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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 photochem-

istry of organic compounds stored in the snowpack leads to volatile organic compound (VOC) production (i.e. CO_2 , CHCl_3 , $(\text{CH}_3)_2\text{S}$, 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 (Vikhmar-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 (Etzel Müller 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 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 accumulated 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
			<i>(Time coverage may differ for various snow properties)</i>		
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- atmosphere	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/

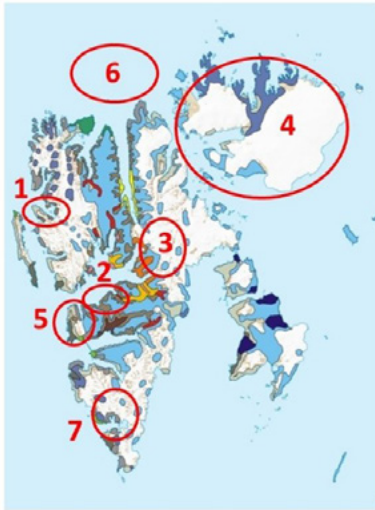
Acronyms: AARI: Arctic and Antarctic Research Institute (Russia); IG PAS: Institute of Geophysics, Polish Academy of Sciences; US: University of Silesia; NPI: Norwegian Polar Institute; UU: University of Uppsala; UNIS: University Centre in Svalbard; Met.no: Norwegian Meteorological Institute; NVE: Norwegian 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 disproportionately 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).



Geographic distribution of research sites
(excluding regional-scale studies)

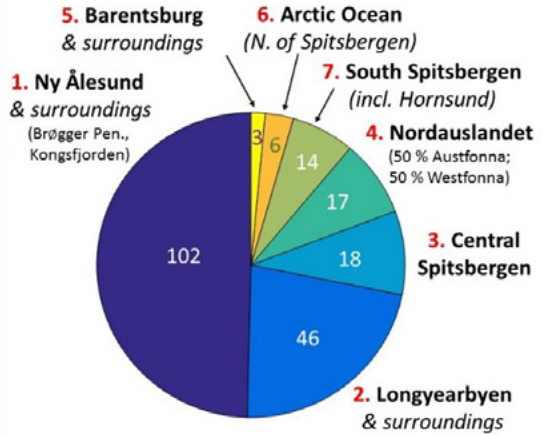


Figure 1: Spatial coverage of snow/snowpack studies in Svalbard published since 2003 (n = 205). Most studies were carried in one of 7 geographic sectors, the Ny Ålesund and Longyearbyen sectors being the most represented.

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; Gislås 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; Merkouridi 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 piecemeal, 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 (Ancy & 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 (Ancy & 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 Norwegian 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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References

- Aalstad, K., Westermann, S., Schuler, T. V., Boike, J., & Bertino, L. (2018). Ensemble-based assimilation of fractional snow-covered area satellite retrievals to estimate the snow distribution at Arctic sites. *The Cryosphere*, 12(1), 247–270. doi:10.5194/tc-12-247-2018
- Aas, K. S., Dunse, T., Collier, E., Schuler, T. V., Berntsen, T. K., Kohler, J., & Luks, B. (2016). The climatic mass balance of Svalbard glaciers: a 10-year simulation with a coupled atmosphere–glacier mass balance model. *The Cryosphere*, 10(3), 1089–1104. doi:10.5194/tc-10-1089-2016.
- Abramova, A., Chernianskii, S., Marchenko, N. and Terskaya, E. (2016) Distribution of polycyclic aromatic hydrocarbons in snow particulates around Longyearbyen and Barentsburg settlements, Spitsbergen. *Polar Record*, 52 (6), 645–659. doi:10.1017/S0032247416000243.
- Aamaas, B., C. E. Bøggild, F. Stordal, T. Berntsen, K. Holmén, J. Ström (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.
- Amoroso, A., Domine, F., Esposito, G., Morin, S., Savarino, J., Nardino, M., et al. (2010). Microorganisms in Dry Polar Snow Are Involved in the Exchanges of Reactive Nitrogen Species with the Atmosphere. *Environmental Science & Technology*, 44(2), 714–719. doi:10.1021/es9027309.
- Andersen, M.S., Fuglei, E., König, M., Lipasti, I., Pedersen, Å. Ø., Polder, A., Yoccoz, N.G., Routti, H. (2015) Levels and temporal trends of persistent organic pollutants (POPs) in arctic foxes (*Vulpes lagopus*) from Svalbard in relation to dietary habits and food availability, *Science of the Total Environment*, 511, 112–122, doi:10.1016/j.scitotenv.2014.12.039.
- Ancey C, Bain V (2015) Dynamics of glide avalanches and snow gliding. *Rev Geophys* 53:745–784.
- Arzel, O., Fichet, T., & Goosse, H. (2006). Sea ice evolution over the 20th and 21st centuries as simulated by current AOGCMs. *Ocean Modelling*, 12(3), 401–415. doi:10.1016/j.ocemod.2005.08.002.
- Baggi S, Schweizer J (2009). Characteristics of wet-snow avalanche activity: 20 years of observations from a high alpine valley (Dischma, Switzerland). *Nat Hazards* 50:97–108.
- Ballesteros-Cánovas, J. A., Trappmann, D., Madrigal-González, J., Eckert, N., Stoffel, M. (2018). Climate warming enhances snow avalanche risk in the Western Himalayas, *Proceedings of the National Academy of Sciences* Mar 2018, 115 (13) 3410–3415; DOI:10.1073/pnas.1716913115
- Bazzano, A., Cappelletti, D., Udisti, R., Grotti, M. (2016) Long-range transport of atmospheric lead reaching Ny-Ålesund: Inter-annual and seasonal variations of potential source areas. *Atmospheric Environment*, 139, 11–19, doi: 10.1016/j.atmosenv.2016.05.026.
