Snow research in Svalbard: current status and knowledge gaps

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1 Overview

1.1 The importance of snow in Svalbard

Next to the ocean, snow is the second largest interface between the atmosphere and Earth's surface during winter. Snow deposited on land or ice surfaces is thermodynamically unstable and in constant evolution through snow metamorphism, which is controlled by temperature gradients in the snowpack. Seasonal snowpacks are therefore very sensitive to changing climate conditions. In Svalbard, the seasonal snowpack (including glaciers) covers ~60 to 100 % of the land between winter and summer. Changes in Arctic snowpack properties have been observed in the last decade in response to high-latitude warming (Bokhorst et al., 2016), and will likely continue in the future, with important anticipated effects on different aspects of the Svalbard environment, as reviewed below. Snow research could therefore become an important vehicle for monitoring and analysing the rate and effects of climate change in Svalbard. However, while efforts are on going to develop more and better remotely-sensed snow products for this region (Malnes et al., 2015; Aalstad et al., 2018), there are presently few regular *in situ* measurements in Svalbard for even basic snowpack properties (snow depth, density, temperature, hardness, the presence of ice layers, etc.). For example, Norway's Environmental monitoring of Svalbard and Jan Mayen (MOSJ) only reports snow cover duration data in three areas (Longyearbyen, Ny Ålesund and Sveagruva). More of these measurements, and others, are needed both to validate space borne observations, and to better understand and anticipate interactions between the changing snow cover and other Earth system components, i.e. the atmosphere, glaciers, soils, freshwater networks, the ocean and sea-ice. In what follows we discuss some of these aspects, with emphasis on recent research from Svalbard.

1.2 Snow-atmosphere interactions: Climatic and biogeochemical consequences

Owing to its high reflectivity (visible albedo of up to 0.9), snow cover plays a crucial role in Earth's energy budget (Lemke et al., 2007). Snow also has a very high specific surface area, allowing it to absorb and scavenge a wide variety of gases and aerosols from the atmosphere (Grannas et al., 2007; Nawrot et al., 2016), including some that affect its radiative properties. For example, many recent studies have focused on the black carbon (BC) content of Arctic snow packs (Aamaas et al., 2011; Forsstrom et al., 2009, Khan et al., 2017; Sviashchennikov et al., 2014), which reduces the albedo of snow because the BC strongly absorbs solar radiation (Pedersen et al., 2015; Warren, 1984; Sviashchennikov et al., 2015). Physical, chemical, and biological processes involving organic matter in the snowpack also have significant impacts on atmospheric and biogeochemical cycles of carbon, nitrogen and other elements (Morin et al., 2008; McNeill et al., 2012). For example, the photochemistry of organic compounds stored in the snowpack leads to volatile organic compound (VOC) production (i.e. CO_2, $CHCl_3$, $(CH_3)_2S$, CS_2, $CHBrCl_2$), and conversely acts as a sink for other compounds such as CO, COS, some halogenated compounds and hydrocarbons. As the Arctic climate warms, seasonal snow coverage is expected to decrease in some areas, exposing new sources of windblown dust and other aerosols, with impacts on the radiative balance of the atmosphere and cryosphere (Kylling et al., 2018). And as snow melts, the impurities stored within, including organic matter, nutrients, impurities and pollutants, can be released to the atmosphere or transferred by melt waters to soil or aquatic ecosystems (Kuhn, 2001, Björkman et al., 2014). Snow also provides nutrients for bacterial and fungal growth and acts as a habitat for a diverse community of micro-organisms (Maccario et al., 2014) that, if active, metabolize chemical compounds and contribute to changes in the composition of the snow and the overlying atmosphere (Domine & Shepson, 2002, Amoroso et al., 2010). These microorganisms can in return, modify the albedo of the snow/ice and affect glacier melt rates (Ryan et al., 2018). Understanding and quantifying these processes necessitates interdisciplinarity and the consideration of a large number of variables, some of which are still difficult to measure in the field and require very specialized instruments and field protocols. Some current process-oriented research in Svalbard contributes to address this knowledge gap (e.g. Björkman et al, 2014: Hodson et al, 2010; Larose et al, 2010), but there remains a great degree of unfulfilled potential which should be addressed in future research priorities.

