Polar Research

PERSPECTIVE

An agenda for the future of Arctic snow research: the view from Svalbard

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Abstract

The Arctic region is warming at over twice the mean rate of the Northern Hemisphere and nearly four times faster than the globe since 1979. The local rate of warming is even higher in the European archipelago of Svalbard. This warming is transforming the terrestrial snow cover, which modulates surface energy exchanges with the atmosphere, accounts for most of the runoff in Arctic catchments and is also a transient reservoir of atmospherically deposited compounds, including pollutants. Improved observations, understanding and modelling of changes in Arctic snow cover are needed to anticipate the effects these changes will have on the Arctic climate, atmosphere, terrestrial ecosystems and socioeconomic factors. Svalbard has been an international hub of polar research for many decades and benefits from a well-developed science infrastructure. Here, we present an agenda for the future of snow research in Svalbard, jointly developed by a multidisciplinary community of experts. We review recent trends in snow research, identify key knowledge gaps, prioritize future research efforts and recommend supportive actions to advance our knowledge of present and future snow conditions pertaining to glacier mass balance, permafrost, surface hydrology, terrestrial ecology, the cycling and fate of atmospheric contaminants, and remote sensing of snow cover. This perspective piece addresses issues relevant to the circumpolar North and could be used as a template for other national or international Arctic research plans.

To access the supplementary material, please visit the article landing page

Keywords

Glacier mass balance; ecosystem; snowpack chemistry; remote sensing; modelling; focal sites

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Abbreviations

BC: black carbon
ESA: European Space Agency
GPS: Global Positioning System
LiDAR: Light Detection and Ranging (remote-sensing method)
LWC: liquid water content
MODIS: Moderate Resolution Imaging Spectroradiometer
NASA: US National Aeronautics and Space Administration
ROS: rain-on-snow
SAR: synthetic aperture radar
SIOS: Svalbard Integrated Arctic Earth Observing System
SWE: snow water equivalent
UAV: unmanned aerial vehicle

Introduction

Changes in terrestrial Arctic snow-cover extent and snowpack properties have occurred in recent decades in response to high-latitude warming (Bokhorst et al. 2016; Mohammadzadeh Khani et al. 2022). Further changes are likely, with large anticipated impacts on the glacier mass balance, surface hydrology, permafrost and terrestrial ecosystems, and geohazards such as snow avalanches, slush flows, landslides and floods. Some Arctic peoples and communities rely on adequate snow-cover conditions for wintertime overland travel in support of subsistence hunting and fishing, recreation or tourism. Anticipating how future changes in snow conditions will transform Arctic landscapes and ecosystems is therefore a major research imperative.

This paper presents an agenda for the future of scientific research into snow that was developed for the European Arctic archipelago of Svalbard, where the seasonal snowpack (including that on glaciers) covers about 98 to about 55% of the land surface in winter and summer, respectively (Killie et al. 2021). Year-round research stations in Ny-Ålesund, Longyearbyen, Hornsund and Barentsburg (Fig. 1) have been focal sites of research cooperation between institutions from about 20 countries for over 15 years. Svalbard occupies a region with a large climatic gradient between relatively mild (Atlantic) oceanic conditions, with limited winter sea-ice extent, in the south-west (76 °N) and a much harsher polar

Citation: *Polar Research* 2023, *42*, 8827, http://dx.doi.org/10.33265/polar.v42.8827

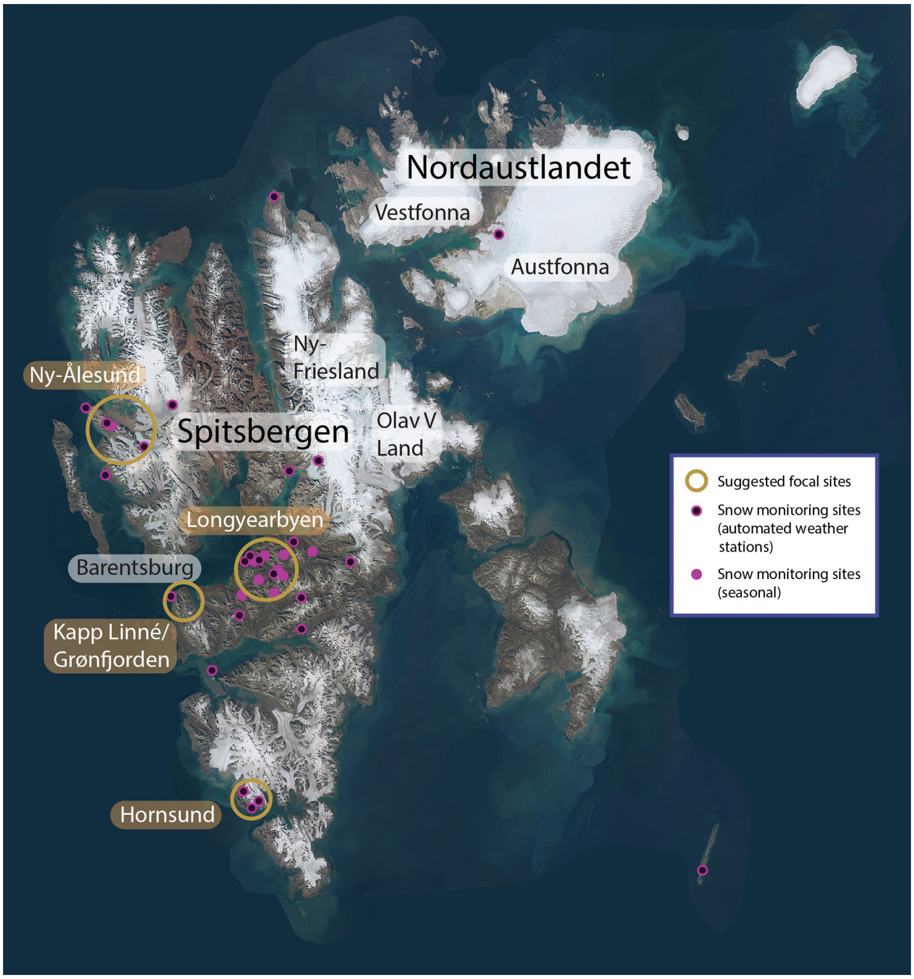

Fig. 1 Existing, instrumented snow monitoring sites in Svalbard, and suggested focal sites for future, coordinated multi-scale research and monitoring efforts: Ny-Ålesund, Longyearbyen, Kapp Linné/Grønfjorden and Hornsund.

climate, with more extensive and persistent sea-ice cover, in the north-east (81 °N). On the whole, Svalbard's climate is mild compared to that of most of the terrestrial High Arctic (mainly Greenland and northernmost Canada), because of the moderating influence of the Norwegian Current. The archipelago also lies at the eastern edge of a marine sector centred on the Kara and Barents seas, which is one of the fastest warming regions of the circumarctic, with an estimated annual trend in excess of 1 °C per decade since 1979 (Rantanen et al. 2022). Svalbard has been warming concomitantly, with the trend reaching 1.3–1.5 °C in the period since 1991 (Isaksen et al. 2022). How such rapid changes will impact seasonal snow conditions in Svalbard is relevant to other terrestrial sectors of the circumpolar North, which may experience similar warming rates in the near future.