- Beaudon, E., Moore, J.C., Martma, T., Pohjola, V.A., Van De Wal, R.S.W., Kohler, J., Isaksson, E. (2013) Lomonosovfonna and Holtedahlfonna ice cores reveal east-west disparities of the Spitsbergen environment since AD 1700, *Journal of Glaciology*, 59 (218), 1069–1083, doi:10.3189/2013JoG12J203.
- Bjerke JW, Tømmervik H, Zielke M, Jørgensen M. Impacts of snow season on ground-ice accumulation, soil frost and primary productivity in a grassland of sub-Arctic Norway. *Environmental Research Letters*. 2015;10:095007. doi: 10.1088/1748-9326/10/9/095007.
- Björkman, M.P., Zarsky, J.D., Kühnel, R., Hodson, A., Sattler, B. and Psenner, R., 2014. Microbial cell retention in a melting High Arctic snowpack, Svalbard. *Arctic, Antarctic, and Alpine Research*, 46(2), pp.471–482.
- Boike, J., Juszak, I., Lange, S., Chadburn, S., Burke, E., Overduin, P.P., Roth, K., Ippisch, O., Bornemann, N., Stern, L., Gouttevin, I., Hauber, E., Westermann, S. (2018): A 20-year record (1998–2017) of permafrost, active layer and meteorological conditions at a high Arctic permafrost research site (Bayelva, Spitsbergen). *Earth System Science Data*, 10(1), 355–390, doi:10.5194/essd-10-355-2018.
- Bokhorst S., Bjerke J. W., Street L. E. Callaghan T. V. and Phoenix G. K. (2011a). Impacts of multiple extreme winter warming events on sub-Arctic heathland: phenology, reproduction, growth, and CO2 flux responses. *Global Change Biology* 17(9). 2817–2830.
- Bokhorst S., Phoenix G. K., Bjerke J. W., Callaghan T. V., Huyer-Brugman F. and Berg M. P. (2011b). Extreme winter warming events more negatively impact small rather than large soil fauna: shift in community composition explained by traits not taxa. *Global Change Biology* 18(3). 1152–1162.

- Bokhorst, S., Pedersen, S. H., Brucker, L., Anisimov, O., Bjerke, J. W., Brown, R. D., Ehrich, D., Essery, R. L., Heilig, A., Ingvander, S., Johansson, C., Johansson, M., Jónsdóttir, I. S., Inga, N., Luoju, K., Macelloni, G., Mariash, H., McLennan, D., Rosqvist, G. N., Sato, A., Savela, H., Schneebeli, M., Sokolov, A., Sokratov, S. A., Terzago, S., Vikhamar-Schuler, D., Williamson, S., Qiu, Y., Callaghan, T. V. (2016). Changing Arctic snow cover: A review of recent developments and assessment of future needs for observations, modelling, and impacts. *Ambio*, 45(5), 516–37.
- Box, J. E., Fettweis, X., Stroeve, J. C., Tedesco, M., Hall, D. K., & Steffen, K. (2012). Greenland ice sheet albedo feedback: thermodynamics and atmospheric drivers. *The Cryosphere*, 6(4), 821–839. doi:10.5194/tc-6-821-2012
- Brooks P. D., Williams M. W. and Schmidt S. K. (1996). Microbial activity under alpine snowpacks, Niwot Ridge, Colorado. *Biogeochemistry* 32(2), 93–113.
- Caduff R, Wiesmann A, Bühler Y, Pielmeier C. Continuous monitoring of snowpack displacement at high spatial and temporal resolution with terrestrial radar interferometry. *Geophysical Research Letters*. 2015;42:813–820. doi: 10.1002/2014GL062442.
- Christianson, K., Kohler, J., Alley, R. B., Nuth, C., & van Pelt, W. J. J. (2015). Dynamic perennial firn aquifer on an Arctic glacier. *Geophysical Research Letters*, 42(5), 1418–1426. doi:10.1002/2014GL062806
- Cooper, E.J., Dullinger, S., Semenchuk, P. (2011). Late snowmelt delays plant development and results in lower reproductive success in the High Arctic. *Plant Science*, 180(1), 157–167, doi:10.1016/j.plantsci.2010.09.005.
- D'Amboise, C. J. L., Müller, K., Oxarango, L., Morin, S., & Schuler, T. V. (2017). Implementation of a physically based water percolation routine in the Crocus/SURFEX (V7.3) snowpack model. *Geosci. Model Dev.*, 10(9), 3547–3566. doi:10.5194/gmd-10-3547-2017
- Dekhtyareva, A., Edvardsen, K., Holmén, K., Hermansen, O., Hansson, H.-C. (2016) Influence of local and regional air pollution on atmospheric measurements in Ny-Ålesund, *International Journal of Sustainable Development and Planning*, 11 (4), 578–587, doi: 10.2495/SDP-V11-N4-578-587.
- Domine, F., & Shepson, P. B. (2002). Air-snow interactions and atmospheric chemistry. *Science*, 297(5586), 1506–1510.
- Domergue, A., Larose, C., Faïn, X., Clarisse, O., Foucher, D., Hintelmann, H., Schneider, D. and Ferrari, C.P. (2010) Deposition of mercury species in the Ny-Ålesund area (79°N) and their transfer during snowmelt. *Environmental Science and Technology*, 44 (3), 901–907. doi:10.1021/es902579m.