1.3 Snow is key for glacial mass balance and climate modelling

Svalbard is an ideal physical laboratory for understanding how changes in snow cover can influence glacial processes, and its consequences for ecosystems. Snow is the dominant mode of accumulation on Svalbard glaciers and therefore controls mass balance change (van Pelt et al., 2016a; Sobota, 2017) due to its high reflectivity that regulates melting efficiency, and its porous properties that store significant volumes of melt (Østby et al., 2017, Christianson et al., 2015; Ivanov, Sviashchennikov, 2015). For example, snow can delay the melt season of glaciers by several days following just 1 to 2 cm of fresh snow fall in the summer (Box et al., 2012; Østby et al., 2013). Smaller, lower elevation Svalbard glaciers are cooling and undergoing a transition from poly-thermal to cold-based temperature conditions (e.g. Hodgkins et al., 1999), which has marked effects on glacier dynamics. Modelling studies have now demonstrated the importance of snow cover for both initiating and maintaining rapid ice flow at the bed of glaciers (Schäfer et al, 2014). Storage of melt water within snow also moderates the transfer of water to the snow/ice interface and further to the subglacial environment via moulins and crevasses, thus further influencing subglacial hydraulics and glacier dynamics (Irvine-Fynn et al., 2011). Therefore, changes in snow cover influences ice dynamics, mass balance and the cascade of melt water, and the sediment and solute (including nutrients) discharged by glacier-fed rivers during the summer (Hodson et al., 2005). However, due to the spatial variability of snow accumulation (Taurisano et al., 2007; Moller et al., 2011), and significant redistribution effects by wind (Sauter et al., 2013; Laska et al., 2017); determining the total amount of mass accumulated on glaciers is difficult, time-consuming and still requires ground validation (van Pelt et al., 2016b).

1.4 Importance of snow over sea ice

Sea ice that forms, grows, and melts on the ocean surface is primarily found in the Polar Regions and is generally overlain by snow. Climate change influences the extent and duration of sea ice cover (Arzel et al., 2006), which in turn affects ocean-atmosphere interactions and impacts marine ecosystems and biogeochemical processes (Montes-Hugo et al., 2009). Sea ice and snow packs are active interfaces, in which a range of physico-chemical and microbially mediated reactions involved in global biogeochemical cycles occur (Amoroso et al., 2010; Domine & Shepson, 2002; Larose et al., 2013a,b; Spolaor et al., 2014; Vancoppenolle et al., 2013). The most prominent example is the formation of reactive halogen species (e.g. Br atoms and BrO) over snow-covered sea ice (Simpson et al., 2007) that can destroy ozone in the boundary layer on a large-scale (Jacobi et al., 2010). Models predicting the consequences of sea ice retreat rarely describe snow cover further than a single layer with invariable properties, despite its dynamical changes and its critical role in modulating sea-ice melt and dynamics. For example, the high albedo of snow almost prevents the ice from absorbing energy and therefore reduces its melting. However, snow is also a very good insulator (Sturm et al., 1997), protecting the ice surface from cooling in winter, which consequently reduces its growth (Sturm et al., 2002). Due to the opacity of the sea-ice-snow system to incoming light, snow also controls the amount of light reaching the ocean surface, thus, controlling the phytoplankton production underneath sea ice (Fernández-Méndez et al., 2018).

1.5 Importance of snow for terrestrial ecosystems

The influence of seasonal snow cover on soil temperature, soil freeze-thaw processes, and permafrost (Etzelmüller et al., 2011, Gisnås et al., 2014) has considerable impacts on the carbon exchange processes and on the hydrological cycle in cold regions. Soil moisture is regulated by the supply of snowmelt water and rainfall as well as by the depth of the top layer of permafrost (thaw depth), which determines the level of groundwater during the growing season. Changes in snow depth and duration can have variable effects on plant growth and health (Opala-Owczarek et al., 2018). A warmer climate may lead to more frequent rain on snow (ROS) events and winter warm spells (Vikhamar-Schuler et al., 2016) with severe impacts for the vertebrate resident communities in Svalbard (sibling vole, Svalbard reindeer, rock ptarmigan and Arctic fox), where population growth rates, survival and reproduction success can be reduced (Hansen et al., 2011, 2013a; Stien et al., 2012). Ice on the ground also impacts the herbivorous populations in relation to foraging availability (Phoenix & Bjerke, 2016). More interdisciplinary research is required to link snow physical properties (such as e.g. snow cover, depth, thermal and optical properties, liquid water and ice content, permeability) to the biology of plants and animals. Changing snow pack properties can therefore, affect the linkage between plants and herbivores, not only by modulating available forage quantity during the ice-covered period, but also through changes to the abundance of forage plants during summer, which impacts animal energy use and their spatial and temporal habitat (Loe et al., 2016; Stien et al., 2010).