The research agenda presented here is based on consultations with, and recommendations from, a multi-national community of experts, stakeholders and community organizations, at the Multidisciplinary Workshop on Snow Research in Svalbard, held by SIOS in 2021 (SIOS 2021). We identify important knowledge gaps and research needs in snow science that are relevant to (1) glacier surface mass balance; (2) terrestrial ecology, permafrost and snow-related hazards; (3) the cycling and fate of atmospheric contaminants and (4) remote sensing of the snow cover. We recommend specific actions in support of research under each theme. Additionally, we suggest recommendations common to all fields in snow research. These joint recommendations highlight how to better integrate field observations and remote sensing data with modelling efforts (including snow–atmosphere dynamic interactions) and harmonize monitoring, observations and snow-related research efforts across Svalbard. The priorities and multidisciplinary approach detailed herewith dovetail with those of the International Arctic Science Committee (IASC 2017), the European Union's PolarNet (EU PolarNet 2019) and the World Climate Research Program's Climate and Cryosphere project (CliC 2021).

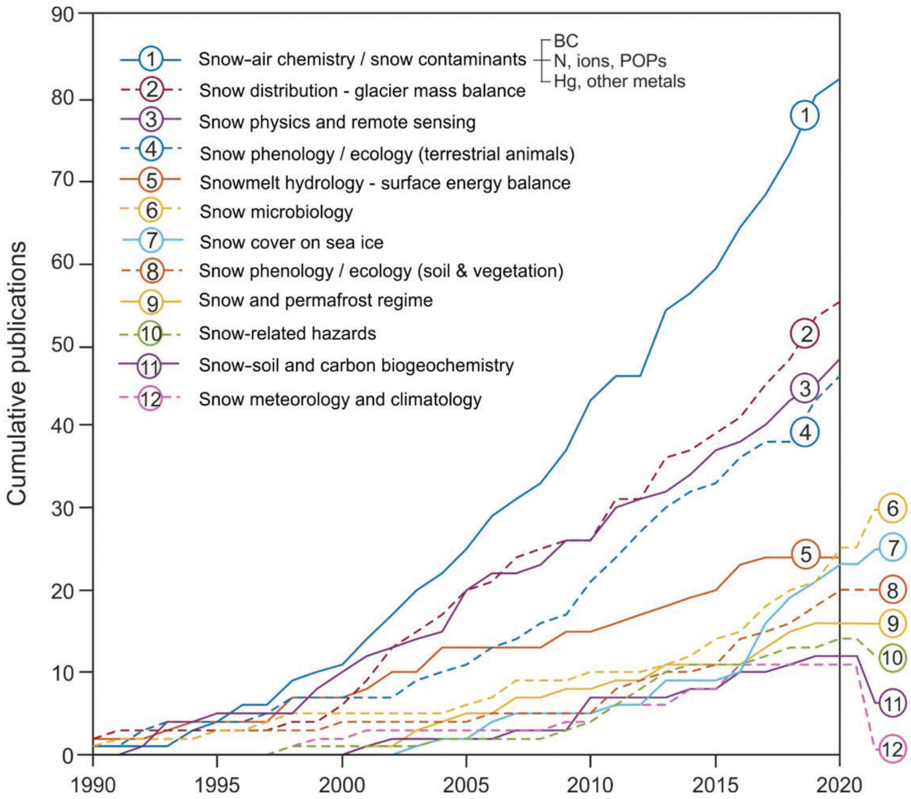

Fig. 2 Trends in snow research in Svalbard since 1990, based on a bibliometric analysis of 377 peer-reviewed publications in the SCOPUS database. See the Supplementary material for methodological details.

Recent trends in snow research in Svalbard

Several areas of snow research in Svalbard have intensified during the last 30 years, as indicated by publication trends (Fig. 2). The steepest rise in publications concerns air–snow chemical interactions, including the cycling of atmospheric reactive nitrogen species and of mercury (Hg), and the air–snow transfer of light-absorbing BC that affects snow albedo. Other topics that experienced a rapid growth in publications are as follows: snow-cover conditions in relation to glacier surface mass balance; physical and optical properties of the snowpack and their retrieval by remote sensing methods; and the phenology and ecology of snow-covered environments, particularly concerning the effects of changes on Svalbard reindeer (*Rangifer tarandus platyrhynchus*) populations. The microbiology of snow-covered ecosystems, absent in pre-2000 publications, has since experienced a rapid (and still accelerating) rise in published research, with a focus on the genomics of cold-resistant microbes. Other topics saw comparatively modest rises, close to the average rate for all publications combined. The most frequently cited papers (≥500 citations) were those on the ecology or phenology of snow-covered environments (1766), glacier mass-balance studies (815), remote sensing of snow-cover properties (716), snow microbiology (692) and the atmospheric deposition of BC in snow (500).

Altogether, our bibliometric survey shows that snow research in Svalbard has expanded and diversified considerably since 1990 (see Winther et al. 2003 for an earlier survey). The trends in Fig. 2 reflect advances in scientific disciplines (e.g., rapid gene sequencing in Arctic microbiology), the development of ground- and space-based observational capabilities and the emergence of concerns linked to the human impact on Arctic climate and the cryosphere. The overwhelming majority of published field-based studies were carried out on Spitsbergen, close to existing research infrastructure, especially in Ny-Ålesund and Longyearbyen. Because the bibliometric survey was limited to works in English, it is likely that some research by Russian, Czech or Polish groups (e.g., in Barentsburg) is underrepresented.