- Dunse, T., Schuler, T. V., Hagen, J. O., Eiken, T., Brandt, O., & Høgda, K. A. (2009). Recent fluctuations in the extent of the firn area of Austfonna, Svalbard, inferred from GPR. *Annals of Glaciology*, 50(50), 155–162. doi:10.3189/172756409787769780.
- Eckhardt, S., Hermansen, O., Grythe, H., Fiebig, M., Stebel, K., Cassiani, M., Baecklund, A., Stohl, A. (2013) The influence of cruise ship emissions on air pollution in Svalbard – A harbinger of a more polluted Arctic? *Atmospheric Chemistry and Physics*, 13 (16), 8401–8409, doi:10.5194/acp-13-8401-2013.
- Eckerstorfer, M., & Christiansen, H. H. (2011). Topographical and meteorological control on snow avalanching in the Longyearbyen area, central Svalbard 2006–2009. *Geomorphology*, 134(3–4), 186–196.
- Eckerstorfer, M., & Christiansen, H. H. (2012). Meteorology, topography and snowpack conditions causing two extreme mid-winter slush and wet slab avalanche periods in High Arctic maritime Svalbard. *Permafrost and Periglacial Processes*, 23(1), 15–25, doi:10.1002/ppp.734
- Eckerstorfer, M., Farnsworth, W.R., Birkeland, K.W. (2014). Potential dry slab avalanche trigger zones on wind-affected slopes in central Svalbard. *Cold Regions Science and Technology*, 99, 66–77, doi:10.1016/j.coldreg.201312.005.
- Eeg-Henriksen, F., Sjømæling, E. (2016). *This is Svalbard 2016: What the figures say*, Statistics Norway, Statistisk sentralbyrå
- Etzelmüller, B., Schuler, T. V., Isaksen, K., Christiansen, H. H., Farbot, H., & Benestad, R. (2011). Modeling the temperature evolution of Svalbard permafrost during the 20th and 21st century. *The Cryosphere*, 5(1), 67–79. doi:10.5194/tc-5-67-2011.
- Fenstad, A.A., Jenssen, B.M., Gabrielsen, K.M., Öst, M., Jaatinen, K. et al. (2016) Persistent organic pollutant levels and the importance of source proximity in Baltic and Svalbard breeding common eiders, *Environmental Toxicology and Chemistry*, 35 (6), 1526–1533, doi:10.1002/etc.3303.
- Fernández-Méndez, M., Olsen, L. M., Kauko, H. M., Meyer, A., Rösel, A., Merkouridi, I., et al. (2018). Algal Hot Spots in a Changing Arctic Ocean: Sea-Ice Ridges and the Snow-Ice Interface. *Frontiers in Marine Science*, 5. https://doi.org/10.3389/fmars.2018.00075
- Forsstrom, S., Strom, J., Pedersen, C. A., Isaksson, E., & Gerland, S. (2009). Elemental carbon distribution in Svalbard snow. *Journal of Geophysical Research-Atmospheres*, 114. doi:10.1029/2008jd011480
- Forland, E. J., R. Benestad, I. Hanssen-Bauer, J. E. Haugen and T. E. Skaugen (2011). "Temperature and Precipitation Development at Svalbard 1900–2100." *Advances in Meteorology* **2011**: 14.

- Gallet, J.-C., Merkouriadi, I., Liston, G. E., Polashenski, C., Hudson, S., Rösel, A., & Gerland, S. (2017). Spring snow conditions on Arctic sea ice north of Svalbard, during the Norwegian young sea ICE (N-ICE2015) expedition: Spring snow conditions on Arctic sea ice. *Journal of Geophysical Research: Atmospheres*. doi:10.1002/2016JD026035
- Gisnås, K., Westermann, S., Schuler, T. V., Litherland, T., Isaksen, K., Boike, J., & Etzelmüller, B. (2014). A statistical approach to represent small-scale variability of permafrost temperatures due to snow cover. *The Cryosphere*, 8(6), 2063–2074. doi:10.5194/tc-8-2063-2014.
- Goutte, A., Barbraud, C., Herzke, D., Bustamante, P., Angelier, F. et al. (2015) Survival rate and breeding outputs in a high Arctic seabird exposed to legacy persistent organic pollutants and mercury. *Environmental Pollution*, 200, 1-9, doi: 10.1016/j.envpol.2015.01.033.
- Graham, R. M., Cohen, L., Petty, A. A., Boisvert, L. N., Rinke, A., Hudson, S. R., et al. (2017). Increasing frequency and duration of Arctic winter warming events: Arctic Winter Warming Events. *Geophysical Research Letters*, 44(13), 6974–6983. doi:10.1002/2017GL073395
- Granberg, M. A., Ask, A. and Gabrielsen, G.W. (2017) *Local contamination in Svalbard: Overview and suggestions for remediation actions*. Tromsø: Norsk Polarinstitutt, Brief Report 44, 48 p.
- Grannas, A. M., Jones, A. E., Dibb, J., Ammann, M., Anastasio, C., Beine, H. J., et al. (2007). An overview of snow photochemistry: evidence, mechanisms and impacts. *Atmospheric Chemistry and Physics*, 7, 4329–4373.