1.6 Importance of snow for high latitude communities and societies in Svalbard

In Svalbard, snow cover affects the entire environment but also has direct and indirect economic, social and cultural impacts, notably including snow avalanche risk (Eckerstorfer & Christiansen, 2012, Eckerstorfer et al., 2014) and fresh water supply in remote settlements like Longyearbyen and Barentsburg. Changes in the frequency and type of winter precipitation will change the avalanche hazard for structures, residents, and visitors in Svalbard (Bokhorst et al., 2016). As a result of more frequent large winter storms, snow clearing costs in Arctic settlements could increase. Regional increases in winter snow accumulation could also lead to a deepening of the permafrost active layer, destabilizing infrastructures on permafrost (Etzelmüller et al., 2011; Instanes, 2016). Conversely, earlier and/or increased snowmelt could cause flooding, and damage to municipal water pipes and drainage systems (Instanes et al., 2016; Shevnina et al., 2017), and the frequency of soil desiccation can affect living conditions. Snow environments also attract hundreds of thousands of (eco) tourists to Svalbard. The snowy spring period (March-May) is getting more attractive with the number of monthly guest nights in April growing from 4000 in 1995 to 16000 in 2015 (Eeg-Henriksen & Sjømæling, 2016). Whether these tourists are looking to observe biodiversity or enjoy outdoor winter activities (e.g. skiing, dog-sledding, snow-mobiling), snow cover changes will affect their recreational activities with important economic impacts for local stakeholders.

1.7 Snow precipitation, wind redistribution and sublimation

Meteorological observations have been conducted around Longyearbyen since 1912, presumably making this the longest record from the High Arctic (Nordli et al., 2014). The recorded precipitation is very low on average—about 190 mm annually—throughout the entire record, which suggests that this area is an Arctic desert. The an annual precipitation in Ny-Ålesund is slightly higher (385 mm) with most precipitation falling in August-October (mainly as rain) and March (mainly as snow), while May-June correspond to the lowest rates (Førland et al. 2011). For the entire Svalbard archipelago, annual precipitation is estimated to range from 190 to 525 mm (Førland, Benestad et al. 2011). The harsh weather conditions (e.g., blowing and drifting snow, undercatch in precipitation gauges during snowfall, and high wind speeds) complicate precipitation measurements in the Arctic (Førland et al. 2011). Despite new techniques, such as snow depth sensors (Hanne H. Christiansen, 2013), correct precipitation values are still difficult to obtain. The precipitation series from Norwegian Arctic stations share a common feature; they all show a positive trend in the annual precipitation through the period as a whole, even though they begin at different points in time (from MOSJ precipitation dataset). Furthermore, snow drift and sublimation could play an important role in snow accumulation and the formation of the annual snow strata (Pomeroy et al. 1998). In particular, wind erosion and sublimation can remove the snow accumulted in the coastal areas, thereby exposing the ground or the ground ice layer if present. Additionally, snow distribution by wind drift could produce accumulation areas and increase the risk of avalanches in certain areas (Eckerstorfer & Christiansen, 2011; Hancock et al., 2018).

2 Current snow-related research in Svalbard

Many different research groups from several countries and scientific disciplines have been or are currently investigating snow or snow-related phenomena in Svalbard. At least some of these groups have produced multi-year datasets of snowpack properties based on *in-situ* observations (Table 1). While some of these data are published (e.g. Boike et al., 2018; Ivanov et al., 2014; Kępski et al., 2017) or available on-line in data repositories, most are not. It would be beneficial to increase their accessibility through SIOS in order to reach a larger community of users.

Table 1: Lists, know to SESS authors, long-term snow related datasets. As open-data policies among research operators on Svalbard are still under development, most of the datasets are not yet accessible on-line.

Region	Responsible institution(s)	Land cover type	Data coverage	Data type(s)	Data access
			(Time coverage may differ for various snow properties)		
Austfonna	UiO/NPI	Glacier	10 years	Snow depth, SWE	Data access on request.
Barentsburg	Murmansk Management of Hydrometeorological Service (Barentsburg research station), AARI	Land	Since 1947	Snow depth (routine measurements) since 1947. Snow-area surveys (surrounding glaciers in Grønfjorden area), since 2002.	Data access on request. Recent snow depth record can be decoded from Barentsburg WMO 20107 SYNOP messages
Pyramiden	AARI	Land, land-fast ice	1948-1957	Snow depth, snow-area surveys	Data access on request.
Central Spitsbergen	UU	Glacier	> 20 years	Snow depth, SWE, ionic composition of annual snow cover	Data access on request.
Hornsund	IG PAS	Glacier	Since 2005	Snow depth	Data accessible via Polish Polar Station Hornsund monitoring database https://monitoring-hornsund.igf.edu.pl
Hornsund	IG PAS	Land	Since 1983	Snow depth, SWE	Data accessible via Polish Polar Station Hornsund monitoring database https://monitoring-hornsund.igf.edu.pl

