support the research priorities. Finally, the agenda paper emphasises the use of snow modelling and the need to better connect field research and modelling communities.

This agenda is not an exhaustive review of snow-related research on Svalbard. However, it draws upon several recent reviews conducted under the auspices of SIOS and published in the State of Environmental Science in Svalbard (SESS) reports (Orr et al. 2019, Van den Heuvel 2020, Moreno-Ibáñez 2021). For a comprehensive list of relevant published studies, readers are therefore referred to these reports. The research priorities presented herewith also dovetail with those identified by other national and international research programs, including in the EU-PolarNet White Papers (Biebow et al. 2019) and the US Arctic Research Plan 2017-2021 (Holdren et al. 2016). A list of acronyms and abbreviations used in the document is provided in appendix 1.

In order to place the outlook of this agenda in historical perspective, we begin by providing a brief analysis of trends in snow-related research on Svalbard over the past 30 years.

1.2 Recent trends in snow-related research on Svalbard

Figure 1 shows trends in snow-related research on Svalbard since 1990, based on a bibliometric analysis of 377 peer-reviewed publications[1] in the SCOPUS database. As can be seen, the research area that saw the largest rise of publications over the past 30 years concerns snow-air chemistry. This theme includes papers on chemical exchanges between the atmosphere and the snowpack, as well as papers quantifying airborne contaminants in snow, including black carbon (BC), mercury (Hg) and other metals, reactive nitrogen (N) species, and various Persistent Organic Pollutants (POPs). Next came research publications on the spatial distribution of snow on the ground, particularly in relation to glacier surface mass balance, based on in situ observations (including ground-penetrating radar) or on modelling. This was followed, in the third rank, by publications on the physical and optical properties of the snowpack (e.g., albedo), most commonly in the context of developing or validating spaceborne remote sensing methods. In the fourth rank came publications about the ecology or phenology of snow-covered environments and terrestrial animals, many of which concerned the impact of changes in snow cover conditions on the health of ungulates.

[1] Publications were sorted based on the principal aspect of snow or snow-related environments that was the object of the published research. Each publication was only counted once per category (no duplication).

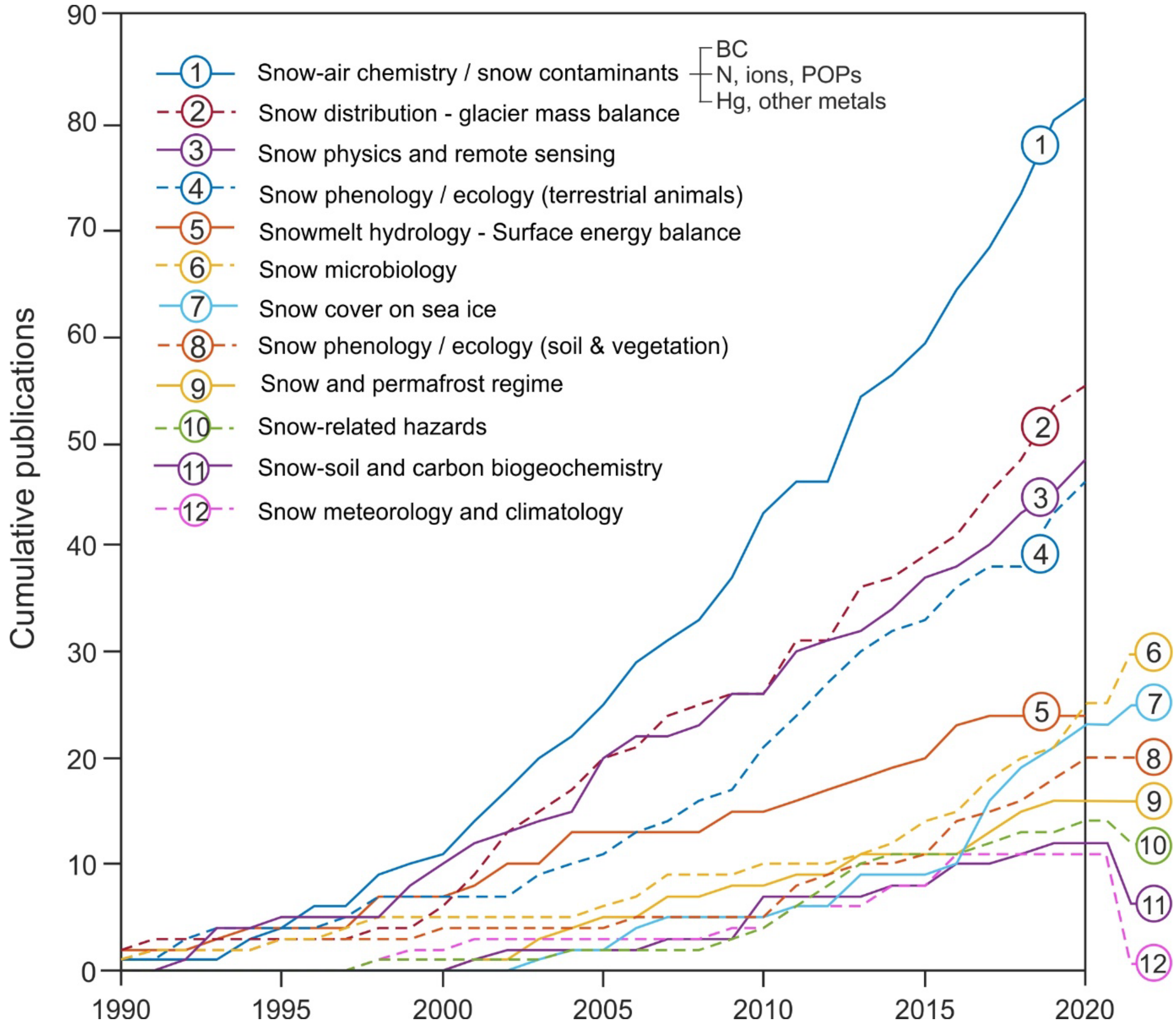

Figure 1: Trends in snow-related research on Svalbard since 1990, based on a bibliometric analysis of 377 peer-reviewed publications in the SCOPUS database.

Next came publications focussed on the surface energy balance of the snowpack, mostly on glaciers, and the impact of warming on snowmelt and runoff hydrology. The microbiology of snow-covered ecosystems, absent in pre-2000 publications, has also seen a rapid, and still accelerating, rise in published research since then, with particular emphasis on the genomics of cold-resistant species. Publications on other topics, such as the effect of snow cover on the permafrost thermal regime, or the properties of snow on sea ice, have also increased, but at comparatively moderate rates. The snow-related publications that were most frequently cited (> 500 citations, in cumulative numbers) were, in decreasing rank order, those that concerned the ecology or phenology of snow-covered environments (1766 citations), glacier snow mass balance studies (815), remote sensing of snow cover properties (716), snow microbiology (692), and the atmospheric deposition of BC in snow (500).

Altogether, the bibliometric survey showed that snow-related research in Svalbard has both expanded and diversified considerably since 1990. The trends revealed by Fig. 1 reflect, to a large extent, the growing concerns about the current and future impact of human activities on Svalbard, either through the long-range delivery of various airborne contaminants, or through the consequences of anthropogenically-induced Arctic warming on glacier mass balance, surface hydrology, and the health of ecosystems. The field of snow microbiology recently and rapidly expanded partly owing to technical advances (e.g., rapid gene sequencing) but also because of the growing recognition of the role played by microbes in the cycling of nutrients and contaminants in snow-covered environments.

Geographically, the overwhelming majority of field-based studies included in the survey were, unsurprisingly, carried out on Spitsbergen, close to settlements and existing research facilities, namely in Ny-Ålesund or on nearby sectors of Brøgger Peninsula, in Longyearbyen and its surroundings (including the much-studied Adventdalen area), on Kapp Linné near Barentsburg, and in the sector near the Polish Polar Station Hornsund. Because the bibliometric survey was largely limited to published works in English, research produced by Russian, Czech or other groups in the vicinity of Barentsburg is likely under-represented. Much of the recently-published work on snow cover properties on sea ice came out of the 2015 Norwegian Young Sea ICE[2] expedition in areas north of Spitsbergen.

2. Science knowledge gaps and needs

2.1 Snow cover and glacier mass balance

There is a set of basic questions the community still struggles to answer that are fundamental to further our understanding of snow. The most important is related to the deposition of snow on glaciers: its amount, timing and variability, during a season but also over several years. Knowledge on the variability of snow deposited over glaciers, as well as over the entire Svalbard archipelago, is needed in order to determine if there is any pattern to snow distribution, and if so, whether changes are or have been occurring. Spatial and vertical precipitation patterns of snow in Svalbard should be measured, focusing on surface snow processes, glacier mass balance, water cycle, and surface energy budget to determine the effects of climate change on the cryosphere in Svalbard (storage/retention of water on land and cooling of the Earth's surface). Furthermore, snow melt considerably affects coastal processes, such as fjord water circulation, marine wildlife, and terrestrial ecosystems. Such large overarching research questions are the focus in this section.

Satellite remote sensing and numerical climate and snow models will be used to understand the aforementioned processes at the regional scale, but it is necessary to validate and reconcile their outputs against ground-based observations on snow conditions made on reference glacier monitoring sites across Svalbard. The complexity of

[2] https://www.npolar.no/en/projects/n-ice2015/

the terrain in the archipelago makes such an exercise challenging and a seamless merging of in situ and remotely-sensed observations with model simulations is not yet in sight, but steps can be taken to make progress towards these goals.

Computer models of varying complexity that can generate gridded predictions (and, for some models, hindcasting) of snow cover and of snowpack properties are being developed and tested. The models are using meteorological data supplied by dynamic downscaling of regional climate model outputs (Schuler et al. 2020). Recent efforts have led to the combined modelling of glacier mass balance, seasonal snow conditions on glaciers and land, as well as runoff across Svalbard in a past (Van Pelt et al. 2019) and future climate (Van Pelt et al. 2021). Using observational datasets as input and for calibration/validation, computer models can provide a spatially and temporally continuous view of long-term trends and patterns of snow conditions. The datasets that are of highest relevance for energy balance and snow model optimisation include measurements of stake mass balance, snow/firn density and temperature, and weather station records. Simulated glacier mass balance and snowpack development critically depend on the description of precipitation (snowfall and rainfall) at the surface. At present, uncertainty concerning the spatial distribution of snow accumulation both at the local and regional scale hamper detailed modelling of mass balance distribution, snow cover patterns, and snow properties across Svalbard.

As snow and ice cover conditions on land and sea continue to evolve under a warming climate, access to some of the current glacier mass balance monitoring sites on Svalbard may become more difficult or hazardous. Hence future mass balance monitoring and assessment is likely to depend increasingly on the use of stationary autonomous sensors with remote access (e.g., automated weather stations with satellite linkage), mobile sensor platforms (e.g., UAVs), observations from remote posts (e.g., time-lapse photogrammetry) and, of course, satellite-based remote sensing.

Albedo observations from in situ solar radiation observations or from remote sensing products are critical for accurate estimation of surface energy balance and melt. The current changes of precipitation patterns in Svalbard, along with more frequent warming events, can easily turn snow into ice which has a lower albedo, significantly changing the surface energy budget and reducing the snow cover duration. It would be beneficial to improve the surface energy budget of glacier along altitude transects and at seasonal timescale.

In recent reviews, Gallet et al. (2019) and Schuler et al. (2020) underscored how a diverse array of remotely-sensed satellite products are now becoming available for snow and ice cover characterization at increasingly high-resolution spatial scales (10 - to 30 m for Sentinel-2 and Landsat-8, respectively; Malnes et al. 2021). Together, these new products can now supply gridded observations of such variables as surface elevation changes, land-surface temperatures and snow/ice albedo which are relevant to glacier mass balance.

As shown in chapter 1.2, most of the snow studies done on glaciers in Svalbard are concentrated on the western coast, namely around Ny-Ålesund, Longyearbyen and

Hornsund. Some research has been also done on the Eastern part (Nordaustlandet) and in the central part (Lomonosovfonna), but apart these specific areas and a few very limited projects which have focused more on spatial variability, there are almost no direct ground observation of snow quantities in Svalbard elsewhere. Consequently, the data which are used to calibrate remote sensing data and/or models are often constituted of an incomplete picture of Svalbard glacier regimes. For example, the western side of Svalbard receives in general more precipitation, especially in the southern part. The western part is also usually warmer. The accumulation and melting time and phase are then different compared to the central part of Svalbard, which is colder and drier. In addition, the Svalbard archipelago is surrounded by water with different and very variable atmospheric inputs, which has consequences for the precipitation amount and phase. The current change in climate also tends to accentuate that variability, and we now observe more frequent weather instability and intrusion of warm air masses coming from the south, even in the middle of the winter. Precipitation in the form of rain is no longer unusual in winter, but almost expected. Compared to the mid 90‘s where only 1 out 5 winters were icy (‘rain on snow event’ in winter), we have now icy winters almost every year. Ice layers are formed in the snow, and in the worst case, ice on the ground (basal ice), which impacts the forage ability for ungulates and can damage vegetation.

Presently, some of the more pressing knowledge gaps and needs are:

Knowledge gaps and needs

- Data on the distribution of snow and its variability on glaciers in the southern, central and the eastern parts of Spitsbergen are almost completely missing. Mid-size and large glaciers are still poorly known and under-represented in mass balance surveys relative to small glaciers, although progress has been made in this regard over the past decade (Schuler et al. 2020).
- A long-standing challenge for the validation of satellite-based products is the disparity between the spatial scale of glacier mass balance measurements, which are typically made at single-stake location along linear transects, and that of snow cover properties retrieved by spaceborne sensors, which are area-averaged values over pixels or grid cells of much larger size. Hence there is a need to establish the local-scale variability of snow cover properties at a variety of spatial scales for several representative ice-covered landscapes of Svalbard.
- Some of the most difficult, yet critical quantities to observe remotely, and also to model, are the amounts of solid and liquid precipitation received at the surface of glaciers. Presently, at most monitored sites, only the net cold-season accumulation can be estimated with some confidence using late winter or spring snowpack measurements at reference stakes. Solid precipitation in other seasons can be estimated using ultrasonic sounders, but these cannot quantify rainfall, which is non-negligible in *any* season on Svalbard. Therefore, an ongoing technical challenge is to find methods by which to improve in situ estimations of received precipitation on glaciers.