Snow cover and glacier mass balance

Glaciers cover about 60 % of Svalbard (Nuth et al. 2013), and the supraglacial snow cover, through its albedo, strongly affects summertime energy exchanges and ablation rates, which, in turn, control glacier mass balance (Aas et al. 2016; Østby et al. 2017; van Pelt et al. 2019). Hence, accurate knowledge of supraglacial snow distribution in space and time is an important requirement to predict how Svalbard glaciers will respond to Arctic climate change.

Increasingly, satellite remote sensing and numerical models are jointly used to monitor, simulate and forecast snow-cover and glacier changes (e.g., Aalstad et al. 2018; Aalsted et al. 2020; van Pelt et al. 2021; Vickers et al. 2021; see also Schuler et al. 2020; Malnes et al. 2021; Schmidt et al. 2023 and references therein), but remote observations and model outputs still need to be validated against ground-based observations of snow conditions made across Svalbard (e.g., Fig. 3). However, the complex terrain in the archipelago makes the merging of data acquired by these various approaches challenging.

Computer models that generate gridded simulations and predictions of snow-cover development require meteorological input data supplied by dynamic downscaling of regional climate model outputs. Recent efforts have led to the combined modelling of glacier mass balance, seasonal snow conditions on glaciers and land, as well as runoff across Svalbard under past and future climates (van Pelt et al. 2019; Schuler et al. 2020 and references therein; van Pelt et al. 2021; Schmidt et al. 2023). Of highest importance for snow model calibration and validation are in situ measurements of snow accumulation at glacier mass-balance stakes and of snow/firn density and temperature (e.g., Taurisano et al. 2007; Laska et al. 2022), as well as weather station records of air temperature and, most importantly, precipitation (snowfall and rainfall). Remote or in situ observations of snow albedo are also critical for accurate estimation of glacier surface energy balance and melt rates.

As snow and ice cover conditions on land and sea continue to evolve under a changing climate, winter or springtime access to some field sites in Svalbard is becoming more difficult or hazardous. Hence, future monitoring and assessment of glacier mass balance and terrestrial snow cover are likely to depend increasingly on the use of stationary autonomous sensors with remote access (data telemetry), mobile sensor platforms such as UAVs, remote

Fig. 3 Snow science in action: (a) setting up an automated ultrasonic snow surface height sensor; (b) ground penetrating radar survey of snow thickness and stratigraphy; (c) collecting surface snow samples to measure concentrations of black carbon aerosols; (d) measurements of several snow parameters along transects covering different ecological gradients to validate snow models; (e) measurements of snow depth and basal ice thickness; (f) operation of ground penetrating radar on a drone; (g) measurement of snow grain size. (Photos: a–c, Jean-Charles Gallet, Norwegian Polar Institute; d–e, Ketil Isaksen, Norwegian Meteorological Institute; f–g, Hannah Vickers, NORCE Norwegian Research Centre.)

observations from fixed land-based posts (e.g., time-lapse photogrammetry) and spaceborne remote sensing. A diverse array of satellite products is now becoming available for snow and ice cover characterization (Gallet et al. 2019; Schuler et al. 2020) at increasingly high-resolution spatial scales, for example, 10 m for the ESA's Sentinel-2 and 30 m for the NASA Landsat-8, respectively (Malnes et al. 2021). These new products supply gridded observations of relevant snow parameters needed for numerical modelling. This progress does not, however, negate the need for validation against in situ, ground-based observations from a range of reference sites.

Knowledge gaps and research needs

Our analysis of published studies showed that the largest share of field-based snow research in Svalbard carried out in recent decades (>60 % of publications, including studies at glacier sites) was concentrated, mainly for logistical reasons, in western, southernmost and, to lesser extent, central Spitsbergen (Fig. 1), where the climate is markedly warmer and wetter compared to other parts of the archipelago (Østby et al. 2017). Extensive snow surveys have also been done on parts of the Austfonna ice cap, on the island of Nordaustlandet (e.g., Taurisano et al. 2007). In contrast, there are almost direct ground observations of snow conditions neither on the Vestfonna ice cap nor on the glaciers and icefields of Ny-Friesland, Olav V Land and most of southern Spitsbergen. As the magnitude and timing of snow accumulation and melt on glaciers of western and southernmost Spitsbergen may not represent conditions elsewhere in the archipelago, where the climate is generally colder and/or drier, the ground data available to calibrate satellite observations or models give an incomplete picture of Svalbard glacier regimes. A more spatially representative spread of ground-based snow-cover observations to better sample different conditions across the glacierized parts of the archipelago would assist in identifying potential regional biases that may be present in model simulations of the supraglacial snow cover and of mass balance.

A long-standing challenge for the validation of satellite-based snow and glacier products is the disparity between the spatial scale of glacier mass-balance measurements, which are typically made at single-stake location along linear transects, and that of snow-cover properties retrieved by spaceborne sensors, which are area-averaged values over pixels or grid cells of much larger size (commonly km^2 or greater). Glacier mass-balance response to climate variations is also conditioned by glacier size, but at present, mid-size and large Svalbard glaciers are under-represented in mass-balance surveys, although some progress has been made in this regard over the past decade (Schuler et al. 2020). Hence, there is a need to quantify the variability of supraglacial snow-cover properties in Svalbard across a broader range of spatial scales than is presently covered.

Some of the most important and challenging parameters to observe remotely in the polar areas and to model are the quantities of solid and liquid precipitation. The current warming trend in Svalbard is accompanied by more frequent intrusion of warm, southerly air masses, even in the middle of the winter (Wickström et al. 2020), with the result that wintertime ROS events are no longer unusual but expected (Vikhamar-Schuler et al. 2016; Peeters et al. 2019). The net effect of these events on glacier mass balance under a future, warmer and wetter climate is still uncertain (van Pelt et al. 2016), in part because of the difficulty in differentiating icy features in the snowpack resulting from episodic winter thaw events from those resulting from refreezing of rainfall during such events (e.g., Łupikasza et al. 2019). Presently, at most glacier sites monitored in Svalbard, only the net cold-season accumulation can be measured with confidence at reference stakes. Solid precipitation in other seasons is estimated using ultrasonic sounders, but these cannot quantify rainfall, which is no longer negligible in any season in Svalbard. Therefore, an ongoing technical challenge is to find methods by which to improve in situ estimations of solid and liquid precipitation on glaciers, and to quantify the contribution to, and impact of, winter thaw and ROS events on glacier surface mass balance. A related research need is to develop a strategy to quantify how much winter snow accumulation is lost by runoff during winter thaw events, rather than being stored as superimposed ice or within firn aquifers.