- Gray, L., Burgess, D., Copland, L., Demuth, M. N., Dunse, T., Langley, K., & Schuler, T. V. (2015). CryoSat-2 delivers monthly and inter-annual surface elevation change for Arctic ice caps. *The Cryosphere*, 9(5), 1895–1913. doi:10.5194/tc-9-1895-2015
- Hagen, J. O., Melvold, K., Pinglot, F., & Dowdeswell, J. A. (2003). On the Net Mass Balance of the Glaciers and Ice Caps in Svalbard, Norwegian Arctic. *Arctic, Antarctic, and Alpine Research*, 35(2), 264–270. doi:10.1657/1523-0430(2003)035[0264:OTNMBO]2.0.CO;2
- Hanbali RM. Economic impact of winter road maintenance on road users. *Transportation Research Record*. 1994;1442:151–161.
- Hancock, H., Prokop, A., Eckerstorfer, M., Hendrikx, J. (2018). Combining high spatial resolution snow mapping and meteorological analyses to improve forecasting of destructive avalanches in Longyearbyen, Svalbard. *Cold Regions Science and Technology*, 154, 120–132. https://doi.org/10.1016/j.coldregions.2018.05.011.
- Hansen, B. B., Aanes, R., Herfndal, I., Kohler, J., & Saether, B. E. (2011). Climate, icing, and wild arctic reindeer: past relationships and future prospects. *Ecology*, 92(10), 1917–1923.
- Hansen, B. B., Groten, V., Aanes, R., Saether, B. E., Stien, A., Fuglei, E., et al. (2013a). 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, E., Gerland, S., Granskog, M. A., Pavlova, O., Renner, A. H. H., Haapala, J., et al. (2013b). Thinning of Arctic sea ice observed in Fram Strait: 1990–2011. *Journal of Geophysical Research: Oceans*, 118(10), 5202–5221. https://doi.org/10.1002/jgrc.20393
- Hodgkins, R., Hagen, J. O., & Hamran, S.-E. (1999). 20th century mass balance and thermal regime change at Scott Turnerbreen, Svalbard. *Annals of Glaciology*, 28, 216–220. doi:10.3189/172756499781821986
- Hodson, A. J., Mumford, P. N., Kohler, J., & Wynn, P. M. (2005). The High Arctic glacial ecosystem: new insights from nutrient budgets. *Biogeochemistry*, 72(2), 233–256. doi:10.1007/s10533-004-0362-0.
- Hodson, A., Roberts, T.J., Engvall, A.C., Holmén, K. and Mumford, P. (2010) Glacier ecosystem response to episodic nitrogen enrichment in Svalbard, European High Arctic. *Biogeochemistry*, 98(1-3), pp.171-184.
- Hung, H., Katsoyiannis, A.A., Brorström-Lundén, E., Olafsdottir, K., Aas, W. et al. (2016) Temporal trends of Persistent Organic Pollutants (POPs) in Arctic air: 20 years of monitoring under the Arctic Monitoring and Assessment Programme (AMAP) (2016) *Environmental Pollution*, 217, 52–61, doi: 10.1016/j.envpol.2016.01.079.
- Instanes, A. (2016) Incorporating climate warming scenarios in coastal permafrost engineering design – Case studies from Svalbard and northwest Russia, *Cold Regions Science and Technology*, 131, 76–87, http://dx.doi.org/10.1016/j.coldregions.2016.09.004
- Instanes, A., V. Kokorev, R. Janowicz, O. Bruland, K. Sand, and T. Prowse (2016), Changes to freshwater systems affecting Arctic infrastructure and natural resources, *Journal of Geophysical Research - Biogeosciences*, 121, 567–585, doi:10.1002/2015JG003125.

- Irvine Fynn, T. D. L., Hodson, A. J., Moorman, B. J., Vatne, G., & Hubbard, A. L. (2011). POLYTHERMAL GLACIER HYDROLOGY: A REVIEW. *Reviews of Geophysics*, 49(4). doi:10.1029/2010RG000350
- Ivanov B.V., Svyashchennikov P.N. (2015). Albedo of the snow-glacier surface of Svalbard. *Atmosphere and Oceanic Physics, Issue of RAS*, 51 (9), pp. 943-948. <https://link.springer.com/journal/11485>
- DOI: 10.1134/S0001433815090108
- Ivanov B.V., Sviashchennikov P.N., Zhuravskiy D.M., Pavlov A.K., Førland E.J. and Isaksen K. (2014). Sea ice metadata for Billefjorden and Grønfjorden, Svalbard. *Czech Polar Reports*, 4(2), 1129-139 pp. <http://www.sci.muni.cz/CPR/>
- Jacobi, H.-W., Morin, S., & Bottenheim, J. W. (2010). Observation of widespread depletion of ozone in the springtime boundary layer of the central Arctic linked to mesoscale synoptic conditions. *Journal of Geophysical Research: Atmospheres*, 115(D17). doi:10.1029/2010JD013940.
- Jones, H.G., 1991. *Snow chemistry and biological activity: a particular perspective on nutrient cycling*. In: Seasonal Snowpacks (pp. 173-228). Berlin: Springer.
- Kallenborn, R., Ottesen, R.T., Gabrielsen, G.W., Schrum, C., Evensen, A., Ruus, A., Benjaminsen, H., Sagerup, K., Christensen, G., Eggen, O., Carlsson, P., Johansson-Karlsson, E., Polder, A., Pedersen, H.R. & Lundkvist, Q. (2011) *PCBs on Svalbard 2011: Status of Knowledge and Management*, Longyearbyen, Office of the Governor of Svalbard, 99 p.