- A further need is to develop a strategy by which to better track and quantify how warming conditions during the cold months (e.g., winter thaws) affect the physical properties of the snow cover on glaciers, and how much, if any, of the winter accumulation is lost by runoff or remains internally stored as a result. Wintertime thaws, and rain-on-snow events in particular, modify the radiative absorption and scattering properties of the snowpack, thus affecting their radiative signatures as seen from space. Detailed investigations on these phenomena are of course easier to carry on seasonal snow at fully instrumented sites such as in Ny-Ålesund, but at least some improved knowledge of temporal changes in the internal texture and structure of the snowpack on glaciers (e.g., frequency of ice layers) is badly needed. Presently, such detailed information is rarely compiled in available mass balance reports.

Recommendations for specific actions

- Undertake repeat overland (snow scooter) or airborne traverse/surveys to measure snow properties across large and remote glaciers with a significant altitudinal range, especially in parts of the archipelago that are currently underrepresented (southern, central and eastern Spitsbergen).
- At some selected glacier sites, the spatial variability of snow cover properties at scales of 10 m^2 to 1 km^2 should be quantified to improve knowledge of the representativeness of area-average values of these properties in gridded satellite products.
- Deploy new, satellite- or radio-linked automatic weather stations at selected remote glaciers in under-represented parts of the archipelago. These should preferably be installed at sites that can be serviced by overland access for the foreseeable future, i.e., avoid sites where the pace of change in surface conditions may hinder access to the instruments in a few years.
- Investigate new, field-deployable technologies that could be used to directly quantify liquid and solid precipitation on glaciers in all seasons.
- Develop new tools or methods to quantify the properties of wet and partially icy snow, with a focus on remote sensing for glacier mass balance model validation.
- Carry out multi-year surveys (e.g., every 5 years) at a selection of sites to track how the frequency of winter thaws and internal refreezing of water within the snowpack will evolve on glaciers in the future. An example of such a survey is one that was carried out in April 2016 across Svalbard, during which the detailed stratigraphy of the snowpack was recorded at 22 sites on 7 glaciers (Barbaro et al. 2021). Such information may serve as a baseline against which future conditions can be compared.

2.2 Snow cover, permafrost, hydrology, and terrestrial ecology

Recent SESS report reviews, Gallet et al. (2019), Pedersen et al. (2020), Christiansen et al. (2019, 2020, 2021) and Killie et al. (2021) underscored how cross-disciplinary actions are needed to better understand the spatial-temporal variation of snow in the landscape, and how this can be captured in models. This also includes the effects of snow distribution, development of the snowpack and redistribution of snow on runoff, snow avalanche and slush flow activity; the continentality and altitudinal dependence on snow deposition and snow redistribution by wind; the influence of ice formation within the snowpack as well as on ground; and the importance of a snow cover for ecosystems and the effects of basal ice formation (an ice layer in between the ground and the above snowpack, or the atmosphere in worst case).

A central theme is related to the impact of snow cover on ecology, particularly effects of snow depth and snow melt on herbivores, microbiology, plant growth dates, nutrient effect on plants, microorganisms, and soils, and how these elements change as the climate changes (Cooper 2014). Recent studies have focused on the consequences of snow disappearance for herbivores and the effect of snow melt on the timing of nesting and on population size (Layton-Matthews et al. 2019). As mentioned above, winter warming events and, in particular, rain on snow (ROS) events in winter turns snow into ice and in the worst case forms a basal ice layer. Basal ice encapsulates vegetation and reduces, if not inhibits, forage capacity of ungulates (Hansen et al. 2013). More winter warming events (Vikhamar-Schuler et al. 2016) and especially more frequent and intensified ROS events (Peeters et al. 2019) also impacts the living conditions in Svalbard, including travelling with snowmobiles and other tourism activities (Hansen et al. 2014).

Snow cover impacts ground temperatures through its insulating effect which reduces heat loss from the ground during the winter season (Christiansen et al. 2019). The near-surface permafrost temperature shows significant inter-annual variations, depending mainly on the history of snow cover, and from one site to another, depending mainly on parameters controlling snow accumulation and soil water/ice content, which may vary over very short distances. The ROS-phenomenon is of particular concern as it can lead to increased ground surface temperature and near-surface permafrost thawing (Isaksen et al. 2007, Westermann et al. 2011). The variability over the entire Svalbard landscape is huge and we have still limited capability to detect ice inside the snowpack with satellite remote sensing tools. Models examining this topic are being developed, but it is complex, particularly as ecologist and climate scientists face challenges when dealing with very different spatio-temporal scales in the field and in model outputs.

There are also other challenges with measuring snow, e.g., with the representativeness of measurement sites, large errors in automated systems related to differentiation between ice and snow on the ground and differentiating between solid and liquid precipitation.

The purpose of SIOS is indeed to develop holistic and comprehensive monitoring of several Earth Science System parameters, including climate and ecosystem fields. However, we are still facing challenges unifying these fields of research. We still have difficulties to clearly identify what are the best variables to monitor, and how to combine in a single field campaign both the critical ecosystem and climate parameters to monitor, and at which spatio-temporal scale. This can be a sensitive topic as both ecologists and geophysicist have had their own ways to monitor their own crucial parameters for decades, and suggestions for changes are not always well-received. Some work is developed towards this end but is not yet implemented. Therefore, it is still difficult to assess the role changes in snow cover have on ecosystems and permafrost and we recommend focussing on following issues.

Knowledge gaps & needs:

- So far, few studies have focused on modelling the internal snowpack processes. These are crucial to estimate the formation of internal and basal ice layers that affect ecosystems, and the thermal resistivity of the snowpack, fundamental for soil temperature and varying by a factor of magnitude when snow has experienced melting. Wintertime thaws and ROS events, the penetration of meltwater in and below the snowpack, and its refreezing within it, need to be monitored, mapped and quantified, in order to establish how these factors impact vegetation, grazing animals and the permafrost thermal regime. In addition, there is a need to better quantify long-term effects on permafrost related to changing snow cover and impact of more frequent, intense and long-lasting warm spells and ROS events.
- Knowledge of the snow-permafrost relationship in Svalbard is presently limited. More studies are needed on the vulnerability of permafrost and changes in active layer depth due to changes in the duration and thickness of the snowpack.
- Previous and present observations focus on understanding snow and permafrost conditions near to settlements and research stations in western and central Svalbard. However, snow cover and ground thermal conditions there are not representative for the northern and eastern reaches of the archipelago, where the temperatures are lower and climate development might be different.
- We have very limited information on snow amount and snow water equivalent on the catchment scale and we do not know how it changes during the melt period (e.g. surface flow on icy layers). High-resolution information on snow depth and basal ice distribution in complex terrain such as tundra, moraines and on mountain slopes is needed.
- More information is needed on how plants respond to changing snow conditions, especially the balance between moss and vascular plants and how this affects the carbon dioxide (CO_2) fluxes and C balance, and C and nutrients in water efflux from the system.
- We must establish how current variability and future changes in snow cover properties, and its duration, impacts or will impact the length of the potential growing season in Svalbard. It is currently discussed that the end of growing season may get delayed or advanced: this clearly affects the C uptake/ efflux at end of season so very important for tundra C balance.
- Studies are needed to quantify variations in abundance among species and ecotypes as a function of snow cover extent and duration.
- Growth and metabolic activity of microorganisms at sub-zero temperatures/ in winter snowpack and biogeochemical implications is understudied.

- It is important to determine how much microbial biomass can be produced in winter in and under the snowpack, and what the effect of changes in snow will be on the Arctic food chain and nutrient resources. Is microbial activity in soil mediated by snow-cover duration? Does this have long-term implications for soil development & biogeochemical cycling? Do changes to the duration of snow cover affect carbon accumulation and nutrient availability in soils on annual/decadal scales? Do changes to snowpack duration change rates of carbon accumulation and nutrient mineralization in soils by altering the balance between heterotrophic/phototrophic microbial community?
- We do not currently understand the complex eco-physiological and molecular-genetic mechanisms of resistance of biological soil crusts (BSC) microalgae to stresses associated with the harsh Arctic conditions. We generally expect that hardened and/or starved BSC microalgae will be more resistant to Arctic winter, melt-freeze cycles, cryostress and desiccation, compared to those growing under more favourable conditions.
- More studies are needed on the seasonality in snowpack microbial/biogeochemical processes. Which microbial processes are driven by seasonal variations in temperature, light, moisture, freeze-thaw processes? Does seasonal variation in e.g., moisture availability, light, etc. drive microbial gene expression, resulting in different effects on nutrient cycling and respiration?
- Similarly, few studies have focused on measuring and modelling and the internal snowpack processes, crucial to determine the formation of weak layers in the snowpack which are a prerequisite for snow avalanche formation (e.g., Eckerstorfer and Christiansen, 2010). Accurate physical snowpack modelling requires weather stations with full energy balance that are located in snow avalanche starting zones. Then the modelled snowpack information is usable for regional snow avalanche forecasting.
- The effect of drifting snow on snow avalanche formation and especially snow cornice formation needs to be better quantified and monitored. Cornices pose a high risk to infrastructure in Longyeardalen. Drifting snow has also influence on snow hydrology or the location of glaciers in central Svalbard (e.g. Jaedicke and Gauer, 2017).
- Only few studies have been conducted on slushflows since they are less frequent than snow avalanches Svalbard (André, 1990, Scherer et al. 1998, Eckerstorfer and Christiansen, 2011). For slush flows to release, the snowpack has to be conducive for effective water infiltration and the meteorological conditions have to facilitate rapid snow melting (during mid-winter thaw and ROS or during spring snow melting). Both the timing of slush flows and their topographic occurrence do not necessarily coincide with snow avalanches. Slush flows release in low-angle depressions with maximum outruns far beyond other slope processes. Geomorphological evidence shows that slush flows have been frequent in the past and in a warming climate, we can expect to experience more slush flows and a general shift towards a wet snow avalanche regime. Mitigations measures against slush flows have been semi-successful in the past 70 years in Longyeardalen. To prevent a high magnitude event, permanent prevent

measures in the head of Vannledningsdalen have to be considered and the deflection dams in the runout zone have to be reconsidered.

Recommendations for specific actions:

- Coordination of research infrastructure and observational measurements must be performed at similar spatial and temporal scales to predict and understand climate impacts on Svalbard snow cover and tundra. Integrated multidisciplinary long-term monitoring actions from the atmosphere to the snow and from the snow to the soil should be initiated. Specifically, we recommend increasing the number of full-scale automatic snow- and weather stations, with new monitoring efforts on e.g., effects of snow distribution on runoff, active layer development, permafrost temperature and for snow avalanche warning. The latter is important not only for research but for operational services.
- Establish long time snow transects or supersites to map and monitor snow cover and redistribution of snow (snow depth and SWE) and understand climate impacts on Svalbard cover, tundra, catchment and run off. Repeated overland (snow scooter) or airborne traverse/surveys should be undertaken to measure snow properties across large and remote glacier and glacier free areas with a significant altitudinal range, especially in parts of the archipelago that are currently underrepresented (southern, central and eastern Spitsbergen) or supersites.
- At some selected sites, the spatial variability of snow cover properties at scales of 10 m^2 to 1 km^2 should be quantified to improve knowledge of the representativeness of area-average values of these properties in gridded satellite products. In addition, such measurements can be used for e.g., model validation.
- Develop new tools or methods to quantify the properties of wet and partially icy snow and wetness (or liquid water content (LWC) in %) in the snowpack, with a focus on remote sensing for snow model validation.
- Although the snow temperature gradient in certain cases may be the opposite to that occurring in non-arctic/non-permafrost regions, data/observations on LWC development in the snowpack has an application far beyond the polar regions, e.g., for slush flow (early warning) studies. The SIOS community should provide protocols for in situ measurements of LWC in snow to ensure available input and Cal/Val-data awaiting future automated procedures and instrumentation.
- Develop a weather station and snow depth sensor network in snow avalanche starting zones to facilitate physical snowpack modelling for snow avalanche and slush flow forecasting. Modelling snowpack dynamics has also implications for research on snow water equivalent, and effect on vegetation, animals, permafrost etc.
- Automated, frequent ground-based LiDAR scans of the cornices would allow for accurate assessment of their dynamics leading up to failure and snow avalanche release (Hancock et al., 2020). LiDAR can also be used for snow depth change mapping.

- Future observation efforts should focus on characterising snow and permafrost environments in northern and eastern parts of Svalbard. Including such areas will most likely allow observations of the full diversity of how snow cover affects permafrost conditions throughout the entire Svalbard landscape.
- Weather data should be used to calibrate spatial and temporal snow models, as the cryosphere has a key role in determining the dynamics of the Svalbard tundra ecosystem. This would be a basis for developing high resolution physically based snow models from joint data sources.
- The ecosystem impact of changing snowpack properties in a warming climate is an important arena for interdisciplinary research between ecology and geophysics. Besides co-location of research infrastructure, there is a need to develop a system that merges available observational datasets on snow properties with state-of-the-art, high-resolution (1-to-500-metre scale), physically based snow models. The goal of this data–model fusion system is to create accurate datasets that have good spatial distribution and evolve with time. Such datasets can be used to better understand relationships between ecosystem processes.
- Consistency in sampling and sample processing for snow microbiology and geochemistry must be addressed to mitigate bias arising from different preservation and processing methods. Sample processing includes fast vs. slow melting prior to filtering, vs. freeze-drying, vs flash-freeze in liquid nitrogen, vs. chemical preservation methods.
- Need to build a strong connection to the remote sensing group to map snow distribution using terrestrial observations (e.g., time lapse camera, terrestrial laser scanning) and drone and satellite-based observations.

2.3 Contaminants and other impurities in the snow cover

This section is concerned with elements and compounds deposited from the atmosphere into the seasonal snowpack. Some of these have natural sources (e.g., dust, sea salts), others are only emitted by human activities (e.g., POPs), and yet others have both natural and anthropogenic sources (e.g., BC, SO_4^{2-} and NO_3^-). "Contaminants" refers more specifically to those elements or compounds that can adversely impact the health of local terrestrial and aquatic ecosystems upon release from snow, e.g., Hg or POPs.