Recommendations for specific actions

We recommend the following actions to address the research gaps and needs identified earlier.

Deploy new satellite- or radio-linked automatic weather stations at selected remote glaciers in understudied parts of Svalbard. Install these stations at sites that can be serviced by overland access for the foreseeable future, that is, avoid sites where the pace of change in surface conditions may hinder access to the instruments in a few years.

Develop and test new techniques that can be used to monitor year-round changes in snow conditions across the archipelago, and in particular, novel approaches that allow detection and quantification of wintertime thaw events due to warming only and/or ROS. Ground-based methods based on attenuation or on interferometric reflectometry of Global Navigation Satellites Signals have shown promising results for quantifying snow wetness and melting–refreezing (e.g., Koch et al. 2019; Song et al. 2022) and should be further developed and tested in Svalbard.

Conduct multi-year surveys (every 5 years) on a selection of glaciers to track the impact of winter warming on the frequency of winter thaws and internal refreezing of water within the snowpack. Such a survey was carried out in April 2016 across Svalbard, during which the detailed stratigraphy of the snowpack was recorded at 22 sites on seven glaciers (Barbaro et al. 2021). Such information, if collected using time-consistent methods, can serve as a baseline against which future conditions can be compared.

Terrestrial ecology, permafrost and snow hazards

Outside of glacier-covered areas, the extent, duration and properties of the seasonal snow cover directly affect terrestrial ecosystems, permafrost conditions and the occurrence of hazardous events such as avalanches or slush flows. Predicting how snow-cover thickness and the timing of snowmelt will evolve under a warmer climate is of special interest to ecology because these changes will affect foraging by herbivores, soil microbiology, nutrient fluxes and plant growth rates (Cooper 2014; Rixen et al. 2022). Snow disappearance/melt has consequences for herbivores, for instance, impacting the timing of goose nesting and the size of herbivore populations (Layton-Matthews et al. 2019). In addition, winter warming or rainfall events can make the snow cover icy or even create a basal ice layer below it, encasing plants and lichen and thus reducing, if not entirely inhibiting, foraging by various animals, especially ungulates such as reindeer (Hansen et al. 2013).

Terrestrial snow cover insulates the ground, limiting heat loss during winter and thereby influencing ground temperature (Christiansen et al. 2019, 2020). Hence, changes in snow thickness or density can lead to changes in ground temperatures. Near-surface permafrost temperatures in Svalbard show large interannual variations, which depend on variations in snow accumulation and on the ice content of snow and underlying soil (Isaksen et al. 2007). Partial melting and refreezing of the snowpack during warm spells can cause its thermal resistivity to drop by an order of magnitude, thereby reducing soil insulation. In windswept areas with relatively thin or discontinuous snow cover, wintertime rainfall can also raise ground temperature and lead to near-surface permafrost thaw (Westermann et al. 2011).

The spatial distribution, internal structure and temperature of terrestrial snow cover are key properties that must be known to forecast or evaluate risks of snow hazards such as avalanches or slush flows (Eckerstorfer & Christiansen 2012). Structurally weak layers may develop in the snowpack through temperature-gradient metamorphism following heavy snowfall events, while abrupt winter warming, for example by ROS events, can lead to rapid increases in snow LWC, priming the snowpack for slush flows. An increase in the frequency of winter warming events leads to a patchier snow cover with more heterogeneous compactness (icier in places, softer in others), rendering overland travel by snow scooter more complicated and risky, thus also impacting residents of Svalbard communities and winter-spring tourism activities (Hansen et al. 2014).

Knowledge gaps and research needs

There are only limited in situ observations of snowpack extent, depth and SWE at the scale of individual catchments in Svalbard. Most previous and current observations of snow and permafrost conditions come from sites near settlements and research stations in western and central Svalbard (Fig. 1). However, snow cover and ground thermal conditions of these locations are unlikely to be representative of the more northern and eastern parts of the archipelago, where temperatures are typically lower, and future climate might evolve differently. High-resolution (spatial and temporal) information on snow distribution is also lacking in complex terrain such as tundra, moraines and mountain slopes.

Monitoring and modelling internal snowpack processes is essential to detect and accurately predict the formation of internal and basal ice layers in the snowpack. As the frequency, duration and magnitude of wintertime thaws and ROS events are expected to increase (Vikhamar-Schuler et al. 2016; Peeters et al. 2019), the penetration of meltwater into and through the snowpack and its refreezing need to be monitored, mapped and quantified to establish the resulting impact on vegetation, grazing animals, permafrost thermal regime and active layer depth. Efforts in method development are needed to produce automated monitoring systems and sensors that can differentiate between ice and snow accumulation on the ground, or between solid and liquid precipitation. The future of terrestrial ecology in Svalbard will depend largely on the response of High-Arctic plants to changing snow-cover conditions. Hence, there is a need to establish how current and future variability in snow cover, properties and duration impact the length of the growing season and, thereby, the end-of-season balance of carbon uptake/efflux in the tundra in Svalbard.

In addition, the growth and metabolic activity of microorganisms at sub-zero temperatures within and under the Arctic snowpack are understudied, as are the biogeochemical implications. Studies are needed to quantify variations in abundance among species and ecotypes as a function of snow-cover extent and duration, to determine how much microbial biomass can be produced in winter within and under the snowpack and to establish how changes in snow cover will affect the Arctic food chain, nutrient resource and cycling of trace gases such as CO_2. Such studies would help to establish which specific microbial processes, in or under snow, are driven or impacted by seasonal variations in temperature, light, moisture and freeze–thaw cycles. Likewise, efforts are needed to clarify how seasonal variations in ambient nival or subnival conditions drive microbial gene expression, and how this, in turn, affects microbial nutrient cycling and respiration.

Future changes in snow cover and, consequently, in soil temperature across Svalbard are also expected to affect microbial processes and nutrient cycling in tundra soils (e.g., Lim et al. 2020; Xu et al. 2021), but the long-term implications for soil development and biogeochemical cycling are still unclear, partly because our knowledge of anticipated microbial community responses to these changes is incomplete. In particular, studies are needed to establish if changes in snowpack duration modify rates of carbon accumulation and nutrient mineralization in soils, for example, by altering the proportions of heterotrophic/phototrophic microbes and, if so, what the response time is for such changes to have measurable effects (years, decades?). Little is understood of the eco-physiological and molecular–genetic mechanisms that determine the resistance of biological soil crust microalgae to harsh Arctic conditions, and how this resistance may be altered under different winter temperatures, melt–freeze cycles, soil wetting or desiccation.