Hornsund	IG PAS	Land	Since 2014	Snow cover extent (time-lapse camera)	Processed time-lapse imagery for period 2014-2016 accessible via PANGAEA: https://doi.org/10.1594/PANGAEA.874387 Unprocessed imagery accessible via Polish Polar Station Hornsund monitoring database https://monitoring-hornsund.igf.edu.pl
Hornsund	US	Glacier	Since 2008	Snow depth (GPR profiles)	Data accessible via Center for Polar Studies database http://ppdb.us.edu.pl/geonetwork
Longyearbyen	UNIS	Glacier	10 years	Snow depth, SWE	Data access on request.
Longyearbyen	NVE	Land		Snow information related to avalanches (eg. imagery, field reports, snow profiles)	Data accessible via regObs data portal https://www.regobs.no/
Ny-Ålesund	NPI	Land, glacier	10 years	Snow depth, SWE Basal ice on land	Data access on request.
Ny-Ålesund	Met.no	Land	1978-2003	Snow depth	Data accessible via eKlima http://eklima.met.no/
Ny-Ålesund	AWI & others	Land	1998-2017	Snow depth and dielectric properties	Data accessible via PANGAEA https://doi.pangaea.de/10.1594/PANGAEA.880120
Ny-Ålesund	CNR-IDPA	Glacier	Since 2011	Chemical composition of annual snow cover	Data access on request.

Ny-Ålesund	CNR-ISAC	Snow- at-mosphere	Since 2009	Vertical temp profile, Climate Change Tower (CCT)	Data access on request.
Ny-Ålesund	CNR-IIA	Land, glacier	2014-2017	Spectral albedo (CCT)	Data access on request.
Ny-Ålesund	CNR-IIA	Land, glacier	Since 1998	Spectral albedo on snow and ice on Brøggerhalvøya	Data access on request.
Ny-Ålesund	AWI-IPEV/CNRS	Land	Since 2016	Snow depth	Data access on request.
Ny-Ålesund	UiO	Land	2012-2014	Snow cover extent (time-lapse camera)	Processed time-lapse imagery for period 2014-2016 can be accessed via PANGAEA: https://doi.pangaea.de/10.1594/PANGAEA.846617
Svea	Met.no	Land	1974-1979; 2009-2018	Snow depth	Data accessible via eKlima http://eklima.met.no/

Acronyms: AARI: Arctic and Antarctic Research Institute (Russia); IG PAS: Institute of Geophysics, Polish Academy of Sciences; US: University of Silesia; NPI: Norwegian Polar Institute; UU: University of Uppsala; UNIS: University Centre in Svalbard; Met.no: Norwegian Meteorological Institute; NVE: Norwegian Water Resources and Energy Directorate; AWI: Alfred Wegener Institute for Polar and Marine Research; CNR: National Research Council of Italy; which includes IDPA: Institute for the Dynamics of Environmental Processes, ISAC: Institute for Atmospheric Science and Climate, and IIA: Institute for Atmospheric Pollution; IPEV: Institut Polaire Paul-Émile Victor, CNRS: National Research Center; UiO: University of Oslo.

2.2 Snow observation platform and data exchange

Currently several platforms exist for both researchers and the public to share and download snow related data (e.g. RIS, REGOBS, MOSJ or eKlima). However, these platforms are usually oriented towards single disciplines or report already processed data. For example, REGOBS mainly focuses on precipitation related hazards, while MOSJ reports mass balance data calculated from snow accumulation and snow melt data, the actual snow density and depth data are absent. Most snow related data from Svalbard are still stored at a personal, network or institutional level and then only available on request (Table 1). Several research organizations and institutes are planning to establish data bases for this kind of data. A common SOIS driven platform for including data stored elsewhere with the possibility to upload and credit new data sets, would therefore be a large contribution to the snow science community. Such a data portal would also benefit from societal inputs. The citizen driven REGOBS platform is a good example on how the public can be engaged in data collection as it improves avalanche prognosis for the region.

3 Knowledge trends, gaps and research needs

A bibliometric analysis was carried out to identify recent trends and possible knowledge gaps in snow-related research in Svalbard. The analysis was based on a survey of >205 peer-reviewed scientific articles published since Winther *et al.* (2003) last presented an overview of snow research in Svalbard. Figure 1 shows that field studies of snow/snowpack properties since 2003 have mostly been carried out near Ny Ålesund or Longyearbyen. These sectors are disproportionally represented relative to the remainder of the archipelago. Glaciers and lowland tundra environments are equally represented in field studies (~37 % of publications each), while snowpack properties on upland plateaus (above ~750 m a.s.l.) and on wetlands are, by comparison poorly studied. This reflects the predominance of glaciological and phenological research in the surveyed publications. Since the Winther *et al.* (2003) review, several new areas of snow-related research have also emerged, notably on snow-atmosphere and snow-soil chemical exchanges, and on microbial communities in snow (up to 5 times more publications between 2003-2018, relative to 1989-2003).