In Svalbard, categories of snow contaminants and impurities that are of greatest concern with respect to their potential environmental impacts are:

a) Light-absorbing particles that can cause tropospheric warming and lower the snow / ice surface albedo, thus enacting climate feedbacks and affecting the timing of snowmelt. These include BC, mineral dust and biogenic particles. Improving current knowledge of the surface radiative forcing by light-absorbing contaminants in snow has been identified as a priority goal in US and European long-term Arctic research plans (Holdren et al. 2016; Biebow et al. 2019), as well as by the Intergovernmental Panel on Climate Change (IPCC;

Meredith et al. 2019) and the Arctic Monitoring and Assessment Programme (Tørseth et al. 2019), to achieve better climate predictability in the future.

b) Radioactive isotopes of elements such as Sr, Cs or Pu, produced by human activities, or naturally occurring radioisotopes of C, Be, Pb, etc. The former are of concern for their potential to adversely affect terrestrial or marine biota (AMAP 2016a), while the latter are useful tracers of atmospheric aerosol sources and transport/removal processes.

c) Inorganic, water-soluble (ionic) aerosols derived from anthropogenic or natural emissions, which can affect the radiative balance of the Arctic atmosphere (e.g., by light scattering; Abbatt et al. 2019) and can also cause acidification of precipitation (AMAP 2006). These include SO_4^{2-} and NO_3^- derived from SO_x and NO_x emissions.

d) Inorganic or organic aerosols that can act as nutrients to Arctic ecosystems. These include many N species, as well as water-soluble (dissolved) and water-insoluble (particulate) organic carbon (WSOC; WIOC, respectively). Other ions, such as those associated with sea-salt aerosols (which dominate the Svalbard snowpack ionic balance) are also of interest as proxies for better understanding basic atmosphere-surface aerosol exchange processes.

e) Bioaccumulative contaminants that can adversely affect the health of Arctic fauna and flora when released in snowmelt. These include Hg (particularly methylated forms) as well as many semi-volatile organic compounds (SVOC) and POPs such as pesticides, PCBs, dioxins, etc. Together, these contaminants are the ones which presently pose the greatest threats to marine and terrestrial ecosystem health in the European Arctic (AMAP 2011, 2016b).

f) Emerging contaminants, whose presence, levels, or potential environment impact in the Arctic are not yet well assessed or quantified. These include the so-called Chemicals of Emerging Concern (CECs; AMAP 2017; Muir et al. 2019). Examples of the latter are per- and polyfluoroalkyl substances (PFAS) and halogenated flame retardants. The dispersion of nano- or micro-plastics and soluble polymers to the polar environment is now also widely recognized (Bergmann et al. 2019). As well, engineered nanoparticles (ENPs) such as carbon nanotubes, Ti, Zn, or Fe oxide nanoparticles are also being increasingly scrutinized in view of their potential adverse effects for human and environmental health, but very little is presently known about their global dispersion.

g) In addition to those, there are others that although now of lesser concern, still deserve continued monitoring in view of their potential toxicity, such as some heavy metals other than Hg (e.g., Pb, Cd, Zn, As).

Knowledge gaps and needs

- At present, knowledge of contaminant and impurity deposition in Svalbard snow comes mostly from studies carried out near established focal sites such as Ny-Ålesund or Hornsund, or from ice cores recovered from icefields of northeastern Spitsbergen. While valuable, these data only cover parts of the spectrum of environments in the archipelago. Hence, there is a need to better quantify regional variations of contaminant and impurity deposition and accumulation in seasonal snow across Svalbard, especially along altitudinal gradients (coast to highlands), and in presently under-represented parts, such as southernmost and northernmost Spitsbergen, Nordaustlandet or Edgeøya.

- There is also a need to characterize the meteorological and atmospheric conditions that control variations in contaminant and impurity deposition and accumulation in Svalbard snow (both in time and space). Air-snow transfer functions need to be developed and parametrized for both volatile and particulate atmospheric species of concern. Understanding the dependence of air-snow transfer of contaminants and impurities on evolving climate conditions is required to anticipate their future synergistic impacts in Svalbard.
- Emissions of mineral dust from mid-/high-latitude sources (e.g., in Iceland, central or northern Eurasia) may increase in future decades owing to drier conditions in some source regions, and/or expansion of some sources, for e.g., in newly-deglaciated forelands. Deposition of locally emitted or long-distance sources have the potential to lower the snowpack albedo, thus hastening spring melt, and at the same time constitute a potential source of micronutrients (oligoelements) to Svalbard ecosystems. However, knowledge of the sources, deposition flux, properties, and radiative impact of dust in Svalbard snow is presently very scant and needs to be improved.
- Recent multi-decadal trends in seasonal snow cover conditions (thickness, duration, etc.) across Svalbard strongly suggest that within a few decades, parts of the archipelago, notably southernmost Spitsbergen, will likely experience winters with intermittent snow cover and frequent freeze-thaw or rain-on-snow episodes. This will inevitably impact the fate of atmospheric constituents deposited in snow, including contaminants. To anticipate how these changes may impact local ecosystems, there is a need to measure and model the partitioning of contaminants between solid, liquid and/or gas phases in the snowpack under evolving winter conditions, and to establish how this will affect rates of transfer of snow contaminants to surface waterways and soils, where they may become bioavailable.
- In conjunction with the point raised above, there is a need to project how future changes in snow cover phenology (e.g., snowfall rate, frequency of winter thaws or rain-on-snow events, timing of spring melt) will impact the potential for release of contaminants from melting snow. For example, how will the onset of spring melt change with respect to active layer thaw (a limiting condition for soil infiltration)? And how will the eventual disappearance of a continuous winter snow cover in parts of Svalbard affect the fate of contaminants deposited from the atmosphere? The latter question also pertains to the seasonal or perennial snow cover on Svalbard glaciers, which acts as a temporary storage reservoir for deposited atmospheric compounds. How will the up-glacier migration of the snowline on glaciers, or even the disappearance of perennial supraglacial snow cover, modify their storage and release to terrestrial and marine waters?

- As the seasonal snowpack on Svalbard evolves in a warming climate, this will also change when, and how strongly, light-absorbing particles such as BC and dust deposited from the atmosphere affect the snow albedo, which in turn affects the rate of snow densification and thaw. For example, wintertime thaw events may enhance the rate at which water-insoluble impurities accumulate on the snow cover surface, thus potentially hastening the positive snow-albedo feedback at the onset of the spring melt season. Hence there is a need to better monitor and to model these changes to anticipate their impact on local surface climate and hydrology.
- At least some types of atmospheric species deposited in snow undergo microbially-mediated transformations in the snowpack which affects their fate (e.g., via respiration or methylation), and conversely these species can affect nival microbial communities. This applies to various forms of WSOC and WIOC, but also to other nutrients (e.g., N species) and even BC and Hg. Presently, the nature, dynamics and magnitude of these interactions are poorly known. Furthermore, algae and bacteria supported by dust-borne nutrients can cause a biologically induced albedo reduction that accelerates snow and glacier melting. Hence, there is a need to better define and quantify the interactions between microbial communities, contaminants (e.g., organic carbon species, nitrates, BC, Hg) and other impurities (e.g., dust) within the snowpack, especially those that can affect the fate of pollutants deposited in snow, or its albedo.
- Ice cores drilled through the accumulation area of Svalbard ice caps have provided critical information on historical variations in the deposition of atmospheric species over decades to centuries that allow recent observations to be placed into proper temporal perspective. As analytical techniques improve, more and more species can now be detected and quantified in polar ice, so there is a rationale for additional ice cores to be recovered in the future. However, the effects of surface melt and meltwater percolation complicate the interpretation of Svalbard cores. To overcome this, there is a need to better quantify the post-depositonal mobility of various atmospheric species (soluble or not) deposited in seasonal snow on glaciers.

Recommendations for specific actions

- Many of the snow impurities and contaminants listed above already are, have been, or will be monitored in air, under WG7 activities of the Ny-Ålesund Atmosphere Research Flagship programme. For at least some of these species (e.g., BC, sulfate and nitrate, Hg), it is recommended to establish or strengthen coordinated programmes of simultaneous measurements in snowfall and/or in snow on the ground which will help to (1) elucidate air-snow transfer functions, and (2) quantify their actual accumulation in seasonal snow to help predict potential releases in runoff. An initiative to this effect is already underway in Ny-Ålesund for some air/snow constituents. Efforts should also be made to extend the capacity to carry out such coordinated observation programmes at other focal research sites in Svalbard, for e.g., in Longyearbyen and Hornsund, to improve coverage across sectors of the archipelago that experience different local climatological conditions.

- To support the actions above, it is recommended to establish or to develop the capacity, at Svalbard focal research sites, to routinely measure a suite of basic snow chemistry parameters, such as pH, conductivity, selected major ions (especially sulfate and nitrate) and WSOC, which are useful indicators of precipitation quality, using harmonised and standardised techniques and protocols. At some sites, such as at Hornsund, this capacity partly already exists. In other sites, facilities may exist, but their access and use need to be optimised, possibly with the help of SIOS (e.g., through the development of a unique user-access platform). Developing these capabilities would help support monitoring activities in Svalbard by avoiding the need to ship samples to mainland laboratories, at least for relatively simple, routine analyses.
- Well-documented protocols should be established for the proper collection and handling (transport, storage, filtration, etc.) of snowpack samples for specialized measurements of contaminants such as ions, BC, trace metals, SVOC, etc. These protocols should draw upon of existing (published) ones, where they exist, to facilitate harmonisation of observations (e.g., Leppänen et al. 2016; Gallet et al. 2018; Meinander et al. 2020). It is especially important that precautions be identified to avoid accidental sample contamination. These efforts of standardisation would dovetail with similar initiatives to harmonise snowpack measurement protocols across Europe under the EU Harmosnow programme (Haberkorn 2019).
- Some relatively simple activities, such as the collection of bulk seasonal snowpack samples to quantify the deposition of particulate impurities (e.g., dust, BC) may be carried out with limited technical training and are thus amenable to active participation by residents in Longyearbyen. Such participation should be encouraged and facilitated when and where it is feasible. In conjunction with this, it is suggested that a repository of filters obtained from melted snow samples be created (e.g., in Longyearbyen). These could be, e.g., duplicates of filters acquired during specific research activities or prepared from samples on a regular or an opportunistic basis. Archived filters stored in this repository would be accessible for researchers to perform measurements to characterise the physico-chemical properties of particulate impurities deposited in snow, in the same way that some national atmospheric monitoring programmes routinely archive air filters.

In addition to the general recommendations above, some specifically targeted research activities should be carried at focal research sites:

- It is recommended to develop and carry out, at sites where the appropriate infrastructure exists (or can be established), experiments to track and quantify, at the catchment scale, the flow of airborne contaminants of interest (for e.g., SVOCs, Hg) from their atmospheric deposition in seasonal snow to their release in meltwater runoff, in order to quantify the fractions of these contaminants that, once deposited, are actually transferred from snow to soils and surface waters. Such experiments could be carried out optimally in instrumented catchments of a manageable size located within easy access range from Svalbard focal research sites. Possible candidate catchments for these studies include Fuglebekken near Hornsund, Foxfonna near Longyearbyen, and Gruvebadet or Bayelva near Ny-Ålesund.

- Physically based models should be developed and tested that couple the evolving dynamics of the seasonal snowpack with its impurity and contaminant content, in order to forecast the fate of these compounds and the rate at which they can be released in soils and hydrological networks. Models presently exist that can forecast the development and thaw of the seasonal snow cover, and others that can forecast the fate of riverborne contaminants at the catchment-scale, but models that can bridge these purposes while integrating within-snowpack chemistry need be developed and validated in Arctic settings. Catchment-scale studies on Svalbard as described above might provide suitable opportunities to calibrate and test such models.
- Understanding the interactions between microbial communities and impurities or contaminants in seasonal snow requires that samples be collected jointly, using established and agreed-upon protocols, in order to enable cross-comparisons between the types of data generated. Analytical approaches that focus on microbial metabolism and activity should also be coupled to snowpack chemistry. Given the dynamic nature of snowpacks, such dedicated cross-disciplinary studies should be carried out over entire snow cover seasons in order to better quantify the transformations that occur over their course, and ideally at dedicated sites where ancillary weather and atmospheric data are available.
- Lastly, it is also recommended to carry out catchment-scale experiments or surveys that would permit measurements of the deposition (flux or net accumulation rate) of atmospheric species in the snowpack at spatial scales (1-10 km^2) that can be compared with outputs from atmospheric transport and depositional models. Presently, ground-based estimates of depositional fluxes tend to be made at single point measurement sites only. Assessing net deposition rates in snow over larger spatial scales would facilitate validation of atmospheric model predictions, and help establish the variability within, and representativity of, grid cell-size flux estimates from these models. This would require close coordination between snow scientists and specialists in the atmospheric modelling community.

Some practical considerations that can help to guide the development of any snow chemistry monitoring programme on Svalbard are provided in Appendix 2.

2.4 Remote sensing of the snow cover

This chapter is organised according to the essential climate variables (ECV) needed for understanding the snow cover on Svalbard. The overview about the potentialities offered by remote sensing of the snow cover in terms of essential climate variables is offered by the SESS reports 2019 (Karlsen et al 2020) and 2020 (Malnes et al. 2021; Killie et al. 2021; Salzano et al. 2021a; Salzano et al. 2021b). According to the GCOS definition, the ECVs are the snow cover area; the snow water equivalent; and the snow depth or height.

The snow-covered area (SCA) represents the extension of surface covered by snow and it is generally estimated using optical remote sensing. This information is defined looking at multi-spectral images since the eighties when Landsat images began to be used (Dozier 1989). Nowadays, several products are available based on Suomi NPP, POES, Terra/Aqua, Landsat and Sentinel platforms. This copiousness is not a weakness; rather, it represents a relevant opportunity to fill the multi-scale gap that affects snow cover monitoring. Remotely sensed images are without doubt the more suitable for synoptic studies and this is particularly true for snow cover studies in remote areas specially for snow cover seasonality (Malnes et al. 2021). Although several data services provide snow products focused on estimating the SCA, Svalbard represents a peculiar environment where specific algorithms are required for improving the description of the snow cover seasonality. From this perspective, the challenge for researchers and end users is not only understanding how snow reflects incident radiation but managing the large amount of data and different snow products now available (Dietz et al. 2012, Gascoin et al. 2019). The integration between sensors at different spatial resolutions (from 10 to 500 meters and more) is a primary component required for the definition of novel products focused on the snow cover area. Ground-based and airborne remote sensing are therefore additional data sources that can significantly contribute to solve the multi-scale gap between satellite observations and in-situ measurements.