- Kępski, D., Luks, B., Migąła, K, Wawrzyniak, T., Westermann, S., Wojtuń, B. (2017). Terrestrial remote sensing of snowmelt in a diverse high-arctic tundra environment using time-lapse imagery, *Remote Sensing*, 9(7), 733, doi:10.3390/rs9070733.
- Khan, A.L., Dierssen, H., Schwarz, J.P., Schmitt, C., Chlus, A., Hermanson, M., Painter, T.H. and McKnight, D.M. (2017) Impacts of coal dust from an active mine on the spectral reflectance of arctic surface snow in Svalbard, Norway. *Journal of Geophysical Research*, 122 (3), 1767-1778, doi:10.1002/2016JD025757.
- Kozak, K., Kozioł, K., Luks, B., Chmiel, S., Ruman, M., Marć, M., Namieśnik, J and Polkowska, Ż. (2015). The role of atmospheric precipitation in introducing contaminants to the surface waters of the Fuglebekken catchment, Spitsbergen. *Polar Research*, 34, 24207.
- Kuhn, M. (2001) The nutrient cycle through snow and ice, a review. *Aquatic Sciences*, 63(2), pp.150-167.
- Kühnel, R., Roberts, T. J., Björkman, M. P., Isaksson, E., Aas, W., Holmén, K. and Ström, J. (2011). 20-Year Climatology of NO₃⁻ and NH₄⁺ Wet Deposition at Ny-Ålesund, Svalbard. *Advances in Meteorology* (2011) doi:10.1155/2011/406508.
- Kylling, A., Groot Zwaaftink, C. D., & Stohl, A. (2018). Mineral dust instantaneous radiative forcing in the Arctic. *Geophysical Research Letters*, 45, 4290–4298, doi:10.1029/2018GL077346.
- Lang, C., Fettweis, X., & Ericpicum, M. (2015). Stable climate and surface mass balance in Svalbard over 1979-2013 despite the Arctic warming. *The Cryosphere*, 9(1), 83–101. doi:10.5194/tc-9-83-2015.
- Larose, C., Dommergue, A. and Vogel, T.M. (2013b) Microbial nitrogen cycling in Arctic snowpacks. *Environmental Research Letters*, 8 (3), art. no. 035004, doi:10.1088/1748-9326/8/3/035004.
- Larose, C., Prestat, E., Cecillon, S., Berger, S., Malandain, C., Lyon, D., et al. (2013a). Interactions between snow chemistry, mercury inputs and microbial population dynamics in an Arctic snowpack. *PLoS ONE*, 8(11). doi:10.1371/journal.pone.0079972.
- Larose, C., Berger, S., Ferrari, C., Navarro, E., Dommergue, A., Schneider, D. and Vogel, T.M. (2010) Microbial sequences retrieved from environmental samples from seasonal Arctic snow and meltwater from Svalbard, Norway. *Extremophiles*, 14(2), pp.205-212.
- Laska, M., Luks, B., Budzik, T. (2016). Influence of snowpack internal structure on snow metamorphism and melting intensity on Hansbreen, Svalbard *Polish Polar Research*, 37, 193-218. doi:10.1515/popore-2016-0012
- Laska, M., Grabiec, M., Ignatiuk, D., Budzik, T., (2017) Snow deposition patterns on southern Spitsbergen glaciers, Svalbard, in relation to recent meteorological conditions and local topography, *Geografiska Annaler: Series A, Physical Geography*, 99(3), 262-287.
- Lemke, P., Ren, J., Alley, R. B., Allison, I., Carrasco, J., Flato, G., et al. (2007). Observations Changes in Snow, Ice and Frozen Ground. In R. K. Pachauri & A. Reisinger (Eds.), *Climate Change 2007: The physical Sciences Basis*. Geneva, Switzerland: IPCC.
- Liston, G. E. (2004). Representing Subgrid Snow Cover Heterogeneities in Regional and Global Models. *Journal of Climate*, 17(6), 1381–1397. doi:10.1175/1520-0442(2004)017<1381:RSSCHI>2.0.CO;2
- Loe, L. E., Hansen, B. B., Stien, A., Albon, S., Bischof, R., Carlsson, A., et al. (2016). Behavioral buffering of extreme weather events in a high-Arctic herbivore. *Ecosphere*, 7(6), e01374.
- Łokas, E., Zaborska, A., Kolicka, M., Różycki, M., Zawierucha, K. (2016) Accumulation of atmospheric radionuclides and heavy metals in cryoconite holes on an Arctic glacier. *Chemosphere*, 160, 162-172, doi:10.1016/j.chemosphere.2016.06.051.

- Maccario, L., Vogel, T. M., & Larose, C. (2014). Potential drivers of microbial community structure and function in Arctic spring snow. *Frontiers in Microbiology*, 5. doi:10.3389/fmicb.2014.00413.
- McClung D., Schaerer, PA (2006) *The Avalanche Handbook* (The Mountaineers Books, Seattle)
- Malnes, E., Eckerstorfer, M., Hindberg, H. & Christiansen, H.H. (2015) Quantification of snow and permafrost properties in a changing climate in Svalbard using satellite-borne and field measurements. 2015 Arctic Frontiers conference, 18-23 January, 2015, Tromsø, Norway.