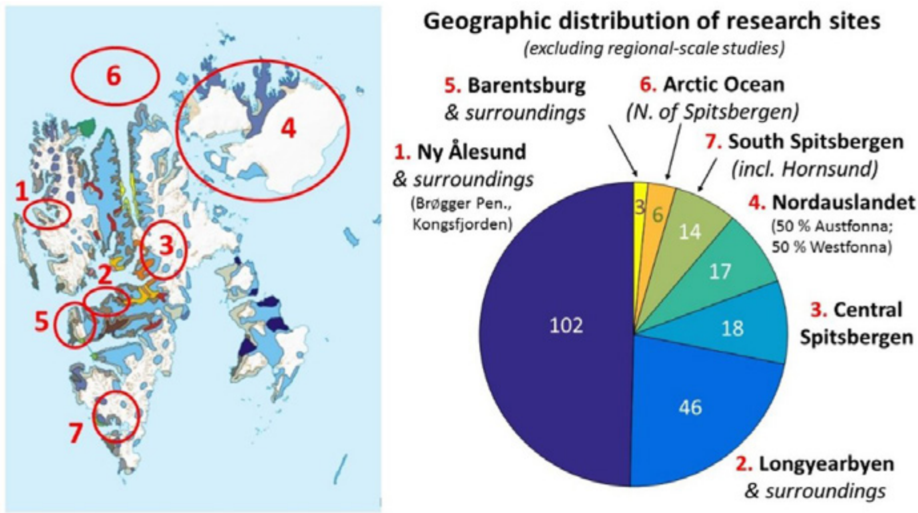

Figure 1: Spatial coverage of snow/snowpack studies in Svalbard published since 2003 (n = 205). Most studies were carried in one of 7 geographic sectors, the Ny Ålesund and Longyearbyen sectors being the most represented.

Based on this survey, and on a review of published literature, several knowledge gaps were identified that are recommended as priority targets for future monitoring-related activities in Svalbard. These gaps mainly relate to snow spatial variability on glaciers and tundra, the role of snow cover on terrestrial ecology, and the impacts, cycling and fate of snow contaminants. Although the N-ICE2015 expedition recently carried out extensive observations on the snow cover of sea ice north of Svalbard (e.g., Merkouriadi et al., 2017a,b), this aspect is not considered hereafter because sea-ice cover has been declining in Svalbard. This renders the development of regular snow-monitoring activities in this environment problematic (Hansen et al., 2013b).

3.1 Variability of supra-glacial snow cover

Since the snow regime on Svalbard has changed markedly over the past few years (van Pelt et al., 2016a), the development of modelling tools for all Svalbard glaciers requires monitoring data sets that capture both spatial changes in transient snow cover (Rotschky et al., 2011) and vertical changes in snow physical properties. There are particularly critical knowledge gaps in snow spatial variability representing glaciers in the southern, central and the eastern parts of Spitsbergen, for which data are almost completely missing. By contrast, there is a clear bias towards monitoring in West Spitsbergen, where the majority of surface mass balance observation networks are situated (Hagen et al., 2003). Despite the development of new observation techniques like Ground Penetrating Radar (GPR; Dunse et al., 2009), terrestrial laser scanning (Prokop et al, 2016) or satellite remote sensing, and the marked improvement in the modelling tools being applied to the entire Svalbard Archipelago (Aas et al., 2016; Lang et al., 2015; Østby et al., 2017; van Pelt et al., 2016b), field programs for monitoring the snow cover conditions on glaciers are still necessary in order to ground truth their outputs. Indeed, the size and location of the glaciers where regular field measurements are already being undertaken are not always optimal for ground truthing remote sensing products, and atmospheric or geomorphological corrections remain very challenging. Models particularly suffer from a lack of field validation for meteorological forcing (Schuler et al., 2013) and snow water equivalent measurements (i.e. precipitation). When snow contains water and ice lenses with different densities and optical refractive indexes, as frequently observed in Svalbard snow packs, absorption and scattering properties of the snow pack are modified. This has an impact upon the information retrieved using remote sensing and GPR. There is an urgent need to pursue research in this field to better calibrate the newly developed observational techniques (Gray et al., 2015), and in so doing, greatly improve the quality of data representing the entire Svalbard Archipelago.