The snow water equivalent (SWE) is key information that current and historical passive microwave sensors provide data on going back to 1980 on a global scale (Pulliainen et al. 2020). Due to the coarse resolution (~20km) these sensors are not suitable for Svalbard with its challenging topography and long coastline. Detailed scale measurements of snow water equivalent using synthetic aperture radar has been a highly desirable task for the remote sensing community for a long time. Unfortunately, current SAR sensors (C- and X-band) do not have sufficient sensitivity, nor the ability to retrieve SWE and snow grain size simultaneously, as these parameters cannot be decoupled in the radiative transfer model for backscatter from a snowpack. Initiatives are still underway to launch new sensor combinations (e.g., SnowCube as a candidate to ESA earth explorer 11), but a realisation of a satellite is still some years ahead. An alternative to measuring SWE using backscatter changes was suggested by Guneriussen et al. (2001) relating SWE to change in interferometric phase between repeated satellite passes. C-band SARs have, however, been suboptimal for this purpose as the interferograms decorrelate rapidly. L-band SAR decorrelates on a longer timescale, and upcoming missions such as NISAR (NASA) and ROSE-L (ESA) should be very suitable. In situ stations such as snow pillows, weighs and Gamma instruments can be used to calibrate and validate EO retrieval methods for SWE but does not match the required area extent to be comparable with satellite resolution (~1km^2). Upcoming sensor concepts such as fibre-optic cables or GPS-IR (McCreight et al. 2014) could be alternatives.

The snow depth or height (SD or SH) is a parameter that can be obtained remotely with some difficulty. Lievens et al. (2019) reported that snow depth can be measured using Sentinel-1 on a global scale using the ratio between co- and cross- polarisation backscatter. The results were validated using in situ observations in several regions. The results remain to be validated independently, and several people in the research community are sceptical, but in principle the same methodology should be tested for Svalbard. Airborne LiDAR can be successfully used to deliver high resolution snow depth measurements, but unfortunately it is not always possible to carry out frequent and repeated overflights. The data deriving from the use of terrestrial lidar could fill the gap of measures, especially if it were possible to use them automatically to guarantee very high frequency of measurements (Harpold et al. 2014). Additional opportunities are offered by the GPS interferometric reflectometry (GPS-IR). The spatial scale of this technique is intermediate, about 1000 m^2. Studies to measure the daily snow depth have been conducted in Ny-Ålesund since 2016.

Additional parameters can be included and retrieved by remotely sensed techniques, for example the snow albedo, snow temperature, layering and liquid water content. The snow albedo is a significant input parameter for the radiative modelling as well as a key information for defining algorithms aimed at identifying different snow cover types. The spectral behaviour of the snow surface is, in fact, characterised in the visible wavelength domain by high reflectance values which can be lowered by the presence of impurities of anthropogenic origin (BC), mineral dust or presence of microorganisms (algae). Albedo measurements in this region of the electromagnetic spectrum represent a fundamental element for energy balance assessments, for melting processes analyses on glaciers and permafrost. In the near infrared wavelengths, the albedo of snow is lower than in the visible and strongly depends on the microphysical characteristics of the snow surface. Therefore, the spectral response of snow in the infrared can be used to derive its microstructural properties.

Development of satellite retrieval techniques need in any case a strong integration with ground-based observations for both validation of retrieval algorithms and for a better interpretation of the remote sensed images. Measuring the spectroradiometrical properties of snow in the field, with instruments like those installed on board the satellites, allows us to calibrate and validate satellite observations and to extend snow observations to regional scale (Killie et al. 2021, Pirazzini et al. 2018). Integration of field spectral measurements, snow surfaces roughness and level of impurity can add information not easily achievable by satellite sensors.

Liquid water content (LWC) or wet snow is also an important snow parameter for Svalbard in a changing climate. Scatterometer data has been used to detect wet snow on Svalbard with acceptable spatial resolution (2.5 km). Rotschky et al. (2011) provided a 10-year time series of snow melt detections over Svalbard using Quikscat. C-band SAR can also be used to map wet snow with ~100m resolution (Nagler and Rott 2000). Retrieval of LWC so far not been achieved with SAR satellites, but a combination of different frequencies and polarisation could in principle be used to invert a radiative transfer model for wet snow.

Sentinel-1 data can be used to detect snow avalanche activity (Eckerstorfer et al. 2017). The method has been tested in Svalbard using Sentinel-1 EW mode, which has a too low resolution to detect small to medium sized snow avalanches (Wesselink et al. 2017). However, Svalbard is now also covered with higher-resolution Sentinel-1 IW mode data that is appropriate to detect sow avalanches. Unfortunately, to date, there are only three

Sentinel-1 passes per 6-day repeat cycle covering Svalbard. The next generation of Sentinel-1 satellites will probably have improved spatio-temporal resolution, thus improving the capability of detecting snow avalanches in Svalbard.

Knowledge gaps and needs

- Snow cover is the driver of many ecological and climatic processes in Arctic areas (Vickers et al. 2020) where in situ observations are often not sufficient to characterise the high spatial variability of snow surfaces and its rapid time-depending changes.
- Referring to the optical remote sensing, some limitations can be described considering the data availability, the data processing, and the next generation of satellite platforms. The revisiting time of the different platforms is a primary limitation on using satellite data since coarse spatially resolved sensors (MODIS or Sentinel-3 for example) overpass more frequently the considered areas than platforms characterised by higher spatial resolution (Landsat or Sentinel-3). Coupling this feature to the cloud cover occurring in Svalbard during the melting season, the number of cloud-free imagery can be strongly reduced, and the analysis of multi-sensor datasets is a primary need. Data processing is, moreover, a major gap since both the bottom-of-atmosphere reflectance retrievals and the snow-detection algorithms are affected by site-specific relations. The importance of these processing phases cannot be constrained only to the already-operating multispectral missions, but it must be approached considering the future availability of satellite and airborne hyperspectral sensors.
- The definition of site-specific algorithms for estimating the snow cover can provide significant improvements for dedicated services and be useful in the Svalbard framework. From this point of view, the contribution of terrestrial photography to snow cover monitoring makes available high-spatial and high-time resolved ground truthing for satellite imagery. Although these observations are limited in terms of spatial extent, the estimations are not affected by cloud cover and a network of observing sites supports the assessment of site-specific relationship between data sources (Salzano et al. 2021b). The integration between optical data obtained by satellite data, ground-based observations, UAV and airborne platforms represents a valuable approach for assessing site-specific relations, but case studies are still limited and more effort is required for investigating the snow cover in different environmental frameworks.
- Referring to microwave remote sensing, the upcoming SWE retrieval methods for L-band SAR need to be tested in Arctic regions simultaneously with extensive field campaigns measuring SWE. Such field campaigns should be complemented with GPR measurements (by air/UAV or by snow mobiles) as these provides more samples. Additionally, there should also be in situ stations (Gamma-instruments, GPS-IR or fibre-optic cables) that can provide continuous measurements of SWE over time and preferably also over an area that is representative (i.e., larger than

one pixel). Distributed ground measurements of liquid water content are much needed to improve remote sensing techniques. Current ground sensors such as the Denoth meter and Snow fork do not provide data over a sufficiently large area to be comparable with satellite data. Transects should be carried out, but also continuous measurement stations (e.g., a Denoth meter measuring continuously on a site) and GPR transect campaigns with focus on LWC should be implemented to understand this parameter better.

Recommendations for specific actions

- Promote the integration between optical data with different spatial resolutions to harmonise the available observations which are limited by the revisiting time of satellites and by the cloud cover occurring in Svalbard. The derived snow cover distribution maps must be harmonised in terms of spatial resolution, areal extent and orographic characteristics of the region.
- Facilitate the use of cloud-based services such as: the Copernicus Data Information Access Services (DIAS), the Virtual Laboratory Platform (Vlab), the ESA Thematic Exploitation Platforms (TEPs), Google Earth Engine (GEE), Amazon Web Services (AWS). These tools designed to deliver products and make them available via SIOS will avoid downloading data and will reduce the data processing time.
- Promote the implementation of in-situ optical observations on the snow cover in the framework of the focal site strategy of Svalbard. The availability of such ground control points will be significant for assessing specific snow thresholds for different satellites sensors and different local conditions.
- Establish a network aimed at harmonising and transferring the observations about fractional snow cover obtained by terrestrial photography. This asset will significantly support the definition of site-specific relations between remotely sensed data and high spatially and timely resolved observations.
- Promote the availability of observations about the spectral reflectance on different snow cover types to support the calibration of different sensors.
- The technological innovation is providing novel hyperspectral sensors that are becoming available both on airborne and satellite platforms. The integration between already-operating sensors and in-situ observations must be oriented on higher spatial resolutions and hyperspectral acquisitions. Comparing modelled outputs with optical data could also improve the snow cover monitoring system.
- Considering the number of satellites and parameters we are interested to retrieve, their relevance for investigations of interactions at the air-snow-vegetation interface, effort should be made to develop 1 or 2 super-sites for cal/val activities (see chapter 3).

- To enable effective sensor integration, a spatially distributed network of ground, UAV and airborne observations is needed to bridge the gaps of different spatial scales. The system that integrates the different types of measures should include also ground-based LiDAR.
- More UAV/Airborne observations with high-frequency radar are recommended to get more accurate SWE estimation at high resolution in Svalbard. Despite relatively poor performances of passive microwave sensors alone for accurate SWE description in complex landscape like Svalbard, the potential of passive microwave in combined with a distributed network of in-situ measurements, UAV and airborne observations at different spatial scales and new techniques such as artificial intelligence still needs further investigation for describing SWE in Svalbard.
- A distributed network of in-situ measurements, UAV and airborne observations (equipped with either optical, lidar or radar sensors) in Svalbard is highly recommended to help better reveal the spatial heterogeneity of snow depth distribution in complex landscape, which can also provide ground truth for validating the downscaling the spaceborne based data products.
- Novel techniques for ground based cal/val measurements of snow depth and snow water equivalent such as GNSS-IR and fibre optic cables should be further investigated. Such techniques may provide SWE or snow depth at a spatial scale comparable with the resolution of satellite sensors and thus provide continuous data series that can improve the development of remote sensing of SWE/snow depth.
- The acquisition plan for Sentinel-1 should be improved over Svalbard to obtain more than 3 IW tracks per repeat cycle over land. This could improve the mapping of avalanches.

2.5 Snow, atmosphere dynamics and modelling perspective

Diverse and complex types of interaction take place between the snowpack and the atmosphere. Precipitation, deposition, transport, drifting and melting are processes that involve both atmospheric conditions and the snowpack at the same time and can significantly change the snowpack characteristics in time scales ranging from a few hours to seasonal and interannual scales. The seasonal snow cover strongly influences boundary layer processes such as turbulent fluxes and radiation (Claussen et al. 2001; Raghuveer et al. 2011). Surface type and heterogeneity have a significant feedback on the polar boundary layer structure. As snow and ice covers grow thinner or vanish completely, more surface features will appear and increase heterogeneity in aerodynamic roughness, topography, texture, and albedo, which modify surface mass and energy fluxes. In the Arctic, the retreat of snow coverage and anticipated snow melting season over land produces an increase in solar energy stored by the Earth-atmospheric system of the same order of magnitude arising from the sea ice reduction (Serreze and Barry 2011). In particular, when the snowpack is melting and the ground is no longer completely covered with snow, local processes are initiated that can either assist or impede melting. The snow layer responds to exchange of the energy and radiation at the interface with the atmosphere and such response modifies the state of the snow layer. The interaction between the changing snow surface conditions and the polar boundary layer is strongly controlled by the surface heterogeneity that drives atmospheric and surface-water dynamics (e.g. snow melting, percolation and refreezing) at different spatial and time scales. These aspects should be taken into account when parameterising the turbulent fluxes (heat and mass) at the surface to improve the quality of model forecast.

Knowledge of the current state of the snow cover on the ground is of paramount importance for numerical weather prediction (NWP) and climate models (Dutra et al, 2010). This is especially true since the horizontal resolution (up to 1 km) of NWP models strongly increased in recent years. Currently, most NWP models use simplified (typically one snow layer) snow cover schemes, which are in general not capable of simulating snow cover formation, evolution and melt with adequate accuracy. In addition, the impact of climate change, including feedbacks and amplifications, can only be assessed and predicted if the coupling between the dynamic processes of snow and ice with other main components of the Earth system can be quantified and modelled (Barnett et al. 2005; Cooper 2014).

Modelling work has recently been developed to simulate the main snow distribution across Svalbard on a daily basis (e.g. Malnes et al. 2021, Killie at al. 2021). Such model simulations are important sources of data to assess the impact of snow cover on surface hydrology, permafrost, terrestrial ecosystems, avalanche danger etc. Such models can use meteorological forcing input data both from historical reanalysis data and from operational weather prediction models, allowing even real-time snow mapping and forecasts for the coming days. Malnes et al. (2021) evaluated results from several such snow map models using satellite data of snow-covered area from MODIS satellites. In addition, a first version of an operational, daily updated snow map service for Svalbard (1x1 km resolution) is planned to be launched on NVE’s natural hazard forecasting website[3]. In addition, dynamical models such as WRF-Hydro will probably also be implemented for Svalbard. The service would improve the forecast and make available a planning tool for scientists, tourism and local communities. Such models will require more detailed forcing data and parameterizations to perform optimally. The assimilation of EO data in hydrological model is a challenging, but important endeavour. More research should be devoted to this topic using e.g., optimal interpolation, particle filter and ensemble-based methods. Increased focus is also needed to compare hydrological models with independent remote sensing datasets (e.g., Malnes et al., 2021).

Snow process models such as SURFEX/CROCUS or SnowPack should also be developed for Svalbard. Such models provide detailed characterization of the snow stratigraphy and can improve avalanche forecast as well as the general understanding of how snow insulates the surface below and releases water depending on the external and internal factors in the snowpack. The models perform adequately when directly forced with available observations from met stations, but often very poorly at places where

[3] www.xgeo.no

observations are lacking. Assimilation of EO data and interpolated forcing data should be an important scientific field in the future to understand arctic snowpacks. Whereas detailed snow models, such as SURFEX/CROCUS (Vionnet et al. 2012), are most suitable for local/point-scale studies of snow conditions, large-scale modelling with high spatial detail is most efficiently done with intermediate-complexity snow models, such as those incorporated in glacier mass balance models (e.g., Van Pelt et al. 2019; Noël et al. 2020).