- Marchenko, S., van Pelt, W. J. J., Claremar, B., Pohjola, V., Pettersson, R., Machguth, H., & Reijmer, C. (2017). Parameterizing Deep Water Percolation Improves Subsurface Temperature Simulations by a Multilayer Firn Model. *Frontiers in Earth Science*, 5. doi:10.3389/feart.2017.00016
- McNeill, V. F., Grannas, A. M., Abbott, J. P. D., Ammann, M., Ariya, P., Bartels-Rausch, T., et al. (2012). Organics in environmental ices: sources, chemistry, and impacts. *Atmos. Chem. Phys.*, 12(20), 9653–9678. doi:10.5194/acp-12-9653-2012
- Merkouriadi, I., Cheng, B., Graham, R. M., Rösel, A., & Granskog, M. A. (2017a). Critical Role of Snow on Sea Ice Growth in the Atlantic Sector of the Arctic Ocean. *Geophysical Research Letters*, 44(20), 2017GL075494. doi:10.1002/2017GL075494
- Merkouriadi, I., Gallet, J. -C., Graham, R. M., Liston G.E., Polashenski, C., Rösel, A., Gerland, S. (2017b). Winter snow conditions on Arctic sea ice north of Svalbard during the Norwegian young sea ICE (N-ICE2015) expedition. *Journal of Geophysical Research: Atmospheres*, 122(20), 10837–10854. doi:10.1002/2017JD026753
- Moller, M., Moller, R., Beaudon, E., Mattila, O.-P., Finkelnburg, R., Braun, M., Grabiec, M., Jonsell, U., Luks, B., Puczko, D., Scherer, D., Schneider, C. (2011). Snowpack characteristics of Vestfonna and De Geerfonna (Nordaustlandet, Svalbard) - a spatiotemporal analysis based on multiyear snow-pit data. *Geografiska Annaler: Series A, Physical Geography* 93, 273–285.
- Montes-Hugo, M., Doney, S. C., Ducklow, H. W., Fraser, W., Martinson, D., Stammerjohn, S. E., & Schofield, O. (2009). Recent changes in phytoplankton communities associated with rapid regional climate change along the western Antarctic Peninsula. *Climate (New York, N.Y.)*, 323(5920), 1470–1473. doi:10.1126/science.1164533
- Morgner E., Elberling B., Strebel D. and Cooper E. J. (2010) The importance of winter in annual ecosystem respiration in the High Arctic: effects of snow depth in two vegetation types. *Polar Research* 29(1), 58–74.
- Morin, S., Savarino, J., Frey, M. M., Yan, N., Bekki, S., Bottenheim, J. W., & Martins, J. M. F. (2008). Tracing the Origin and Fate of NO_x in the Arctic Atmosphere Using Stable Isotopes in Nitrate. *Science*, 322(5902), 730–732. doi:10.1126/science.1161910
- Naaim M, Durand Y, Eckert N, Chambon G (2013) Dense avalanche friction coefficients: Influence of physical properties of snow. *J Glaciol*, 59:771–782.
- Nawrot, A.P., Migala, K., Luks, B., Pakszys, P., Głowacki, P. (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
- Nordli, Ø., R. Przybylak, A. E. J. Ogilvie and K. Isaksen (2014). "Long-term temperature trends and variability on Spitsbergen: the extended Svalbard Airport temperature series, 1898–2012." *Polar Research* 33(1): 21349.
- Opala-Owczarek, M., Pirożnikow, E., Owczarek, P., Szymański, W., Luks, B., Kępski, D., et al. (2018). The influence of abiotic factors on the growth of two vascular plant species (*Saxifraga oppositifolia* and *Salix polaris*) in the High Arctic. *CATENA*, 163, 219–232. <https://doi.org/10.1016/j.catena.2017.12.018>
- Pedersen, C. A., Gallet, J. C., Ström, J., Gerland, S., Hudson, S. R., Forsström, S., et al. (2015). In situ observations of black carbon in snow and the corresponding spectral surface albedo reduction. *Journal of Geophysical Research: Atmospheres*, 120(4), 1476–1489. <https://doi.org/10.1002/2014JD022407>
- Phoenix, G. K., & Bjerke, J. W. (2016). Arctic browning: extreme events and trends reversing arctic greening. *Global Change Biology*, n/a-n/a. <https://doi.org/doi:10.1111/gcb.13261>
- Pomeroy, J. W. (2001). *An Interdisciplinary Examination of Snow-Covered Ecosystems* (H.G. Jones D.A. Walker and R.W. Hoham, J. W. P.). Cambridge University Press.
- Pomeroy, J.W., Gray, D.M., Shook, K.R., Toth, B., Essery, R.L.H., Pietroniro, A., Hedström, N. (1998). An evolution of snow accumulation and ablation processes for land surface modelling. *Hydrological Processes*, 12, 2339–2367
- Popova VV., 2011. The snow storage contribution in major changes of river runoff in the Arctic Ocean drainage basin during the current warming period. *Ice and Snow*, 51:69–78.
- Prokop, A., Friedt, J.-M., Enzenhofer, U., Tolle, F. (2016). *Back Calculation of Avalanche Dimensions From Laser Scanning and sfm Photogrammetry*. Proceedings of International Snow Science Workshop 2016 Proceedings, Breckenridge, CO, USA.

- Qiu J. (2014). Avalanche hotspot revealed. *Nature*. 509:142–143. doi:10.1038/509142a.
- Rinke, A., Maturilli, M., Graham, R. M., Matthes, H., Handorf, D., Cohen, L., et al. (2017). Extreme cyclone events in the Arctic: Wintertime variability and trends. *Environmental Research Letters*, 12(9), 094006. doi:10.1088/1748-9326/aa7def
- Rotschky, G., Vikhamar Schuler, T., Haarpaintner, J., Kohler, J., & Isaksson, E. (2011). Spatio-temporal variability of snowmelt across Svalbard during the period 2000–08 derived from QuikSCAT/SeaWinds scatterometry. *Polar Research*, 30(1), 5963. doi:10.3402/polar.v30i01.5963.