Two actions that will improve the state of the science mentioned above include: i) undertaking repeat traverses to measure snow properties across larger, remote glaciers with a significant altitudinal range, and ii) the establishment of a denser network of meteorological data collection sites that better represent local conditions and can thus be used to validate or correct the data products used for larger-scale glacier modelling. Automatic weather stations should be deployed at remote targeted glaciers and measurements during the traverses should be sufficient for all important ground truthing purposes, as well as describing the critical physical and chemical properties beneath the snow surface. Defining the exact location is however slightly premature at present, as this should be coordinated with glaciological studies and other relevant groups interested in working in these areas.

3.2 Seasonal snow cover and terrestrial ecology

Observations of snow on bare ground and tundra ecosystems on Svalbard are even more scarce than on glaciers (see Table 1 above), and the spatial distribution of snow is hard to model (Liston, 2004). Consistent observations and simulations of temporal and spatial patterns of snow accumulation (Aalstad et al., 2018; Gisnås et al., 2014, Kępski et al., 2017) and possibly later melt water production are needed to assess climate change influences on terrestrial flora and fauna, as well as permafrost thermal regime. This also involves precipitation sampling (for which procedures are needed with respect to calibration, routines and timing). Melt water penetration in the snow pack and internal refreezing also needs to be improved due to the complexity of the processes involved and also the lack of field data (D'Amboise et al., 2017). The seasonal variability of snow also needs to be assessed, in terms of properties and duration because this sets the length of the potential growing season. Extreme warming events have been observed more frequently in the Arctic recently (Graham et al., 2017; Rinke et al., 2017, Vikhamar-Schuler et al. 2016), with observable effects on the snow pack (Gallet et al., 2017; Merkouriadi et al., 2017a,b), but observations are still limited. Basic snow properties (temperature, density, ice quantity) should be more consistently measured and recorded in standardised formats suitable for modellers. Wet snow processes are very complex and not fully understood, so development of a snow dedicated super-site network should be undertaken.

The variation among species and even among ecotypes as a function of snow amount and type is still poorly understood. For instance, intermittent mild periods and snowmelt during winter may be beneficial for some aspects, like the enhancement of heterotrophic processes and increased nutrient availability (e.g. Morgner et al., 2010), and detrimental for others, like damage and mortality of soil fauna and vegetation (Bokhorst et al., 2011a, b). The extent of wintertime microbial biomass production both within and under the snow pack as well as effect of snow change on the Arctic food chain and nutrient resources are topics that have rarely been studied. Ecosystem changes in the Arctic can be rapid and can directly affect life quality, in the same manner as the amount of contaminants in the snow (Forsström et al., 2009, Stohl 2006, Kühnel et al., 2011), which can also be transferred to the ecosystem (Björkman et al., 2014, Kozak et al., 2015) and the local population.

Actions to be undertaken are to determine the amount of snow and ice on the ground, in addition to basic parameters on the internal structure of the snow (snow hardness for example) in areas where observation of ecosystem parameters are being carried out. Linking the spatial and temporal scale between climate and ecosystem research is a very challenging question. We have to use the existing data, and engage discussion with ecologists in order to determine the best suitable field measuring protocols, and be in cooperation with projects such as COAT (http://www.coat.no/) in Svalbard, which is a part of SIOS.

Determining transfer functions between atmosphere and snow surfaces of aerosols and micro-organisms is a complex task for which field work is essential. Understanding the transfer of aerosols and micro-organisms from the atmosphere to the snow surface requires information on their atmospheric content, their properties, their interactions with clouds, deposition processes as well as post-depositional evolution once deposited on the snow pack. Developing a program to combine these various fields of research is essential and requires that atmospheric and snow bio-physical and chemical researchers collaborate. This is something that can be facilitated through SIOS. A strong atmospheric group is working and developing platforms in Svalbard, especially in Ny-Ålesund. Communication is essential in order to be able to link all research fields, especially in terms of area where the work would be developed, or the potential creation of a super-site where larger group will work together and develop a larger interdisciplinary program. A common platform to better describe and understand the process is necessary, but bearing in mind that protocols, background data, manpower, research facilities (laboratories) and large international expertise is needed.

3.3 Cycling, fate and impacts of contaminants in snow

Because of its relative proximity to the continental land mass, Svalbard is a receptor for long-range contaminants emitted from mid- to high-latitude source regions of Eurasia (Stock et al., 2014; Winiger et al., 2015; Dekhtyareva et al., 2016; Hung et al., 2016; Nawrot et al. 2016). These contaminants include BC, secondary aerosols derived from acidifying gases (SO_x, NO_x), trace metals and also complex, persistent organic pollutants (POPs) sourced from human activities. Emissions of some impurities from natural sources, such as forest fires, are also indirectly affected by anthropogenic climate warming, leading to potential future increases (Stohl et al., 2007; Yittri et al., 2014). Some air contaminants reaching Svalbard, such as BC, are in particulate form which, when deposited in the snowpack, affect its radiative properties (Warren, 1984). Others, such as toxic metals (e.g., Hg) and POPs, are bio-accumulative and can adversely affect the local fauna (e.g, Fenstad et al., 2014; Andersen et al., 2015; Goutte et al., 2015). Local sources of snow cover contamination include dust dispersion from mining activities, fuel and waste incineration, or transport (Eckhart et al., 2013; Abramova et al., 2016; Granberg et al., 2017; Kahn et al., 2017). Presently, many contaminants in air and precipitation are monitored by research installations in Ny Ålesund. There are, however, comparatively few systematic observations elsewhere across the Svalbard Archipelago.