Knowledge gaps and needs

- Hydrological models, snow process models, climate models, regional weather forecasts and reanalysis rely heavily on observations from met stations. Due to insufficient temporal and geographical coverage of these time-series in the past it is really challenging to parameterize the models to obtain reliable historical time series and good forecasts at detailed scales. Satellite remote sensing time series dating back to the 1980s could be used to close part of the gap, but more research is needed to understand how such time series can be used. Recently improved quality in remote sensing may be utilized cleverly to bridge this gap.
- Knowledge gaps related to energy balance and vertical heat fluxes at the air-snow interface exists for polar regions, also when the snowpack layer is thinning. Understanding of persistent snow patches and their impact for energy balance should be studied further.
- Surface heterogeneity and near surface airflow have large impacts on snow transport and distribution. Some studies have been carried out on Svalbard, but more should be done to understand how wind redistribution of snow can provide protective environments for plants and animals, but also dangerous snow deposits in avalanche terrain. Detailed scaled modelling is a requirement to understand these processes and provide warnings.
- Understanding of melting processes should be improved by integrating models and observations on detailed as well as large scales.
- Data on the distribution of snow and its variability on glaciers and glacier free areas from most of Svalbard especially in the southern, central and the eastern parts of Spitsbergen are almost completely missing (e.g., Malnes et al. 2021, Killie et al. 2021, Salzano et al. 2021). Such data are needed for model validation.

Recommendations for specific actions

- Promote extensive diagnostics activities of NWP models, through comparison with integrated in-situ, airborne and satellite observations.
- Improve the study of turbulence processes at the air/snow interface, also making use of new observation technologies to better understand the impact and effect of variability on spatial scale of meters and tens of meters.

- Increased focus on hydrological modelling and snow process modelling on Svalbard.
- Further development of physically based models, covering the whole of Svalbard, are also needed for improving predictions of the seasonal snow cover evolution under a future, warmer climate.

3. Potential focal sites for snow monitoring and research

Focal sites for snow monitoring and research are locations that are suitable for long-term monitoring of diverse snow parameters and at the same time allow for cross-disciplinary studies in order to integrate and complement these observations. They should be easily accessible and have already established infrastructure and solutions for power supply and data transfer. In Svalbard such sites are mainly located on the western coast, in connection with existing settlements, which has the advantage that they often are manned all-year round. However new technology development and better power and communication solutions will reduce the need of manned stations and allow for automated instrumentations also in other areas of Svalbard. This will lessen the geographical bias and offer the possibility to cover the strong climate gradient along the East-West axis of the Svalbard archipelago.

In focal sites, monitoring and research should be coordinated and data made openly available in order to make the most of monitoring efforts and funding. This will make it possible to answer the overarching questions of the impact of snow on the Earth System. Harmonisation of protocols and data as well as coordinated campaigns using calibrated instrumentations are a prerequisite of achieving a unified approach to these scientific challenges. A recent overview of existing methods and instruments for measuring snow properties is provided in table A6 in Pirazzini et al. (2018).

Several focal sites are needed to be able to compare different environmental settings, incl. e.g., precipitation patterns, topography, the proximity to glaciers. Currently we suggest four potential focal sites: Ny-Ålesund, Kapp Linné/Grønnfjorden area, Longyearbyen area and Hornsund (Figure 2). Further, we recommend to strongly promote technological development and innovation that would allow us in the future to add remote focal sites in East and Central Svalbard with minimised environmental footprint.

Ny-Ålesund

Ny-Ålesund is the northernmost settlement in Svalbard. The location is characterised by a heterogenous landscape in a coastal setting. Historically, Ny-Ålesund was a coal mining settlement, but is nowadays dedicated to science. The Ny-Ålesund Research Station[4] is an international hub with long-established collaboration between more than 20 research institutions. Diverse multidisciplinary research and environmental monitoring results in a

[4] https://nyalesundresearch.no

high density of measurements and long-term series on which new research projects can built.

Four scientific flagships have been established with extensive cross-disciplinary and cross-flagship collaboration: The atmosphere flagship, the glaciology flagship, the terrestrial ecosystems flagship, and the marine Kongsfjorden system flagship. The three first flagships, and especially the intensive monitoring of atmospheric parameters constitute a solid base on which a focal site for snow research and monitoring can be built. Due to its international nature, it is also a good place for show-casing studies.

A snow super site has been established in Ny-Ålesund as a collaborative effort between several international institutions. Close to the Gruvebadet atmosphere laboratory, the seasonal evolution of the snowpack and its chemical and microbial composition is being studied since 2018. In addition, optical snow characteristics (broadband and spectral albedo) as well as snow depth are measured at the Climate Change Tower since 2010. In 2017 these observations have been improved and complemented with web cam observation of snow cover. Supporting measurements of atmospheric conditions, radiation fluxes and atmospheric composition at Gruvebadet, the Zeppelin Atmosphere Observatory (472 masl), the Climate Change Tower, and a Baseline Surface Radiation Network site complement the described snow related measurements.

Ny-Ålesund can be reached by small planes from Longyearbyen up to several times a week and has good logistical facilities, incl. housing and field support. Ny-Ålesund provides good lab facilities, e.g., labs dedicated to marine and terrestrial research.

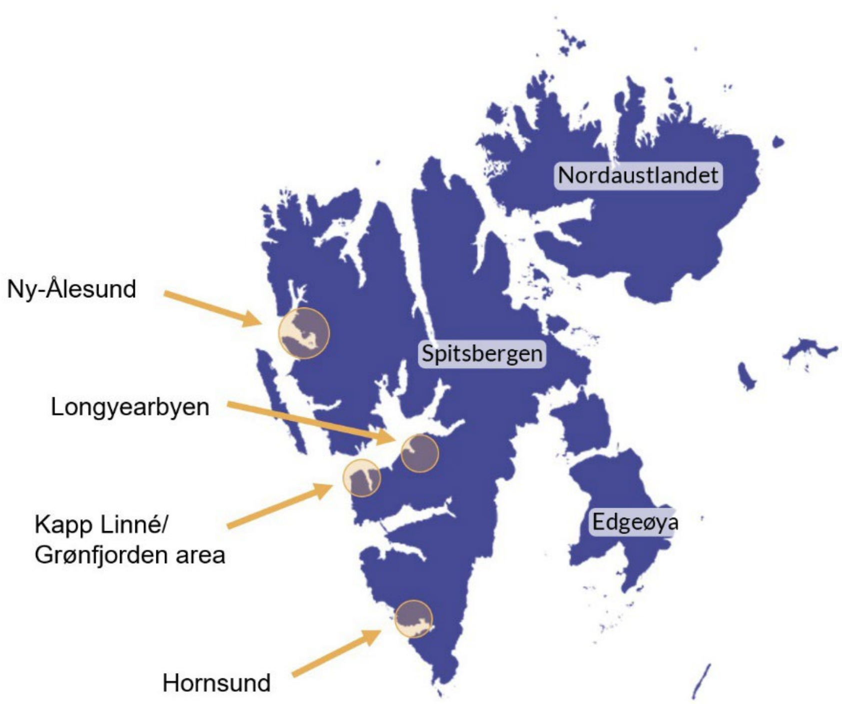

Figure 2: Suggested focal sites for snow monitoring and research in Svalbard.

Kapp Linné/Grønnfjorden area

Kapp Linné is originally a small radio station on the southern side of the mouth of Isfjorden with an Atlantic High-Arctic maritime climate. In present, there are hotel facilities, and it can be reached by boat in summer and snow scooter in winter. In the area the Kapp Linné Environmental Observatory (KLEO) was established in 2019 as an international collaborative site within SIOS building on up to 18 years of hydroclimate measurements in Linnédalen.

Through the SIOS-InfraNor project[5], the Norwegian Water Resources and Energy Directorate established a hydrological station at Linné river in 2020. Research in the Grønfjorden area with base in Barentsburg complement the research with multi-year hydrological and precipitation studies. In addition, permafrost conditions are monitored by boreholes at Kapp Linné and Barentsburg, both of which are integrated in an extensive set of permafrost monitoring sites across Svalbard (Christiansen et al. 2020, 2021).

Longyearbyen

Longyearbyen is the main settlement of Svalbard and has daily flight connections to the Norwegian mainland and good hotel facilities. It has more than 2000 inhabitants, a school, a folkehøyskole[6], and a large variety of tourism companies, and is thus a good place for community-based observation as well as outreach activities. The University Centre in Svalbard conducts research in diverse fields in the vicinity of Longyearbyen and makes it also a hub for education of future scientists.

Several operational weather stations in and near Longyearbyen provide real-time data, ensuring fast data access for researchers, operational weather- and avalanche forecasting, local rescue services, tourism and the general public. Due to a considerable avalanche risk in the proximity of the settlement, extensive monitoring and observation programmes in relation to avalanche risk have been established. In the adjacent valley Adventdalen there is a well-established research site for permafrost allows for cross-disciplinary studies on snow and permafrost interactions. Seasonal microbial production and biogeochemistry is being monitored year-round on Foxfonna, where also thermistor strings measuring the influence of rain and refreezing on the thermal state of snow.

Both the University Centre in Svalbard and the Norwegian Polar Institute provide logistical support and lab facilities in Longyearbyen, where also several commercial logistics and equipment providers can be found.

Hornsund

The Polish Polar Station Hornsund is the southernmost inhabited location in Svalbard. It is located in one of the fastest warming parts of Svalbard and has conducted long-term

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[5] https://sios-svalbard.org/InfraNor
[6] https://www.folkehogskole.no/en/about

monitoring of environmental parameters since 1979. Research programmes include studies on meteorology, seismology, Earth magnetism, permafrost, and glaciology. The Hornsund area is especially suitable for catchment studies since it provides several different catchment areas with and without glacier influence. Several studies are already ongoing and provide long-term data series. The station in Hornsund offers both lodging and lab facilities (2 wet labs and an ion chromatography lab) and can be reached by boat.

4. Data management

4.1 Data documentation (Metadata, file format, licenses)

Well documented research data is the key step for making data publishable, discoverable, citable and reusable. In order to achieve this, information about data, i.e., metadata, should be provided at different levels.

The first, and probably most well-known type is **discovery metadata**, which has the purpose of making data findable, both in metadata catalogues and data portals. It describes who did what, where and when, how to access data and potential constraints on the data. It shall also link to further information on the data like extended metadata information or site metadata. Examples of this type of metadata are the Global Change Master Directory Directory Interchange Format (GCMD DIF)[7] and ISO 19115[8]. The GCMD DIF metadata standard is widely used and provides a specific set of attributes for describing Earth science data at the collection level and implements a number of predefined controlled vocabularies that should be used in specific sections of the metadata. On the other hand, the ISO 19115 metadata standard - and its extension for imagery and gridded data, ISO 19115-2[9]- can be implemented in several profiles. This means you can use the ISO 19115 structure and elements, but with specific requirements, including the use of controlled vocabularies and/or a different multiplicity of elements (e.g., while being optional in the ISO 19115 standard, an element can become mandatory in a specific profile). A commonly used profile is the WMO Core profile, used by the WMO Information System (WIS) to create a catalogue of all information that is made available through the WIS.

A second type of metadata is known as **use metadata**, which has the purpose of making data understandable once data is found. Use metadata describe the actual content of a dataset and how it is encoded. It enables users to understand the data without any further communication with the data provider or data contact point. It describes content of variables using standardised vocabularies, units of variable, encoding of missing values, map projections etc. The adoption of standardised use metadata is essential for achieving interoperability between data, thus making it possible to exchange, combine, compare and

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[7] https://earthdata.nasa.gov/esdis/eso/standards-and-references/directory-interchange-format-dif-standard

[8] https://www.iso.org/standard/26020.html

[9] https://www.iso.org/standard/39229.html

analyse data coming from different sources. By using standardised use metadata, the content of the data will be understood also by people that are not familiar with the data themselves, thus allowing for a correct reusability of datasets and avoiding misinterpretation of the data provided. Examples of such type of metadata are the Climate and Forecast convention (CF)[10] and the Darwin Core archive (DwC), which is mostly used by the biodiversity community. The CF conventions define metadata that provide a definitive description of what the data in each variable represents, and the spatial and temporal properties of the data. Particularly relevant is the use of CF standard names[11] for variables, which allows to univocally identify the physical quantity which is represented, as well as the associated units in which values are provided. The use of CF convention is commonly linked to the use of netCDF file format. NetCDF is a binary file format used to order and store data and metadata, with well-defined rules for how data should be correctly structured, whole the CF conventions are guidelines and recommendations on what metadata to include and how within a netCDF file. Once a netCDF file is following the CF conventions (netCDF/CF), it becomes self-describing. A good practice when encoding netCDF files is to comply with the Attribute Convention for Data Discovery[12], which describes the discovery attribute that can and should be included in a netCDF/CF file. In this case, discovery metadata will be directly connected to the data themselves and can be extracted for ingestion in searchable catalogues.

A third type of metadata, site metadata, refers to the description of the context in which the data was collected. It should describe the observed variable, the conditions under which it was observed, how it was measured or classified, and how the data have been processed, in order to provide users with confidence that the data are appropriate for their application. It describes the location of an observation, the instrumentation, procedures etc. To a certain extent it overlaps with discovery metadata, but practically it extends the information included in it. The WMO Integrated Global Observing System (WIGOS) metadata standard[13] covers this type of metadata, providing ten different categories, each one with one or more metadata elements and a list of tables with controlled vocabularies to be used to fill such elements.

Providing rich and standardised metadata along with the data is the first step towards making data FAIR (Wilkinson et al. 2016)[14], meaning making data findable, accessible, interoperable and reusable. Particularly, the findability principles are linked with the provision of discovery and, to a certain extent, to site metadata. More in detail, discovery metadata should provide unique identifiers for the data they describe, and should be generous and extensive, including descriptive information about the context, quality and condition, or characteristics of the data. Once such described data are exposed in metadata catalogues or portals they are easily findable. The accessibility of the data

[10] https://cfconventions.org/
[11] http://cfconventions.org/Data/cf-standard-names/current/build/cf-standard-name-table.html
[12] https://wiki.esipfed.org/Attribute_Convention_for_Data_Discovery_1-3
[13] https://library.wmo.int/doc_num.php?explnum_id=10109
[14] https://www.go-fair.org/fair-principles/

depends on the information provided to access them and data access points, together with the used protocols (which should be open, free, and universally implementable), should be included in the metadata records. As mentioned above, interoperability between data, and integration in workflows is achieved by using standardised use metadata and the available controlled vocabularies and standard terms. Finally, the reusability of data is strongly linked with information given in the metadata, namely providing a license for data access and use (as mentioned below), as well as citation elements that are used to correctly and rightfully cite and acknowledge the source and authors of the data which have been re-used.

Recommendations

- ISO19115 records must at least state the unique id, temporal extent and spatial location, scientific content, responsible data centre and PI as well as links to the actual data
- ISO19115 records should contain GCMD Science Keywords or some other machine-readable vocabulary following the FAIR guiding principles. The vocabulary used must be identified
- All datasets should have a unique identifier issued by the host data centre. The identifier is set by the authoritative source for the dataset
- All times must be encoded as ISO8601
- The use of controlled vocabularies is recommended when available
- For GCMD DIF Related_URL has several subtypes. The existing list of type and subtype must be used to allow the SIOS Data Portal to filter the purpose of the URLs provided. When types are “View Data Set Landing Page”, “View Extended Metadata”, “View Professional Home Page”, and “View Project Home Page”, no subtype is needed.