- Ryan, J.C., Hubbard, A., Stibal, M., Irvine-Fynn, T.D., Cook, J., Smith, L.C., Cameron, K. & Box, J. (2018) Dark zone of the Greenland Ice Sheet controlled by distributed biologically-active impurities. *Nature Communications* 9, 1065. doi: 10.1038/s41467-018-03353.
- Sauter, T., M. Möller, R. Finkelnburg, M. Grabiec, D. Scherer and C. Schneider (2013). Snowdrift modelling for the Vestfonna ice cap, north-eastern Svalbard. *The Cryosphere*, 7 (4), 1017–1314.
- Schäfer, M., Zwinger, T., Christoffersen, P., Gillet-Chaulet, F., Laakso, K., Pettersson, R., Pohjola, V. A., Strozzzi, T., and Moore, J. C. (2012). Sensitivity of basal conditions in an inverse model: Vestfonna ice cap, Nordaustlandet/Svalbard, *The Cryosphere*, 6, 771–783, doi:10.5194/tc-6-771-2012.
- Schimel p. J., Bilbrough C. And Welker J. M. (2004). Increased snow depth affects microbial activity and nitrogen mineralization in two Arctic tundra communities. *Soil Biology and Biochemistry* 36(2), 217–227.
- Schuler, T.V., Dunse, T., Østby, T.I., Hagen, J. O. (2013). Meteorological conditions on an Arctic ice cap—8 years of automatic weather station data from Austfonna, Svalbard. *International Journal of Climatology*, 34(6), 2047–2058. doi:10.1002/joc.3821
- Schweizer, J., J. B. Jamieson, and M. Schneebeli, (2003). Snow avalanche formation. *Rev. Geophys.*, 41(4), 1016, doi:10.1029/2002RG000123.
- Schweizer J (1999). Review of dry snow slab avalanche release. *Cold Reg Sci Technol* 30:43–57.
- Semenchuk, P.R., Elberling, B., Cooper, E.J. (2013). Snow cover and extreme winter warming events control flower abundance of some, but not all species in high arctic Svalbard, *Ecology and Evolution*, 3(8), 2045–7758, doi:10.1002/ece3.648
- Semenov VA. (2013). Climate-related change of snow contribution in the development of dangerous hydrological phenomena on rivers. *Ice and Snow*. 53:107–112.
- Shevnina, E., Kourzeneva, E., Kovalenko, V. and Vihma, T. (2017) Assessment of extreme flood events in a changing climate for a long-term planning of socio-economic infrastructure in the Russian Arctic. *Hydrology and Earth System Science*, 21, 2559–2578, doi:10.5194/hess-21-2559-2017.
- Simpson, W. R., Carlson, D., Honninger, G., Douglas, T. A., Sturm, M., Perovich, D., & Platt, U. (2007). First-year sea-ice contact predicts bromine monoxide (BrO) levels at Barrow, Alaska better than potential frost flower contact. *Atmospheric Chemistry and Physics*, 7, 621–627.
- Sobota, I. (2017). Selected problems of snow accumulation on glaciers during long-term studies in north-western Spitsbergen, Svalbard. *Geografiska Annaler: Series A, Physical Geography*, 99(2), 177–192. doi:10.1080/04353676.2017.1297679
- Sosnovsky AV, Nakalov PR, Nenashev SV. (2014). Physical-geographical aspects of formation of artificial firn-ice massives. *Ice and Snow*. 54:113–119.
- Spolaor, A., Vallenga, P., Gabrieli, J., Martma, T., Björkman, M. P., Isaksson, E., et al. (2014). Seasonality of halogen deposition in polar snow and ice. *Atmospheric Chemistry and Physics*, 14(18), 9613–9622. doi:10.5194/acp-14-9613-2014.
- Stien, A., Loe, L. E., Mysterud, A., Severinsen, T., Kohler, J., & Langvatn, R. (2010). Icing events trigger range displacement in a high-arctic ungulate. *Ecology*, 91(3), 915–920. doi:10.1890/09-0056.1
- Stien, A., Ims, R. A., Albon, S. D., Fuglei, E., Irvine, R. J., Ropstad, E., et al. (2012). Congruent responses to weather variability in high arctic herbivores. *Biology Letters*, 8(6), 1002–1005. doi:10.1098/rsbl.2012.0764.
- Stock, M., Ritter, C., Aaltonen, V., Aas, W., Handorf, D., Herber, A., Treffeisen, R., Dethloff, K. (2014) Where does the optically detectable aerosol in the European arctic come from? *Tellus, Series B: Chemical and Physical Meteorology*, 66 (1), art. no. 21450, doi: 10.3402/tellusb.v66.21450.
- Stohl, A. (2006) Characteristics of atmospheric transport into the Arctic troposphere. *Journal of Geophysical Research* (111) D11306, doi:10.1029/2005JD006888.
- Stohl, A., Berg, T., Burkhart, J.F., Fjæraa, A.M., Forster, C., Herber, A. et al. (2007) Arctic smoke - Record high air pollution levels in the European Arctic due to agricultural fires in Eastern Europe in spring 2006, *Atmospheric Chemistry and Physics*, 7 (2), 511–534.

- Sturm, M., Holmgren, J., König, M., & Morris, K. (1997). The thermal conductivity of seasonal snow. *Journal of Glaciology*, 43(143), 26–41.