The seasonal snow cover (on land or glaciers) is a convenient sampling medium for air contaminants where air or precipitation sampling is impractical. Knowledge of concentrations in late winter/spring snow is essential to assess the surface radiative impact of BC. For other contaminants, it is the total burden of contaminants in the snow pack prior to spring snowmelt that matters, because this is what can enter soils and waterways upon release by snowmelt. Several studies point to the existence of gradients of contaminant deposition in snow across the Svalbard Archipelago, either due to spatial heterogeneity of air transport patterns, and/or to precipitation gradients and orographic effects (e.g., Beaudon et al., 2013, Vega et al., 2015). Hence for some contaminants, fluxes measured at Ny-Ålesund may not be representative of deposition across the rest of the Archipelago. Also, while some POPs have been measured in snow (e.g,. Kallenborn et al., 2011, Xie et al., 2015, Abramova et al., 2016, Vecciato et al., 2018), the data have been disseminated piecewise, some in journal articles, other in government reports, such that an ensemble view is difficult to grasp. Furthermore, with the exception of a few case studies (e.g. Dommergue et al., 2010, Björkman et al., 2014), the fate of contaminants, once deposited in snow, remains poorly known. Finally, there is a growing recognition that biogeochemical transformations in the snow pack itself can impact the fate of contaminants deposited in snow, but the nature of these interactions is under-studied (e.g. Hodson et al, 2010; Larose et al., 2013a,b).

In view of the above, a set of research goals to be pursued in future snow research on Svalbard are: (1) better define and quantify regional gradients of contaminant deposition and accumulation in seasonal snow packs across the Svalbard archipelago; (2) identify the meteorological conditions (and other factors) that account for inter annual variations in contaminant accumulation in snow in different geographical parts of the archipelago; (3) determine the fate of contaminants in the seasonal snow pack by quantifying the fractions that actually enter soils and waterways upon snowmelt; (4) establish how future changes in snow cover phenology (e.g., rate of accumulation, frequency of winter thaws, timing of spring melt) will impact the release of contaminants from melting snow; and (5) investigate interactions between particulate organic matter, microbial communities, and contaminants (such as nitrates, BC or metals) within the snow pack thaw are relevant to the fate of these contaminants.

3.4 Snow, as a constituent in natural hazards and hydrology

Changes in snow temporal and spatial variability have a number of societal impacts on the economy (Bokhurst et al. 2016) including the cost of snow removal (Hanbali, 1994), maintenance and prevention costs of freezing damage infrastructure (Bjerke et al. 2015) and road and structure maintenance costs (Sosnovsky et al. 2014). Changes in the magnitude and timing of spring runoff also impact flood and reservoir management (Popova, 2011, Semenov, 2013). The landscape in Svalbard is high relief, largely without vegetation, with continuous snow cover for most of the year and wide plateaus with deep valleys that allow for snow drifting (Eckerstorfer & Christiansen, 2012). This makes it especially at risk for avalanches with detrimental costs for inhabitants.

Snow avalanche activity, which is often spontaneous but also caused by external loading, is linked to snow variability and weather conditions and their interactions with topography (McClung & Schaerer, 2006). The frequency, magnitude, seasonality, and typology of avalanche events are also variable, which makes them difficult to predict (Schweizer, 1999). Snow avalanches are defined as masses of snow or ice that move rapidly down a sloping surface. To understand their dynamics it is important to understand the processes resulting in the formation, growth, and degradation of snow crystals and how these processes affect the snowpack throughout the winter season (Schweizer et al. 2003). For example, powder snow avalanches generally occur after intense snow precipitation during cold winter conditions (Baggi & Schweizer 2009), while wet and dense flows often coincide with warm spells (Ancey & Bain 2015). The increasingly wetter and milder Arctic climate will likely increase the frequency of avalanches (Eckerstorfer & Christiansen 2012, Qiu, 2014). Increasing air temperature increases the shear deformation rate of snowpacks due to a rise in liquid water content, which favors increased strain at the interface of slab and/or weak layers, and ultimately, the release of wet snow avalanches (Ancey & Bain, 2015). The increase in the liquid water content of snow can also, in some cases, reduce friction once it begins moving, increasing avalanche runout distances (Naaim et al., 2013).