4.2 File formats

Most of the snow-related field observations are recorded as tabular data. Due to popularity and ease of use by the observers, the MS Excel spreadsheet (xls and xlsx) is so far the most common format for recording manually measured basic physical properties of snow cover e.g. snow depth, SWE, snow density, and snow stratigraphy. The MS Excel format is also broadly used among environmental chemists working with snow on Svalbard. Snow microbiologists more often using CSV formats, as it is easier to digest by statistical tools. In the case of automatic (e.g. precipitation, ultrasonic snow depth, gamma-ray SWE) or geophysical measurements (Ground Penetrating Radar snow depth) various text formats (csv, txt, dat) are more common. In the avalanche research community, for recording the snow stratigraphy profiles, Canadian Avalanche Association Markup Language[15] is a standard. However, due to the complexity and lack of easy-to-use analysis tools it is not

[15] http://caaml.org/

widely used outside the avalanche research community. Contrary to the field researchers, modelers use ASCII text formats (csv, txt, dat) and netCDF/CF. In the remote sensing community various file formats are used, depending on processing level. For snow distribution satellite and mid to short range products (e.g., time-lapse Fractional Snow Cover) geoTIFF is the most common format. Despite all the advantages, due to complicated saving and reading procedures, so far, only modellers are open to use the netCDF/CF formats as a standard data exchange format.

Recommendations

- Text formats (e.g., CSV or tab-delimited text) should be used as a common format for sharing snow-related datasets, as this can be easily used by both field researchers, modellers, and remote sensing communities.
- Where possible, CSV datasets should be accompanied by a NetCDF file.
- NetCDF following the Climate and Forecast Convention (version 1.6 or higher) with NetCDF Attribute Convention for Dataset Discovery is recommended for file format wherever possible.
- For datasets representing time series or profiles it is required to add the global attribute featureType with the appropriate content. If no featureType is found in the data, it is assumed that the data are gridded in nature.
- It is not recommended to combine information from several stations in a single NetCDF/CF file.
- Easy to use tools for NetCDF->CSV and CSV->NetCDF data conversion should be developed. As snow data might be specific there is a need to develop these tools in close cooperation with researchers (e.g., a Rosetta tool specific for snow profiles).
- Where possible, standard measurements protocols and tools should be used, e.g., WMO Guide to Instruments and Methods of Observation (WMO 2018)[16] or Gallet et al. 2018.

4.3 Licenses

Data may be protected by one or more intellectual property rights. Use of data requires a license from the data owner or a repository licensed by the owner to share the data. Data licenses present several unique issues concerning data ownership and data usage.

As the author of your work, you can decide what others can do with the dataset you are sharing, and the conditions under which you are providing access to these materials. This is possible by giving your work the appropriate license. The licenses do not reduce, limit, or restrict any rights under exceptions and limitations to copyright.

[16] https://library.wmo.int/index.php?id=12407&lvl=notice_display#.YDzCnFVKi00

You are free to draft your own terms, but it is common to apply a pre-made license template. There are several options to choose from that vary in their terms, and in their suitability for data and materials as opposed to source code. For all material, except source code, creative commons licenses are the most common choice. They always require attribution to the original source, and optionally disallow commercial use and derivative works. You can also require others to share modifications under the same terms[17].

Recommendations

- SIOS promotes open science and supports making scientists work available to the public with proper management of products rights. SIOS recommends using the CC BY-NC (Creative Commons Attribution-NonCommercial 4.0 International) to promote open science. This license excludes commercial use of the materials. More information about the recommended and other CC licenses (also for commercial use of the datasets) can be found here: https://creativecommons.org/licenses/.
- The Norwegian Ministry for Government Administration, Reform and church Affairs recommends all data owners in the public sector to use a licence and expect that the majority of Norwegian Public Sector Open data will be licensed under the NLOD[18].

4.4 Data repositories

Snow data is now scattered across many different repositories which are thematic, national, international and institutional. The FAIRness level of these varies, e.g., citation (DOI), interoperability or long preservation. Some of the repositories give access to metadata only, not actual data. Table 1 provides an overview of the essential snow data repositories for Svalbard. Most of them are integrated with the SIOS data management system, which allows you to search for data in all connected repositories from one search interface, the SIOS Data Access Portal[19].

Recommendations

- Use repositories connected to the SIOS data management system (SIOS Data Management Plan).
- Use repositories that follow FAIR data principles (SDMS Interoperability Guidelines):
    - Making data findable – DOI, standard metadata
    - Making data accessible - free and open access to the data

[17] https://how-to-open.science/share/licenses/
[18] https://data.norge.no/nlod/en/2.0/
[19] https://sios-svalbard.org/metadata_search

- Making data interoperable - interoperability interfaces, file format (NetCDF)
- Increase data re-use – licenses, long preservation

Table1: Overview of essential snow data repositories for Svalbard

Repository / Country	URL	Characteristic	Available snow datasets
Arctic Data Centre / Norway	http://arcticdata.met.no/	DOI, metadata interoperability interfaces are available, licenses: CC and NLOD, discovery metadata: ISO19115 and GCMD DIF, part of SIOS Data Management System (SDMS)	Field observations on land, glaciers and sea ice (physical, optical and chemical features, snow depth), GPR and remote sensing products, models result.
PANGAEA / Germany	http://pangaea.de/	DOI, metadata: ISO 19115, licenses: CC, metadata interoperability interfaces are available	Field observations on land, glaciers and sea ice (physical, optical and chemical features, snow depth), GPR and remote sensing products, models result.
Italian Arctic Data Center (IADC)/ Italy	http://arcticnode.dta.cnr.it/cnr/index.php	Metadata: ISO19115 and GCMD DIF, interoperability, discovery, visualization, download; Licenses: CC part of SDMS; DOI (planned)	Field observations (optical properties chemical features, snow depth, snow temperature, heat flux) and remote sensing products.
Norwegian Marine Data Centre / Norway	http://www.nmdc.no/	Metadata: DIF, licenses: CC, part of SDMS	Field observations on sea ice (snow depth, chemical features).
Norwegian Polar Institute / Norway	http://data.npolar.no/	DOI, metadata interoperability interfaces are available, metadata: JSON, licenses: CC, part of SDMS	Field observations on land, glaciers and sea ice (physical, optical and chemical features, snow depth), GPR and remote sensing products, models result.
Polish Polar DataBase / Poland	http://ppdb.us.edu.pl/geonetwork	DOI (during implementation), metadata interoperability interfaces are available, metadata: ISO 19115, licenses: CC, part of SDMS	Field observations (physical features, snow depth), GPR and remote sensing products

National Infrastructure for Research Data (NIRD) Research Data Archive / Norway	https://archive.norstore.no/	DOI, licenses: CC and NLOD, metadata: Dublin Core, only available to Norwegian affiliated scientists	Field observations (snow depth), model results.

4.5 Data management plan

A data management plan is a document that describes how data are handled within a community (research project, research group etc.). It identifies responsibilities for data collection (identification of planned and actual datasets linked with information on Principal Investigator(s) etc.), preparation (quality control, data reduction, staging for publication), FAIR documentation (file formats, application of controlled vocabularies at the discovery and use level etc.), sharing (Persistent Identifiers/DOI, FAIR web services etc.) and long-term preservation (contingency plans and link with sharing). A data management plan is a tool for the data generating community to properly plan and manage the data collected. As such it is a living document that should be prepared in the proposal stage or as a very first activity in the project. Throughout the project, a proper data management plan is used to track the evolution of datasets from planned to a published and well-preserved dataset that is left as the scientific legacy of the project or research activity. As proper data management comes at a cost, a good data management plan should have a section on how resources (manpower and funding) is allocated to data management activities. However, with proper planning of data management, it is a cost-reducing factor for projects and research activities to fulfil the data management requirements often imposed by funding bodies.

Recommendations

A website with examples and guidance[20] on how to create a proper data management plan has been made available by the Digital Curation Centre (DCC). Several template generators for data management plans exist. Among the most commonly used at the European scene are

- EasyDMP[21]
- DMPonline[22]

Both these can offer dedicated templates for communities where some information is pre-filled to the template and both solutions are in line with requirements for European funding.

20 https://www.dcc.ac.uk/resources/data-management-plans/guidance-examples
21 https://easydmp.eudat.eu
22 https://dmponline.dcc.ac.uk

5. References

Aamaas B, Bøggild CE, Stordal F, et al. (2011) Elemental carbon deposition to Svalbard snow from Norwegian settlements and long-range transport. Tellus, 63B: 340 -351, doi:10.1111/j.1600-0889.2011.00531.x

Abbatt JPD, Leaitch WR, Aliabadi AA et al. (2019) Overview paper: New insights into aerosol and climate in the Arctic. Atmos Chem Phys, 19: 2527–2560, doi:10.5194/acp-19-2527-2019

Agnan Y, Douglas TA, Helmig et al. (2019) Mercury in the Arctic tundra snowpack: temporal and spatial concentration patterns and trace gas exchanges. Cryosphere, 12: 1939–1956, doi:10.5194/tc-12-1939-2018

AMAP (2006) AMAP Assessment 2006: Acidifying Pollutants, Arctic Haze, and Acidification in the Arctic. Arctic Monitoring and Assessment Programme, Oslo, 112 pp

AMAP (2011) AMAP Assessment 2011: Mercury in the Arctic. Arctic Monitoring and Assessment Programme, Oslo, 193 pp

AMAP (2016a) AMAP Assessment 2015: Radioactivity in the Arctic. Arctic Monitoring and Assessment Programme, Oslo, 89 pp

AMAP (2016b). AMAP Assessment 2015: Temporal Trends in Persistent Organic Pollutants in the Arctic. Arctic Monitoring and Assessment Programme, Oslo, Norway. vi+71pp

AMAP (2017) AMAP Assessment 2016: Chemicals of Emerging Arctic Concern. Arctic Monitoring and Assessment Programme, Oslo, 353pp

André M-F (1990) Frequency of debris flows and slush avalanches in Spitsbergen: a tentative evaluation from lichenometry, Polish Polar Research, 11 (3-4), 345-363

Barbaro E, Kozioł K, Björkman MP et al. (2021) Measurement report: Spatial variations in ionic chemistry and water-stable isotopes in the snowpack on glaciers across Svalbard during the 2015–2016 snow accumulation season, Atmos.Cem.Phys., 21, 3163-3180, doi: 10.5194/acp-21-3163-2021

Barnett TP, Adam JC, and Lettenmaier DP (2005) Potential impacts of a warming climate on water availability in snow-dominated regions, Nature, Vol 438, 303-309, doi:10.1038/nature04141

Bergmann M, Mützel S, Primpke S et al. (2019) White and wonderful? Microplastics prevail in snow from the Alps to the Arctic, Sci. Adv. 5: eaax1157, doi:10.1126/sciadv.aax1157

Biebow N, Quesada A, Vaughan D et al. (2019) The coupled polar climate system: Global context, predictability and regional impacts. EU Polarnet White Paper 1, EU-PolarNet, Bremerhaven, pp. 6–19.

Christiansen HH, Gilbert G, Demidov N et al. (2019) Permafrost thermal snapshot and active-layer thickness in Svalbard 2016-2017. In: Orr et al. (eds): SESS report 2018, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp. 26–47.

Christiansen HH, Gilbert G, Demidov N et al. (2020) Permafrost temperatures and active layer thickness in Svalbard during 2017/2018. In: Van den Heuvel et al. (eds): SESS report 2019, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp. 236–249.

Christiansen HH, Gilbert GL, Neumann U et al. (2021) Ground ice content, drilling methods and equipment and permafrost dynamics in Svalbard 2016-2019. In: Moreno-Ibáñez et al (eds) SESS report 2020, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 258 - 275, doi:10.5281/zenodo.4294095

Claussen M, Brovkin V, and Ganopolski A (2001) Biogeophysical versus biogeochemical feedbacks of large-scale land cover change, Geophysical Research Letters, 28 (6), 1011-1014

Cooper EJ (2014) Warmer shorter winters disrupt terrestrial Arctic ecosystems. Annual Review of Ecology, Evolution and Systematics (45): 271–95, doi:10.1146/annurev-ecolsys-120213-091620

Dietz AJ, Kuenzer C, Gessner U, and Dech S (2012) Remote sensing of snow – a review of available methods. Int. J. Rem. Sens., 33:13: 4094-4134, doi:10.1080/01431161.2011.640964

Dozier, J (1989) Spectral signature of alpine snow cover from the Landsat Thematic Mapper, Remote Sens. Environ., 28, 9-22, doi:10.1016/0034-4257(89)90101-6

Dutra E, Balsamo G, Viterbo P et al. (2010) An Improved Snow Scheme for the ECMWF Land Surface Model: Description and Offline Validation, Journal of Hydrometeorology, 11, 899-916, doi: 10.1175/2010JHM1249.1

Eckerstorfer M and Christiansen HH (2010) The "High Arctic Maritime Snow Climate" in Central Svalbard, Arctic, Antarctic, and Alpine Research, 43(1): 11-21, doi: 10.1657/1938-4246-43.1.11

Eckerstorfer M and Christiansen HH (2011) Meteorology, Topography and Snowpack Conditions causing Two Extreme Mid Winter Slush and Wet Slab Avalanche Periods in High Arctic Maritime Svalbard. Permafrost and Periglac. Process. doi: 10.1002/ppp.734

Eckerstorfer M, Malnes E, and Müller K (2017) A complete snow avalanche activity record from a Norwegian forecasting region using Sentinel-1 satellite-radar data. Cold Reg. Sci. Technol., 144: 39-51, doi:10.1016/j.coldregions.2017.08.004

Forsström S, Ström J, Pedersen JCA et al. (2009) Elemental carbon distribution in Svalbard snow. J. Geophys. Res. Atmos. 114, D19112, doi:10.1029/2008JD011480

Gallet J-C, Björkman MP, Borstad CP et al. (2019) Snow research in Svalbard: current status and knowledge gaps. In: Orr et al. (eds): SESS report 2018. Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 83–107, doi:10.5281/zenodo.4293804

Gallet J-C, Björkman MP, Larose C et al. (2018) Protocols and recommendations for the measurement of snow physical properties, and sampling of snow for black carbon, water isotopes, major ions and microorganisms. Tromsø: Norwegian Polar Institute, Short Report 46, 29 p., available at: http://hdl.handle.net/11250/2486183

Gascoin S, Grizonnet M, Bouchet M et al. (2019) Theia Snow collection: high-resolution operational snow cover maps from Sentinel-2 and Landsat-8 data. Earth Syst Sci, 11: 493–514, doi:10.5194/essd-11-493-2019

Grenfell TC, Doherty SJ, Clarke AD et al. (2011) Light absorption from particulate impurities in snow and ice determined by spectrophotometric analysis of filters. Appl. Opt., 50, 14: 2037-2048, doi:10.1364/AO.50.002037

Guneriussen T, Hogda KA, Johnsen H, and Lauknes I (2001) InSAR for estimation of changes in snow water equivalent of dry snow. IEEE T. Geosci. Remote, 39(10): 2101-2108, doi:10.1109/36.957273

Haberkorn A (Ed.) (2019) European Snow Booklet, 363 pp, doi:10.16904/envidat.59

Hancock H, Eckerstorfer M, Prokop A, and Hendrikx J (2020) Quantifying seasonal cornice dynamics using a terrestrial laser scanner in Svalbard, Norway, Nat. Hazards Earth Syst. Sci., 20: 603–623, doi:10.5194/nhess-20-603-2020, 2020.