Forecasting snow avalanches using physical snowpack models requires precipitation and energy balance data from avalanche starting zones, and efforts are therefore needed to augment/improve such observations in areas of high risks, for example, near Longyearbyen (Engeset et al. 2020). Some physical processes relevant to snow avalanches in windy Arctic settings like Svalbard are at present poorly monitored and quantified. This is especially true for drifting snow leading to the formation of cornices, which pose a high risk to infrastructure near Longyearbyen. An improved understanding of drifting snow processes would also benefit glacier mass-balance modelling in Svalbard (e.g., Jaedicke & Gauer 2005). There have been comparatively few studies on slush flows in Svalbard as they are less frequent than snow avalanches (Scherer et al. 1998; Eckerstorfer & Christiansen 2011). However, lichenometric evidence shows that slush flows were common in the past (André 1990) and are likely to occur more frequently under a warming and wetter climate. Therefore, meteorological conditions that are conducive to slush flow releases, namely, rapid winter or springtime thaws or ROS events, coupled with the presence of highly permeable snowpacks, need to be monitored, mapped and anticipated.

Recommendations for specific actions

The impact of changing snowpack properties on ecoystems in a warming climate is an important arena for interdisciplinary research between ecology and geophysics, and our recommendations pertaining to Svalbard are as follows.

Expand monitoring and data collection efforts on snow–permafrost interactions beyond the Longyearbyen and Adventdalen areas to other sectors, such as the northern and eastern parts of Spitsbergen. This expansion is essential to encompass the diversity of snowpack conditions and permafrost regimes encountered across the Svalbard landscape. The expanded observations should include quantification of the snowpack LWC and of icy layers, which can have a large impact on bulk thermal conductivity of the snow and, hence, active layer depth.

Establish a network of automated weather stations and snow-depth sensors in Svalbard's known avalanche starting zones, for example, near Longyearbyen (Engeset et al. 2020), and obtain automated, frequent ground-based LiDAR scans of snow cornices in these high-risk areas, which would allow for accurate assessment of their dynamics leading up to failure and snow avalanche release (Hancock et al. 2020).

Atmospheric contaminants and snowpack chemistry

A wide variety of airborne particulate and water-soluble impurities are deposited in Arctic snow from terrestrial, oceanic and atmospheric sources. Svalbard's proximity to the European and Russian mainland causes it to be disproportionally impacted by anthropogenic emissions of contaminants, relative to Greenland or Arctic Canada. Here, 'contaminants' refers to atmospheric species that can compromise the health of terrestrial and aquatic ecosystems upon release from snow, for example, pesticides. The atmospheric species (contaminants or other) deposited in Svalbard snow that are of greatest interest or concern now are listed below.

Light-absorbing particles. These include BC and airborne mineral dust, both of which are short-lived climate forcers that can lower snow albedo, enacting positive radiative climate warming feedbacks (Kylling et al. 2018; Tuccella et al. 2021). An improved knowledge of these forcings is a priority goal in Europe's long-term Arctic research plans (EU PolarNet 2019), as well as for the Intergovernmental Panel on Climate Change (Meredith et al. 2019) and the Arctic Monitoring and Assessment Programme (Tørseth et al. 2019) to achieve better Arctic climate predictability. Other light-absorbing aerosols of interest are airborne carbonaceous species ('brown carbon,' e.g., humic-like substances), which are primarily sourced from biomass and fossil fuel burning and terrestrial biogenic emissions and contribute to lowering snow reflectance, particularly on glaciers during the summer wildfire season (Wu et al. 2016; Brown et al. 2022).

Bioaccumulative contaminants. These contaminants can build up in Arctic biota to levels that are toxic to organisms or make them unfit for human consumption. They include Hg (especially methylated forms) as well as volatile persistent organic pollutants derived from, among other sources, insecticides, pesticides, fossil fuel and waste incineration (AMAP 2016). Other chemicals of emerging Arctic concern are halogenated compounds such as hydrophobic surfactants and brominated flame retardants. Together, they pose threats to marine and terrestrial ecosystem health in the European Arctic and require continued monitoring in the future (AMAP 2017).

Sulphates and nitrates. These acidifying water-soluble aerosols, which contribute to Arctic haze, are primarily sourced from oxidized sulphur and nitrogen gases emitted at lower latitudes by combustion of fossil fuels or of biomass (AMAP 2006). As the seasonal sea-ice extent around Svalbard declines, oceanic sources of sulphate (from biogenic reduced sulphur gases or from sea spray) are likely to become increasingly important (Dall´Osto et al. 2017), as could emissions from marine shipping traffic (Eckhardt et al. 2013). Sulphate aerosols and their precursors influence Arctic climate by scattering incoming radiation or modifying cloud properties, whereas atmospheric nitrate in precipitation is a nitrogen source to terrestrial ecosystems. With changing trends in global emissions (e.g., air pollution in Asia, boreal wildfires and greater open-sea aerosol fluxes), there is a strong rationale to continue monitoring these atmospheric species and evaluate their environmental impacts.

Nutrients. In nutrient-limited High-Arctic terrestrial environments, atmospheric deposition of reactive nitrogen species, labile organic carbon or dust-borne mineral elements can help support nival or glacial microbial ecosystems. Atmospheric deposition of nutrients on glaciers can also stimulate algal growth, thus enhancing the natural bio-albedo feedback effect (Hotaling et al. 2021). Hence, there is considerable interest in pursuing and advancing research on these subjects in Svalbard.

Microparticles and nanoparticles. The global dispersion of micro- and nanoplastics recently came to the attention of researchers worldwide, and these contaminants have since been detected in Svalbard snow (Bergmann et al. 2022) and in a snowmelt-fed lake (González-Pleiter et al. 2020). Other human-made materials such as engineered titanium or silver nanoparticles have potential adverse effects on environmental health, but little is known of their dispersion to remote regions. Given the high biological, chemical and physical reactivity of nanoparticles, their potential to bioaccumulate in aquatic food chains (Uddin et al. 2020) and their ease of transport by air, there is a strong incentive to investigate their occurrence in Arctic snow (Hamilton et al. 2022).