Although relationships between climate and snow avalanches remain unclear due to the general lack of long-term observations (Ballesteros-Cánovas et al., 2018), the ongoing warming and changes in precipitation will likely impact snow avalanche activity. Several actions will improve the state of the science and risk mitigation for hazards related to changes in snow regime: i) the establishment of a denser network of snow monitoring sites near infrastructure that are equipped with seismic sensors and infrasound arrays; ii) the use of radar (e.g. Radarsat-2, TerraSAR-X, and Cosmo-Skymed) to help predict and quantify avalanche events around Svalbard (Caduff et al. 2015); and iii) the establishment of coordinated actions to improve risk management of snow avalanches and disaster risk policies.

4 Summary and other suggestions

With respect to the above-mentioned gaps, we collected the crucial missing information regarding snow research in Svalbard and provide some recommendations on how to improve it in the frame of SIOS. The recommendations are listed in three main research thematic areas: snow on glaciers, snow on land and snow-atmosphere interactions, plus a last section regarding other strategic topics. Certainly more themes could be listed but these are the ones where current data have already been collected and monitoring programs are ongoing.

Supra-glacial snow coverage

1. Improve the spatial resolution of glaciers being monitored to include glaciers from central and eastern Svalbard. Set up glacier monitoring programs that engage with future and early career snow scientists (e.g. at Slakbreen).
2. Based on the traverse organized in Spring 2018, we can use existing infrastructure (e.g. Pyramiden, Barentsburg as science polygons of Russian Science Centre on Svalbard - RSCS) as a base to carry out glacier measurements, store and prepare samples to be sent to Longyearbyen or Barentsburg (chemical-analytic laboratory of RSCS) for analysis. The advantage is better safety, shorter field days and access to the central part of Svalbard.
3. Focus more on snow melt (including inside layer radiation melting), even during winter, and better quantify the ice amount in snow packs.
4. Utilize/develop new tools to better quantify wet snow properties, with a focus on remote sensing and model validation.

Seasonal snow on land

1. Promote scientific exchange among users of different research infrastructures.
2. Promote interdisciplinarity that links soil, snow and atmospheric research, and the effect of snow on biodiversity.
3. Funding for year-round monitoring commitments.
4. Using common and merged protocols to simplify field sampling but able to fulfil the goals.
5. Establish 2 to 3 super-sites with a holistic approach with measurements from the ground to the atmosphere throughout the year. This is logistically only possible on land, but would be more than interesting in bringing knowledge on winter snow conditions in Svalbard. Only permanently and annually functioning sites can then be concerned.

Impacts, cycling and fate of contaminants in snow

1. Need for coordinated studies of snow cover contamination at multiple sites across Svalbard, using standardized protocols and laboratory facilities.
2. SIOS can assist by being a central repository and clearing house for relevant data on snow properties measured across the archipelago.
3. Develop improved logistical solutions for transporting field samples to Longyearbyen or Barentsburg when specialized measurements cannot be performed in the field or at local field stations.
4. Promote catchment-scale studies (where feasible) that address the issue of the fate of contaminants released by snow melt.
5. Foster a closer cooperation and integration between the aerosol research community (largely focused Ny Ålesund) and the broader snow research community across Svalbard.

Other suggestions

Networking: in order to improve long term monitoring and also coverage, more nations working in Svalbard should be part of SIOS. SIOS could be a tool for improving communication among researchers by facilitating and organizing interdisciplinary snow workshops and by establishing working groups and programs. By focusing on programs with specific research focus in targeted areas, SIOS could enrol institutes and nations that have not been working much or at all together before, and create a synergy.

Snow data exchange platform: should be facilitated through SIOS and this is one of the main goals. However, beforehand discussion on data sharing and format would be recommended due to the different timing, type, geographical location and vertical structure of the snow data sets that could exist. Suggestions should be provided by SIOS. Data sets should include at least the type of the temporal resolution of the data of the most vital interest for a start for the SIOS project (depth, density, SWE and temperature). The data present in the exchange platforms, which is to be used by the entire research community, should be accessible in English.

Improve involvement: Involve UNIS and students from Norwegians Universities (as well from Europe and Russia) in basic snow and glacier monitoring programs (ex. April glaciology course with GPR and SWE, chemistry, microbiology, winter or summer field school on base of RSCS): SIOS would help in transferring knowledge, form the next generation of polar researchers, and make good use of the collected data for master and PhD students at UNIS, and by also helping researchers to use and publish the collected data.

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