- Sviashchennikov P.N., Ivanov B.V. and Govorina I.A. (2014). Environmental pollution impact on radiation properties of atmosphere, snow and ice cover: Study from Barentsburg (Spitsbergen archipelago). *Czech Polar Reports*, 4(2), 178–184 pp. <http://www.sci.muni.cz/CPR/>
DOI: 10.5817/CPR2014-2-18.
- Sviashchennikov P., Urazgildeeva A., Kurochkin Y., Ivanov B., Chistiakov K., Divin D. and Hudson S. (2015). Investigation of the spectral composition of the reflected and penetrating deep into the snow cover short- wave radiation in the vicinity of the village of Barentsburg (Svalbard). *Ice and Snow*, 55(3), c. 67-72. DOI:[10.15356/2076-6734-2015-3-67-72](https://doi.org/10.15356/2076-6734-2015-3-67-72)
- Taurisano, A., Schuler, T. V., Hagen, J. O., Eiken, T., Loe, E., Melvold, K., & Kohler, J. (2007). The distribution of snow accumulation across the Austfonna ice cap, Svalbard: direct measurements and modelling. *Polar Research*, 26(1), 7–13. doi:10.1111/j.1751-8369.2007.00004.x
- Vancoppenolle, M., Meiners, K. M., Michel, C., Bopp, L., Brabant, F., Carnat, G., et al. (2013). Role of sea ice in global biogeochemical cycles: emerging views and challenges. *Quaternary Science Reviews*, 79 (Supplement C), 207–230. doi:10.1016/j.quascirev.2013.04.011.
- van Pelt, W.J.J., Kohler, J., Liston, G.E., Hagen, J.O., Luks, B., Reijmer, C.H., Pohjola, V.A. (2016) Multi-decadal climate and seasonal snow conditions in Svalbard, *Journal of Geophysical Research - Earth Surface*, 121, doi:10.1002/2016JF003999.
- van Pelt, W. J., J. W. J., Pohjola, V. A., & Reijmer, C. H. (2016a). The Changing Impact of Snow Conditions and Refreezing on the Mass Balance of an Idealized Svalbard Glacier. *Frontiers in Earth Science*, 4., <https://doi.org/doi:10.3389/feart.2016.00102>
- Vecchiato, M., Barbaro, E., Spolaor, A., Burgaya, F., Barbante, C., Piazza, R. and Gambaro, A. (2018) Fragrances and PAHs in snow and seawater of Ny-Ålesund (Svalbard): Local and long-range contamination. *Environmental Pollution* 242B, 1740-1747, doi:10.1016/j.envpol.2018.07.095.
- Vega, C.P., Björkman, M.P., Pohjola, V.A., Isaksson, E., Pettersson, R., Martma T., Marca, A. and Kaiser, J. (2015) Nitrate stable isotopes and major ions in snow and ice samples from four Svalbard sites. *Polar Research*, 34, art. no. 23246, . doi:10.3402/polar.v34.23246.
- Vikharnar-Schuler, D., Isaksen, K., Haugen, J.E., Tømmervik, H., Luks, B., Schuler, T.V., Bjerke, J.W. (2016). Changes in winter warming events in the Nordic Arctic Region, *Journal of Climate*, 29 (17), 6223–6244, doi: <http://dx.doi.org/10.1175/JCLI-D-15-0763.1>
- Warren, S. G. (1984). Impurities in snow: Effects on albedo and snow melt (Review). *Annals of Glaciology*, 5, 177–179.
- Winiger, P., Andersson, A., Yttri, K.E., Tunved, P., Gustafsson, O. (2015) Isotope-based source apportionment of EC aerosol particles during winter high-pollution events at the Zeppelin observatory, Svalbard, *Environmental Science and Technology*, 49 (19), 11,959–11,966. doi:10.1021/acs.est.5b02644.
- Winther, J.G., Bruland, O., Sand, K., Gerland, S., Marechal, D., Ivanov, B., Głowacki, P. and König, M. (2003) Snow research in Svalbard—an overview. *Polar Research* 22(2), 125–144.
- Xie, Z, Wang, Z., Mi, W., Möller, A., Wolschke, H. & Ebinghaus, R. (2015) Neutral poly-/perfluoroalkyl substances in air and snow from the Arctic. *Scientific Reports* 5, 8912, doi:10.1038/srep08912.
- Yttri, K.E., Lund Myhre, C., Eckhardt, S., Fiebig, M., Dye, C., Hirdman, D., Ström, J., Klimont, Z., Stohl, A. (2014) Quantifying black carbon from biomass burning by means of levoglucosan - A one-year time series at the Arctic observatory Zeppelin, *Atmospheric Chemistry and Physics*, 14 (12), 6427–6442, doi:10.5194/acp-14-6427-2014.
- Zhang, T. J. (2005). Influence of the seasonal snow cover on the ground thermal regime: An overview. *Reviews of Geophysics*, 43(4). doi:10.1029/2004rg000157
- Østby, T. I., Schuler, T. V., Hagen, J. O., Hock, R., Kohler, J., & Reijmer, C. H. (2017). Diagnosing the decline in climatic mass balance of glaciers in Svalbard over 1957–2014. *The Cryosphere*, 11(1), 191–215. doi:10.5194/tc-11-191-2017
- Østby, T. I., Schuler, T. V., Hagen, J. O., Hock, R., & Reijmer, C. H. (2013). Parameter uncertainty, refreezing and surface energy balance modelling at Austfonna ice cap, Svalbard, 2004–08. *Annals of Glaciology*, 54(63), 229–240. doi:10.3189/2013AoG63A280.