Radioactive isotopes. Anthropogenic radioisotopes (e.g., strontium, caesium and plutonium) in aerosol form reach Svalbard (Gwynn et al. 2004). Historically, these were primarily from former Soviet nuclear weapon test sites in Novaya Zemlya and some European mainland sources, for example, the 1986 Chernobyl accident, but radioisotopes from the 2011 Fukushima nuclear power plant disaster also reached Svalbard (Burakowska et al. 2021). With the growing push for diversification and decarbonization of the energy sector in Western nations, nuclear electricity production is likely to see a renewal (e.g., Finland), with associated risks of accidental nuclide releases. Hence, there is a continued need to monitor background radioactivity levels in the European Arctic, including in precipitation.

Knowledge gaps and research needs

Current knowledge of the deposition of atmospheric species in snow in Svalbard comes mostly from studies near established research sites such as Ny-Ålesund or from ice cores drilled in central or north-western Spitsbergen. It is necessary to quantify the variability in atmospheric deposition in snowfall across latitudinal (south–north) and altitudinal (coast to highlands) gradients and to characterize meteorological conditions that control atmospheric deposition rates both in time and space. Air–snow transfer functions need to be developed and parametrized for both volatile and particulate atmospheric species of concern. Understanding how these functions might change in future warmer climate conditions is also required.

Recent trends in seasonal snow-cover conditions (thickness and duration) across Svalbard indicate that the southern parts of the archipelago will experience intermittent winter snow cover and more frequent ROS episodes in coming decades (Vikhamar-Schuler et al. 2016; Rixen et al. 2022). The resulting effects on the fate of contaminants stored in snow are uncertain. For example, how does episodic snow wintertime thaw contribute to the dispersion of contaminants in tundra environments? Likewise, how will migration of the snowline up-glacier affect the release in runoff of contaminants deposited in supraglacial snow and stored in firn? To answer these and related questions, there is a need to describe and model the partitioning of contaminants in snow between solid, liquid and/or gas phases under evolving winter conditions, and their transfer rates to runoff and soils.

The evolution of the seasonal snowpack in Svalbard under a changing climate may alter both the timing and magnitude of the impact of light-absorbing particles (such as BC and mineral dust) on snow and ice albedo, and indirectly snow ripening and surface melt rates. For example, wintertime thaw may concentrate particles near the snowpack surface, further lowering the albedo at the onset of spring (Doherty et al. 2013). Hence, there is a need to document and model these changes to anticipate their impact on snowmelt hydrology.

The sources and deposition rates of BC in Svalbard snow are documented (Winiger et al. 2019; Zdanowicz et al. 2021). In contrast, for dust, the sources, rates of deposition and contribution to snow darkening remain poorly known. Svalbard has local dust sources and receives some from distant sources, for instance, Asia and Iceland (Groot Zwaaftink et al. 2016; Crocchianti et al. 2021). As the climate changes and the terrestrial cryosphere shrinks, the extent and emission strength of high-latitude dust sources will probably increase (e.g., in newly deglaciated forelands; Meinander et al. 2022), with impacts on Arctic surface albedo, for instance on glaciers where mineral micronutrients can enhance the growth of snow algae, thereby darkening the surface (Hotaling et al. 2021). In light of this, there is a need to quantify dust deposition in Svalbard snow, identify the likely source contributions and estimate how these may change in the future (Di Mauro et al. 2023).

Some atmospherically deposited species undergo microbially mediated transformations in snow, for example, through respiration of organic carbon, assimilation of nitrogen or (de-)methylation of Hg (Boetius et al. 2015; Sharma Ghimire et al. 2019). Many such transformations remain poorly understood. In particular, the role of nival microbes in the cycling of atmospheric carbon compounds needs to be clarified and quantified. This is of special relevance for carbonaceous species that may support micro-organisms responsible for biological albedo reduction on snow and icefields and may also help to identify snow-dwelling microbes that are tolerant to, and can degrade, organic contaminants.

Ice cores drilled through ice caps in Svalbard have enabled the reconstruction of past deposition of atmospheric species such as sulphate, nitrate and BC over decades to centuries, providing a historical context for modern observations (e.g., Wendl et al. 2015; Osmont et al. 2018). As analytical techniques have improved, more and new species can now be reliably quantified in ice (Barbante et al. 2017), and novel dating methods have been developed (e.g., Jenk et al. 2007), so there is a rationale for additional cores to be recovered before firn warming and increasing surface mass loss rates on Svalbard ice caps compromise the integrity of such records beyond any possibility of interpretation.

Recommendations for specific actions

Many airborne species of special interest listed earlier are monitored in air in Ny-Ålesund under its Atmosphere Research Flagship programme (Neuber et al. 2011). To advance current knowledge of their deposition and subsequent cycling in snow, we recommend the following future work.

Measure at least some species (e.g., BC, sulphate and nitrate, Hg), simultaneously in snowfall and snow on the ground to elucidate air–snow transfer functions (e.g., Jacobi et al. 2019) and to quantify depositional fluxes so as to predict later releases in runoff.

Extend such air–snow co-measurements to other sites, such as Longyearbyen and Hornsund, to include sectors of the archipelago that experience different climatological conditions than Ny-Ålesund.

Quantify atmospheric deposition fluxes in snow over larger spatial scales (1–10 km^2), rather than point measurements, to facilitate comparisons with predictions from atmospheric transport and deposition models and establish the variability within, and representativeness of, grid cell-scale estimates from these models. This requires close coordination between snow scientists and specialists in the atmospheric modelling community.

In support of the above, develop the capacity at key research sites to routinely measure basic snow chemistry parameters, such as pH, conductivity, selected major ions (especially sulphate and nitrate) and water-soluble organic carbon, which are useful indicators of precipitation quality, using harmonized and standardized techniques and protocols. This would avoid the need to ship samples to mainland laboratories for relatively simple, routine analyses.

Optimize access to local analytical facilities in Svalbard (existing or future) through, for example, a user-access web platform.

Integrate snowpack chemistry in studies of microbial metabolism and carry out such integrative studies over entire snow-cover seasons at dedicated sites where ancillary weather and atmospheric data are available.