Hansen BB, Grotan V, Aanes R et al. (2013) Climate events synchronize the dynamics of a resident vertebrate community in the High Arctic. Science, 339(6117): 313–315, doi:10.1126/science.1226766

Hansen BB, Isaksen K, Benestad RE et al. (2014) Warmer and wetter winters: characteristics and implications of an extreme weather event in the High Arctic. Environ. Res. Lett., 9(11): 114021, doi:10.1088/1748-9326/9/11/114021

Harpold AA, Guo Q, Molotch N et al. (2014) LiDAR-derived snowpack data sets from mixed conifer forests across the Western United States. Water Resources Research 50(3): 2749-2755, doi: 10.1002/2013WR013935

Holdren JP, Burke T, Dickinson T et al. (2016) U.S. Arctic Research Plan 2017-2021, U.S. National Science and Technology Council, Washington, 84 pp

Isaksen K, Benestad RE, Harris C, and Sollid JL (2007) Recent extreme near-surface permafrost temperatures on Svalbard in relation to future climate scenarios. Geophys. Res. Lett., 34(17), doi: 10.1029/2F2007GL031002

Jacobi H-W, Obleitner F, Da Costa S et al. (2019) Deposition of ionic species and black carbon to the Arctic snowpack: combining snow pit observations with modelling. Atmos. Chem. Phys., 19: 10361–10377, doi:10.5194/acp-19-10361-2019

Jaedicke C and Gauer P (2017) The influence of drifting snow on the location of glaciers on western Spitsbergen, Svalbard, Annals of Glaciology 42,2005: 237 - 242, doi:10.3189/172756405781812628

Karlsen SR, Stendardi L, Nilsen L et al. (2020) Sentinel satellite-based mapping of plant productivity in relation to snow duration and time of green-up. In: Van den Heuvel et al. (eds): SESS report 2019, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 42-57, doi:10.5281/zenodo.4704361

Kaspari S, Skiles SM, Delaney I et al. (2015). Accelerated glacier melt on Snow Dome, Mt. Olympus, Washington, USA, due to deposition of black carbon and mineral dust from wildfire. J. Geophys. Res. Atmos., 120: 2793–2807, doi:10.1002/2014JD022676

Kavan J, Nývlt D, Láska K et al. (2020) High-latitude dust deposition in snow on the glaciers of James Ross Island, Antarctica, Earth Surf. Process. Landforms 45: 1569–1578, doi:10.1002/esp.4831

Killie MA, Aaboe S, Isaksen K et al. (2021) Svalbard snow and sea-ice cover: comparing satellite data, on-site measurements, and modelling results. In: Moreno-Ibáñez et al (eds) SESS report 2020, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 220-235, doi:10.5281/zenodo.4293804

Kos G, Kanthasami V, Adechina N, and Ariya PA (2014) Volatile organic compounds in Arctic snow: concentrations and implications for atmospheric processes. Environ. Sci.: Processes Impacts 16: 2592, doi: 10.1039/c4em00410h

Kozioł KA, Moggridge HL, Cook JM, and Hodson AJ (2019) Organic carbon fluxes of a glacier surface: A case study of Foxfonna, a small Arctic glacier. Earth Surf. Proc. Land. 44 (2): 405–416, doi:10.1002/esp.4501

Kwok KY, Yamazaki E, Yamashita N et al. (2013) Transport of perfluoroalkyl substances (PFAS) from an arctic glacier to downstream locations: Implications for sources. Sci. Tot. Environ. 447: 46-55, doi:10.1016/j.scitotenv.2012.10.091

Layton-Matthews K, Hansen BB, Grøtan V et al. (2019) Contrasting consequences of climate change for migratory geese: Predation, density dependence and carryover effects offset benefits of high-arctic warming. Global Change Biology 26(2):1-16, doi:10.1111/gcb.14773

Leppänen L, Kontu A, Hannula H-R et al. (2016) Sodankylä manual snow survey program. Geosci. Instrum. Method. Data Syst., 5: 163–179, doi:10.5194/gi-5-163-2016

Lewandowski M, Kusiak MA, Werner T et al. (2020) Seeking the sources of dust: Geochemical and Magnetic studies on “cryodust” in glacial cores from southern Spitsbergen (Svalbard, Norway). Atmosphere 2020; 11(12):1325. doi:10.3390/atmos11121325

Lievens H, Demuzere M, Marshall HP et al. (2019). Snow depth variability in the Northern Hemisphere mountains observed from space. Nat. Commun.,10, 4629, doi:10.1038/s41467-019-12566-y

Lim S, Faïn X, Zanatta M, Cozic J et al. (2014) Refractory black carbon mass concentrations in snow and ice: method evaluation and inter-comparison with elemental carbon measurement, Atmos. Meas. Tech. 7: 3307–3324, doi:10.5194/amt-7-3307-2014

MacInnis JJ, Lehnherr I, Muir DCG et al. (2019) Fate and transport of perfluoroalkyl substances from snowpacks into a lake in the High Arctic of Canada. Environ. Sci. Technol. 53: 10753−10762, doi:10.1021/acs.est.9b03372

Malnes E, Vickers H, Karlsen SR et al. (2021) Satellite and modelling based snow season time series for Svalbard: Inter-comparisons and assessment of accuracy. In: Moreno-Ibáñez et al (eds) SESS report 2020, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp. 202-217, doi:10.5281/zenodo.4294072

Materić D, Kasper-Giebl A, Kau D et al. (2020) Micro- and nanoplastics in alpine snow: a new method for chemical identification and (semi)quantification in the nanogram range. Environ. Sci. Technol. 54: 2353−2359, doi:10.1021/acs.est.9b07540

McCreight JL, Small EE and Larson KM (2014) Snow depth, density, and SWE estimates derived from GPS reflection data: Validation in the western U. S. Water Resources Research 50 (8), 6892-6909, doi: 10.1002/2014WR015561

Meinander O, Heikkinen E, Aurela M and Hyvärinen A (2020) Sampling, filtering, and analysis protocols to detect black carbon, organic carbon, and total carbon in seasonal surface snow in an urban background and Arctic Finland (>60˚ N). Atmosphere 2020, 11: 923, doi:10.3390/atmos11090923

Meredith M, Sommerkorn M, Cassotta S et al. (2019) Polar Regions. In: IPCC Special Report on the Ocean and Cryosphere in a Changing Climate, eds. H.-O. Pörtner, D.C. Roberts, V. Masson-Delmotte et al. Intergovernmental Panel on Climate Change, World Meterological Organization, Geneva, pp. 203-320

Moreno-Ibáñez M, Hagen JO, Hübner C, Lihavainen H, Zaborska A (eds) 2021: SESS report 2020, Svalbard Integrated Arctic Earth Observing System, Longyearbyen

Muir D, Zhang X, de Wit CA et al. (2019) Identifying further chemicals of emerging arctic concern based on ‘in silico’ screening of chemical inventories. Emerging Contaminants, 5, 2019: 201-210, doi:10.1016/j.emcon.2019.05.005

Nagler T and Rott H (2000). Retrieval of wet snow by means of multitemporal SAR data. IEEE Transactions on Geoscience and Remote Sensing, 38(2): 754-765

Nawrot AP, Migała K, Luks B et al. (2016). Chemistry of snow cover and acidic snowfall during a season with a high level of air pollution on the Hans Glacier, Spitsbergen. Polar Science, 10 (3): 249-261, doi:10.1016/j.polar.2016.06.003

Noël BPY, Jakobs CL, van Pelt WJJ et al. (2020). Low elevation of Svalbard glaciers drives high mass loss variability. Nature Communications, 11, 4597. doi:10.1038/s41467-020-18356-1

Orr E, Hansen, G, Lappalainen H, Hübner C, Lihavainen, H (eds) 2019: SESS report 2018, Svalbard Integrated Arctic Earth Observing System, Longyearbyen

Pedersen ÅØ, Stien J, Albon S et al. (2020) Climate-Ecological Observatory for Arctic Tundra. In: Van den Heuvel et al. (eds): SESS report 2019, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp. 58–83

Peeters B, Pedersen ÅØ, Loe LE et al. (2019) Spatiotemporal patterns of rain-on-snow and basal ice in high Arctic Svalbard: detection of a climate-cryosphere regime shift. Environ. Res. Lett., 14(1): 015002, doi:10.1088/1748-9326/aaefb3

Petzold A, Ogren JA, Fiebig M et al. (2013) Recommendations for reporting “black carbon” measurements. Atmos. Chem. Phys., 13: 8365–8379, doi:10.5194/acp-13-8365-2013

Pirazzini R, Leppänen L, Picard G et al. (2018) European in-situ snow measurements: Practices and purposes. Sensors 2018, 18:2016, doi:10.3390/s18072016

Pulliainen J, Luojus K, Derksen C et al. (2020) Patterns and trends of Northern Hemisphere snow mass from 1980 to 2018. Nature, 581(7808): 294-298, doi:10.1038/s41586-020-2258-0

Raghuveer K, Vinukollu EF, Wood CR et al. (2011) Global estimates of evapotranspiration for climate studies using multi-sensor remote sensing data: Evaluation of three process-based approaches, Remote Sensing of Environment, 115, 801–823

Reynolds RL, Goldstein HL, Moskowitz B et al. (2020) Dust deposited on snow cover in the San Juan Mountains, Colorado, 2011–2016: Compositional variability bearing on snow-melt effects. J. Geophys. Res. Atmos.,125, e2019JD032210, doi:10.1029/2019JD032210

Rotschky G, Schuler TV, Haarpaintner J et al. (2011) Spatio-temporal variability of snowmelt across Svalbard during the period 2000–08 derived from QuikSCAT/SeaWinds scatterometry. Polar Res., 30(1): 5963, doi:10.3402/polar.v30i0.5963

Salzano R, Aalstad K, Boldrini E et al. (2021a) Terrestrial photography applications on snow cover in Svalbard. In: Moreno-Ibáñez et al (eds) SESS report 2020, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 236-251, doi:10.5281/zenodo.4294084

Salzano R, Killie MA, Luks, B, and Malnes E (2021b) A mulit-scale approach to snow cover observations and models. In: Moreno-Ibáñez et al (eds) SESS report 2020, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 236-251, doi: 10.5281/zenodo.4294092

Scherer D, Gude M, Gempeler M, and Parlow E (1998) Atmospheric and hydrological boundary conditions for slushflow initiation due to snowmelt. Ann. Glaciol. 26, 377-380.

Schmitt CG, All JD, Schwarz JP et al. (2015) Measurements of light-absorbing particles on the glaciers in the Cordillera Blanca, Peru. The Cryosphere, 9: 331–340, doi:10.5194/tc-9-331-2015

Schrlau JE, Geiser L, Hageman KJ, et al. (2011) Comparison of lichen, conifer needles, passive air sampling devices, and snowpack as passive sampling media to measure semi-volatile organic compounds in remote atmospheres. Environ. Sci. Technol. 45: 10354–10361, doi: 10.1021/es202418f

Schuler TV, Glazovsky A, Hagen JO et al. (2020) New data, new techniques and new challenges for updating the state of Svalbard glaciers. In: Van den Heuvel et al. (eds): SESS report 2019, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp. 108-134

Schwarz JP, Doherty SJ, Li F et al. (2012) Assessing Single Particle Soot Photometer and Integrating Sphere/Integrating Sandwich Spectrophotometer measurement techniques for quantifying black carbon concentration in snow. Atmos. Meas. Tech., 5: 2581–2592, doi: 10.5194/amt-5-2581-2012

Serreze MC and Barry RG (2011) Processes and Impacts of Arctic Amplification: A Research Synthesis. Global and Planetary Change, 77, 85-96. doi:10.1016/j.gloplacha.2011.03.004

Skaar JJ, Ræder EM, Lyche JL, Ahrens L and Kallenborn R (2019) Elucidation of contamination sources for poly- and perfluoroalkyl substances (PFASs) on Svalbard (Norwegian Arctic), Environ. Sci. Poll. Res. 26: 7356–7363, doi:10.1007/s11356-018-2162-4

Spolaor A, Barbaro E, Cappelletti D et al. (2019) Diurnal cycle of iodine, bromine, and mercury concentrations in Svalbard surface snow. Atmos. Chem. Phys., 19: 13325–13339, doi:10.5194/acp-19-13325-2019

Spolaor A, Moroni B, Luks B et al. (2021) Investigation on the sources and impact of trace elements in the annual snowpack and the firn in the Hansbreen (Southwest Spitsbergen). Front. Earth Sci. 8:536036, doi:10.3389/feart.2020.536036

Svensson J, Ström J, Kivekäs N et al. (2018) Light-absorption of dust and elemental carbon in snow in the Indian Himalayas and the Finnish Arctic, Atmos. Meas. Tech., 11: 1403–1416, doi:10.5194/amt-11-1403-2018

Tørseth K, Andrews E, Asmi E et al. (2019) Review of Observation Capacities and Data Availability for Black Carbon in the Arctic Region, EU Action on Black Carbon in the Arctic. Technical Report 1, Arctic Monitoring and Assessment Programme, Oslo, iv+35 pp

Van den Heuvel F, Hübner C, Błaszczyk M, Heimann M, Lihavainen H (eds) 2020: SESS report 2019, Svalbard Integrated Arctic Earth Observing System, Longyearbyen