Set up a repository of filters obtained from melted snow samples (e.g., in Longyearbyen), just as some national atmospheric monitoring programmes routinely archive air filters. Archived filters could be used to characterize particulate matter in snow, including microbes. Collecting bulk snowpack samples for impurities such as dust or BC requires only limited technical training and is amenable to participation by residents in Longyearbyen on an opportunistic basis (e.g., Hermanson & Le Cras 2018).

Where the appropriate infrastructure exists (or can be established), conduct experiments to quantify, at the catchment scale, the flow of contaminants of interest (e.g., Hg) from atmospheric deposition in snow to release in runoff, to establish how much is transferred to soils and surface waters. Such experiments could be carried out in instrumented catchments of a manageable size located within easy access range from focal research sites in Svalbard, such as Fuglebekken (near Hornsund), Foxfonna (near Longyearbyen) and Gruvebadet or Bayelva (near Ny-Ålesund).

Remote sensing of snow cover

The Global Climate Observing System defines the snow-cover area, SWE and snow depth as Essential Climate Variables. The potential for remote sensing of these and other properties of the snow cover has grown in parallel with the advent of new sensors (Karlsen et al. 2020; Killie et al. 2021; Malnes et al. 2021; Salzano, Aalsted et al. 2021; Salzano, Killie et al. 2021). The snow-cover area is generally estimated using optical remote sensing and has been monitored globally from Landsat multi-spectral images since the 1980s (Dozier 1989). Such imagery is particularly well-suited for synoptic-scale studies of snow-cover seasonality in remote areas (Malnes et al. 2021). Nowadays, several additional snow-cover products are available from NASA's Suomi National Polar-orbiting Partnership and the MODIS instruments on its Terra and Aqua satellites, US National Oceanic and Atmospheric Administration's Polar Orbiting Environmental Satellites and ESA's Sentinel satellites. This large amount of data offers the opportunity to monitor global snow cover at different spatial scales.

Spaceborne observations of SWE by passive microwave sensors are available with global-scale coverage going back to 1980 (Pulliainen et al. 2020). However, their coarse spatial resolution (ca. 20 km) makes these sensors unsuitable for Svalbard, with its complex topography and long, intricate coastline. Obtaining fine-scale measurements of SWE using active microwave sensors such as SAR has long been a goal of the remote sensing community. An alternative way to measure SWE using SAR backscatter, possibly suited for Svalbard, was proposed by Guneriussen et al. (2001), which relates SWE to changes in interferometric phase between repeat satellite passes. This could be implemented using L-band in future satellite missions by NASA, the Indian Space Research Organisation and ESA's Radar Observation System. In situ measurements of SWE using snow pillows, snow scales or gamma radiation attenuation instruments can be used to calibrate and validate satellite retrievals of SWE, but the present spatial scale of such measurements in Svalbard is still well below satellite resolution (ca. 1 km^2), making comparisons difficult. New sensor concepts such as fibre-optic cables or GPS Interferometric Reflectometry (McCreight et al. 2014) could be alternatives.

Compared with snow-cover area or SWE, the snowpack depth (thickness) is not easily retrieved by remote sensing methods. Lievens et al. (2019) showed that snow depth can be estimated using the ratio between co- and cross-polarized SAR backscatter measured from ESA's Sentinel-1 satellite. While their results were validated using in situ observations from non-polar regions, they remain to be tested in Svalbard against field measurements. Airborne LiDAR can be used to derive snow-depth measurements at high spatial resolution (a few m), but carrying out frequent and repeated overflights in Svalbard is both difficult and costly. Data derived using ground-based LiDAR could help fill the spatial scale gap of airborne/spaceborne measurements, especially if it were possible to automate the method to obtain frequent measurements (Harpold et al. 2014). Additional opportunities are offered by the GPS interferometric reflectometry method (spatial scale ca. 1 km^2).

Other snow parameters that can be retrieved by remotely sensed methods include snow albedo, temperature, internal layering and LWC (i.e., snow wetness). Measurements of the spectral albedo of snow, especially in the visible and near-infrared range in which the incident light flux is largest, are essential for surface energy balance computations and to simulate melting and permafrost thaw. Albedo variations across visible and near infrared wavelengths strongly depend on microphysical characteristics of a snow surface, and measurements in this spectral range can therefore also be used to derive snow microstructural properties (Salzano, Lanconelli et al. 2021). Furthermore, snow albedo is also lowered by the presence of impurities of anthropogenic origin (especially BC), mineral dust and microorganisms (e.g., algae), and methods are now being explored to retrieve data on these impurities from airborne or spaceborne observations (Huovinen et al. 2018; Di Mauro et al. 2020; Kokhanovsky et al. 2021). Measuring the spectral reflectance properties of snow in the field with radiometers like those installed onboard satellites will be essential to validate such methods and later expand them to regional scales (Pirazzini et al. 2018; Killie et al. 2021). Field measurements of snow surface roughness (which influences light scattering) and of the types and amounts of impurities in snow (which influence absorption) will also be needed to this end.

Detecting and measuring snow wetness is particularly important in Svalbard, in the context of rapid climate change. Radar scatterometers (e.g., onboard NASA's Quikscat satellite) were successfully used to detect wet snow in Svalbard with a spatial resolution of 2.5 km (Rotschky et al. 2011). The C-band of SAR can also be used to map wet snow with ca. 100 m resolution (Nagler & Rott 2000). Retrieval of LWC has so far not been achieved, but a combination of different SAR frequencies and polarization could, in principle, be used to invert a radiative transfer model for wet snow.

Spaceborne SAR can also be used to detect snow avalanche activity (Eckerstorfer et al. 2017). The method was tested in Svalbard using ESA's Sentinel-1 Extra Wide mode SAR data, although its resolution is too low to detect small- to medium-sized avalanches (Wesselink et al. 2017). Svalbard is now covered with higher-resolution Sentinel-1 Interferometric Wide mode SAR data, but the temporal resolution is limited by the satellite's six-day repeat cycle. The next generation of Sentinel satellites will have better spatio-temporal resolution, improving the capability of detecting snow avalanches in Svalbard.