Van Pelt WJJ, Pohjola VA, Pettersson R et al. (2019) A long-term dataset of climatic mass balance, snow conditions and runoff in Svalbard (1957–2018). The Cryosphere, 13, 2259-2280. doi:10.5194/tc-13-2259-2019

Van Pelt WJJ, Schuler TV, Pohjola VA, and Pettersson R (2021). Accelerating future mass loss of Svalbard glaciers from a multi-model ensemble. Journal of Glaciology, first-view. doi:10.1017/jog.2021.2

Vecchiato M, Barbaro E, Spolaor A et al. (2018) Fragrances and PAHs in snow and seawater of Ny-Ålesund (Svalbard): Local and long-range contamination. Environ. Poll., 242B: 1740-1747, doi:10.1016/j.envpol.2018.07.095

Vickers H, Karlsen SR and Malnes E (2020) A 20-Year MODIS based snow cover dataset for Svalbard and its link to phenological timing and sea ice variability. Remote Sens. 12(7): 1123

Vikhamar-Schuler D, Isaksen K, Haugen JE et al. (2016) Changes in winter warming events in the Nordic Arctic Region. J. Climate, 29 (17): 6223-6244, doi:10.1175/JCLI-D-15-0763.1

Vionnet V, Brun E, Morin S et al. (2012) The detailed snowpack scheme Crocus and its implementation in SURFEX v7.2, Geosci. Model Dev., 5, 773–791, https://doi.org/10.5194/gmd-5-773-2012

Wesselink DS, Malnes E, Eckerstorfer M and Lindenbergh RC (2017) Automatic detection of snow avalanche debris in central Svalbard using C-band SAR data. Polar Res., 36(1): 1333236, doi:10.1080/17518369.2017.1333236

Westermann S, Boike J, Langer M, Schuler TV and Etzelmüller B (2011) Modeling the impact of wintertime rain events on the thermal regime of permafrost. The Cryosphere, 5(4): 945-959, doi:10.5194/tc-5-945-2011

Wilkinson MD, Dumontier M, Aalbersberg I et al. (2016) The FAIR Guiding Principles for scientific data management and stewardship. Sci. Data, 3: 160018, doi:10.1038/sdata.2016.18

Appendix 1: Acronyms and abbreviations

As	Arsenic
AWS	Amazon Web Service
BC	Black Carbon
Be	Beryllium
BSC	Biological Soil Crust
C	Carbon
CC	Creative Commons
Cd	Cadmium
CEC	Chemical of Emerging Concern
CF	Climate and Forecast convention
Cs	Caesium
CV-AFS	Cold Vapour Atomic Fluorescence Spectroscopy
DCC	Digital Curation Centre
DIF	Directory Interchange Format
DMP	Data Management Plan
DOC	Dissolved Organic Carbon
DOI	Digital Object identifier
DwC	Darwin Core archive
eBC	equivalent Black Carbon
ECV	Essential Climate Variables
ENP	Engineered NanoParticles
EW	Extra Wide mode
FAIR	Findable, Accessible, Interoperable, Reusable
Fe	Iron
GC	Gas Chromatography
GCMD	Global Change Master Directory
GC-MS	Gas Chromatography coupled to Mass Spectrometry
GCOS	Global Climate Observing System
GEE	Google Earth Engine
GNSS-IR	Global Navigation Satellite System Interferometric Reflectometry
GPR	Ground-Penetrating Radar
GPS-IR	Global Positioning System – Interferometric Reflectometry
HBV	Hydrologiska Byråns Vattenbalansavdelning
Hg	Mercury
IC	Ion Chromatography
ICP-MS	Inductively-Coupled Plasma Mass Spectrometry
ISO	International Organization for Standrdization
ISSW	Integrating Sandwich Spectrophotometer
IW	Interferometric wide (mode)
LAHM	Light Absorption Heating Method
LC-MS	Liquid Chromatography coupled to Mass Spectrometry
LiDAR	Light Detection And Ranging
masl	meter above sea level
MS	Mass Spectrometer
N	Nitrogen

netCDF	Network Common Data Form
NLOD	Norwegian Licence for Open Government Data
NO_{3-}	Nitrate
NWP	Numerical weather prediction
OC	Organic carbon
Pb	Lead
PCB	Polychlorinated biphenyl
PFAS	Per- and Polyfluoroalkyl Substances
POES	Polar Operational Environmental Satellites
POP	Persistent Organic Pollutant
PSAP	Particle Soot Absorption Photometer
Pu	Plutonium
RfS	Reflectance Spectroscopy
rBC	refractory Black Carbon
RfS	Reflectance Spectroscopy
ROS	Rain On Snow
SAR	Synthetic-Aperture Radar
SCA	Snow-Covered Area
SESS	State of Environmental Science in Svalbard report
SIOS	Svalbard Integrated Arctic Earth Observing System
SO_4^{2-}	Sulfate
SP2	Single Particle Soot Photometer
Sr	Strontium
Suomi NPP	Suomi National Polar-orbiting Partnership
SVOC	Semi-Volatile Organic Compound
SWE	Snow Water Equivalent
TEP	Thematic Exploitation Platform
Ti	Titanium
TOC	Total Organic Carbon
TOT	Thermo-optical Transmittance method
UAV	Unmanned Aerial Vehicles
Vlab	Virtual Laboratory Platform
WIGOS	WMO Integrated Global Observing System
WIOC	Water-insoluble organic carbon
WIS	WMO Information System
WMO	World Meteorological Organization
WSOC	Water-soluble organic carbon
XRF	X-Ray Fluorescence
Zn	Zinc

Appendix 2: Considerations for snow chemistry monitoring

Below are some practical considerations that can help to guide the development of any snow chemistry monitoring programme on Svalbard, irrespective of where it is carried out. These are not exhaustive, but should apply irrespective of where such a programme is carried out.

Type/frequency of sampling: This depends largely on the programme objectives. If the goal is to compare the concentrations of compounds in air and snow (e.g., to develop air-snow transfer functions), then sampling during precipitation events is preferable. If the goal is to quantify concentrations of impurities in surface snow (e.g., to assess the radiative impact of light-absorbing particles), then sampling the surface layers on a regular basis (e.g., weekly) is indicated. And if the goal is to quantify the net accumulation of atmospherically deposited species in seasonal snow over the course of the winter, then sampling the bulk snowpack at weekly to monthly intervals may be the best strategy. The above is not an exhaustive list.

Spatial scale of sampling: Establishing the representativity of single point measurements of snowpack composition is challenging, because spatial variability is scale-dependent, and also changes for different atmospheric species (e.g., those that are reactive and volatile vs. those that are more inert and irreversibly deposited). Here again, the objectives of the monitoring programme should guide the proper spatial strategy. If the goal is to quantify net accumulation of atmospheric species at the catchment scale, a single sampling point is clearly insufficient, but if the goal is to compare the composition of air and falling snow, then sampling as close to the air-sampling site is necessary. Whenever the goal is to estimate atmospheric deposition at a relatively large spatial scale (e.g., 1-10 km^2), an initial survey should be carried to establish the variability of snow composition on multiple scales within the study area (e.g., 1, 100, 1000 m^2). This can help determine how many sampling points are needed to obtain a satisfactory signal-to-noise ratio, and also what is the possible uncertainty of large-scale flux estimates in snow based on local snowpack heterogeneity.

Sampling quantity needs: The choice of how much snow should be collected is contingent on the desired time/depth resolution (e.g., event-based vs. regular sampling, surface layers vs. bulk snowpack) and on the specific needs of the analytical methods to be employed (see below). Logistical limitations (for e.g., ease of transport and storage capacity) obviously also come into play. With respect to analytical methods, the mass of snow needed for reliable quantification of impurity/contaminant ranges from a few g for sulfate and nitrate, to ~5-8 kg for BC, and up to ~20 kg for POPs. The large sample needs for POPs, coupled with stringent clean sampling protocols required for many contaminants (e.g., Hg, pesticides) imply that different monitoring strategies are needed in each case.

In view of the considerations outlined above, two different levels may be envisioned for routine sampling and/or measurements of contaminants in snow, which may be conducted in parallel, albeit following separate timetables.

Level 1 monitoring should seek to provide a relatively quick and easy, *qualitative to semi-quantitative* assessment of temporal changes in the amount of certain types of contaminants in the snowpack. Such measurements should be easily carried out, with only limited instrumentation or advanced technical skills needs, and could be done by volunteers from local communities with minimal training. This echoes one of the key recommendations of the 2019 EU-Polarnet White Papers, which stressed that, *«whenever possible, data and information should be collected by local stakeholders and indigenous people without creating any additional burden or pressure for them»* (EU-Polarnet White Paper 4, p. 46).

Level 2 would aim instead to produce *quantitative* data of high quality and reliability that can be compared to measurements in air, precipitation or snow on the ground produced elsewhere in the world. Such measurements would demand much more rigorous protocols and data quality control measures, sophisticated instruments, and skilled technicians.

Clearly this is a simplification, because for some contaminants, the collection of field samples may be done with minimal equipment and training, even if the actual measurements (e.g., in a laboratory) require far more advanced tools and skills. In such a situation, field sampling may be a Level I activity, even if analysis is a Level 2 activity. Also, it should be obvious that while contaminants that are suitable for Level 1 monitoring are almost certainly also suitable for Level 2 monitoring, the opposite is not true.

Table 2 summarizes information about the estimated feasibility for monitoring impurities or contaminants in Svalbard snow, based on recently published studies. This table is not exhaustive, and only lists some, not all, species. The analytical methods listed are among the most commonly used. Many contaminants (such as Hg, SVOC, PFAS) can only be monitored at level II, given the present state of technology. The highly specific sampling and/or measurement methods needed to obtain usable data for these contaminants are not easily applicable to level I monitoring. However, a few impurity and contaminant types, such as BC, dust or acidifying aerosols, could be monitored at both levels I and II.

Both BC and dust are largely made of water-insoluble particulate matter, which can easily be filtered out from melted snow with low-cost equipment. Some measures of BC and/or dust mass content can then be carried out on filters using light- or heat-absorption methods, or magnetic and gravimetric techniques. While these techniques do not yield fully quantified, species-specific data on BC and dust, they can nevertheless be employed for semi-quantitative/qualitative assessments. Identifying dust composition (e.g., to establish the percentage of light-absorbing minerals) is more demanding, but filters (if adequately prepared) can easily be sent to laboratories for analysis using methods such as XRF. Likewise, filters measured by light-based techniques for BC can subsequently be used for more advanced measurements using methods such as TOT.

With regards to acidifying aerosols such as sulfate and nitrate in snow, the most widely used analytical method is ion chromatography, but this is not suitable for level I monitoring (although some spectrophotometric methods may be). Unfortunately, most cheap and easily operable portable water quality analysers presently on the market have insufficiently low sensitivities (typically, ppm range) to quantify the ppb-level concentrations that are usually found in polar snow. While less specific, an alternative is to measure the specific conductance and/or pH of melted snow samples, as these parameters can be determined using easily affordable electrolytic probes, provided that proper protocols are observed.

References in table 2: 1: Grenfell et al. (2011); **2**: Svensson et al. (2018); **3**: Forsström et al. (2009); **4**: Aamaas et al. (2011); **5**: Schmitt et al. (2015); **6**: Schwarz et al. (2012); **7**: Lim et al. (2014); **8**: Kaspari et al. (2015); **9**: Lewandowski et al. (2020); **10:** Kavan et al. (2020); **11**: Reynolds et al. (2020); **12**: Nawrot et al. (2016); **13**: Jacobi et al. (2019); **14**: Agnan et al. (2019); **15**: Spolaor et al. (2019); **16**: Spolaor et al. (2021); **17**: Kozioł et al. (2019); **18**: Schrlau et al. (2011); **19**: Kos et al. (2014); **20**: Vecchiato et al. (2018); **21**: Kwok et al. (2013); **22**: MacInnis et al. (2019); **23**: Skaar et al. (2019); **24**: Bergmann et al. (2019); **25**: Materić et al. (2020).

Contaminant	Measurement method	Method or instrument designation[b]	Reported quantity[c]	Typical levels (units)	Snow volume required	Monitoring feasibility level: Field sampling I	Field sampling II	Measurement I	Measurement II	Examples
Black carbon (BC)[a]	Light absorption	PSAP, ISSW	[eBC]	ppb	5-10 L	X	X	X	X	1,2
	Thermo-optical method	TOT	[EC]	ppb	5-10 L	X	X		X	3,4
	Heat absorption	LAHM	[eBC]	ppb	5-10 L	X	X	X		5
	Laser incandescence	SP2	[rBC]	ppb	10 mL	X	X		X	6,7
Mineral dust	Gravimetry		[dust]	ppm	5-10 L	X	X	X	X	8
	Magnetic susceptibility			T or mT	5-10 L	X			X	9
	X-ray fluorescence	XRF	[elements]	ppm	5-10 L	X	X		X	10
	Reflectance spectroscopy	RfS	[minerals]	ppm		X	X		X	8,11
	Mass spectrometry	MS	[oxides]	ppm		X	X		X	8,11
Electrolytes	Specific conductance	Cond. probe	Spec. Cond.	S cm^{-1}	10-50 mL			X	X	12
Acids (pH)	pH meter	pH meter	pH		10-50 mL	X	X	X	X	12
Sulfate & nitrate	Ion chromatography	IC	[SO_4^{2-}], [NO_3^-]	ppb	10 mL	X			X	13
Mercury (Hg)	Fluorescence spectrometry	CV-AFS	[Hg]	ppt	100 mL		X		X	14
	Mass spectrometry	ICP-MS	[Hg]	ppt	100 mL		X		X	15
Other metals	Mass spectrometry	ICP-MS	[metal]	ppt	1 L		X		X	16
Organic carbon (OC)	Infrared absorption	OC analyzer	[TOC], [DOC]	ppb	1-5 L	X	X		X	17
Semi-volatile organic compounds (SVOC)	Gas chromatography coupled to mass spectrometry	GC-MS	[SVOC]	ppb	10-50 L		X		X	18,19,20
Perfluoroalkyl substances (PFAS)	Liquid chromatography coupled to mass spectrometry	LC-MS	[PFAS]	ppq	1-5 L		X		X	21,22,23
Microplastics	Mass spectrometry	MS	[polymer]	ppb	10 mL		X		X	24,25

[a]Terms for BC are after Petzold et al. (2013); [b]Acronyms are listed in appendix. [c]Brackets denote mass or volumetric concentrations.

Appendix 3: Workshop participants

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