Knowledge and technology gaps and associated research needs

Current SAR sensors (C- and X-band) have neither sufficient sensitivity nor the ability to retrieve SWE and snow-grain size simultaneously, as these parameters cannot be decoupled in the radiative transfer model of snowpack backscatter. Initiatives are underway to develop sensor combinations for future satellite missions (e.g., ESA's Earth Explorer 11), but the launch of a new satellite is still years away. An inherent difficulty with optical remote sensing of Arctic snow cover is the limited cloud-free imagery available during the melting season. In addition, satellites carrying optical sensors with relatively coarse spatial resolution (e.g., those onboard NASA's Terra and Aqua, or ESA's Sentinel-3) overpass more often than those carrying higher-resolution sensors (e.g., Landsat), making it challenging to merge these data. A further difficulty is that bottom-of-atmosphere reflectance retrievals, and snow-detection algorithms are affected by site-specific factors which must be accounted for when processing the data. Hence, developing improved, site-specific algorithms for retrieving snow cover from optical airborne or spaceborne, multi- to hyperspectral sensors is needed, and Svalbard is a well-suited test area for this task. With respect to microwave remote sensing, newly developed SWE retrieval methods for L-band SAR in the Arctic need to be tested and validated against extensive in situ SWE measurements across a range of landscapes (e.g., tundra and glaciers). There is also a need for continuous in situ SWE measurements at reference field sites using gamma ray scintillators, GPS Interferometric Reflectometry or other methods (Royer et al. 2021), so as to provide ground-truthing of temporal variations in SWE during the melt period. Likewise, spatially distributed, in situ measurements of snow LWC are much needed to improve remote sensing retrieval techniques. Point measurements with dielectric probes such as the Denoth metre and snow fork (Techel & Pielmeier 2011) do not provide data over a sufficiently large area to be directly comparable with satellite data.

Recommendations for specific actions

On the basis of the needs described earlier, we recommend the following.

Time-lapse terrestrial photography of the snow cover or UAV-based surveys made at a network of reference sites could contribute meaningfully to address the research needs described by providing detailed site-specific data for ground-truthing satellite retrievals. This is a promising approach for developing site-specific snow-cover retrieval algorithms, but case studies are limited (e.g., Aalstad et al. 2020; Salzano, Killie et al. 2021).

Increased ground-penetrating radar measurements by aircraft, UAVs or snow scooters are recommended as they can quickly provide snow-depth data over large areas from which SWE can then be inferred over spatial scales close those of spaceborne sensors.

Improving the frequency of Sentinel 1 acquisitions over Svalbard to more than three Interferometric Wide tracks per repeat cycle is recommended to fill knowledge gaps in SWE retrieval and improve avalanche risk mapping.

In brief, improved use of ground-based and airborne remote sensing methods (e.g., using UAVs) is recommended to tackle challenges in integrating and bridging gaps between data acquired by sensors at different temporal (overpass frequency) and spatial resolutions (Dietz et al. 2012; Gascoin et al. 2019).

Snow-cover modelling

Complex dynamic interactions couple the Arctic atmosphere and snow cover. Precipitation, wind-blown drifting, metamorphism and melting transform the snow cover on hourly to interannual time scales. In turn, the snow cover influences the atmospheric boundary layer and its structure through turbulence and skyward radiation (Claussen et al. 2001; Vinukollu et al. 2011). As Arctic snow and ice cover get thinner and/or more discontinuous under a warming climate, the aerodynamic roughness and albedo of land surfaces will become more heterogeneous, which will modify surface mass (water vapour) and energy fluxes. The anticipated resulting net increase in energy stored by the Earth–atmosphere system is of the same order of magnitude as that arising from sea-ice cover reduction (Serreze & Barry 2011).

Considering this, knowledge of the current and changing state of the snow cover (extent, duration, roughness and reflectance) is of paramount importance to improve the reliability of numerical weather predictions and for longer-term climate modelling (Dutra et al. 2010). Although the horizontal resolution of numerical weather prediction models has improved in recent years (up to 1 km), most such models still use simplistic (typically one-layer) snow-cover schemes that are inadequate to accurately simulate snowpack development and melt. The longer-term impact of Arctic climate change and its associated feedbacks can only be assessed if the dynamic coupling between snow/ice conditions and the lower atmosphere is modelled realistically (Barnett et al. 2005; Cooper 2014).

Knowledge gaps and research needs

Recent model developments now allow for simulations of daily snow distribution across Svalbard using meteorological input data from historical reanalysis data and operational weather prediction models, thereby allowing real-time snow mapping and forecasts (Killie et al. 2021; Malnes et al. 2021). Such simulations can help assessing the influence of snow conditions on surface hydrology, permafrost, terrestrial ecosystems, avalanche risks, etc. In addition, an operational, daily updated snow-map service for Svalbard (1 × 1 km resolution) is planned to be launched on the Norwegian Water Resources and Energy Directorate's natural hazard forecasting website (www.xgeo.no). However, there is an ongoing need to provide improved snowmelt forecasts that serve as a planning tool for scientists, tourists and local communities, and coupled meteorological–hydrological models such as the Weather Research and Forecasting Model Hydrological model are likely to be implemented for Svalbard (e.g., Eidhammer et al. 2021).

Large-scale modelling of snow-cover development at a level of detail suitable for glacier surface mass-balance assessments is already possible using models (e.g., Østby et al. 2017; van Pelt et al. 2019; Noël et al. 2020). More detailed snow process models, such as MétéoFrance's SURFEX/CROCUS (Vionnet et al. 2012), which was tested for a three-year period in Ny-Ålesund (Zweigel et al. 2021) or the SNOWPACK model of the Swiss Federal Institute for Snow and Avalanche Research (Bartelt & Lehning 2002), need to be further developed for larger areas. Such models provide detailed characterization of local/point-scale snow stratigraphy and can be used not only to improve avalanche forecasts (Lehning & Fierz 2008) but also to clarify factors controlling snowpack thermal insulation, and water storage and release. These models perform well when forced with meteorological observations from nearby stations, but more poorly where these are lacking. A holistic approach where models and observations are closely integrated in an Earth system digital twin could be a future concept for the snow research in Svalbard. Digital twins suggested by EU's Destination Earth are information and communications technology concepts where big data and artificial intelligence infrastructure act on model and Earth Observation data guided by FAIR principles (Wilkinson et al. 2016) to create a system that can simulate Earth system components (like the hydrological cycle) in a flexible way. It can also predict 'what if' scenarios like 'detailed snow cover in Svalbard in 2100 given a certain CO_2 scenario,' as well as more daily life situations, such as predictions about winter tourism and snow avalanche conditions.

Recommendations for specific actions

We recommend the following.

Provide coupled meteorological–hydrological models with detailed meteorological input data. In addition, the assimilation of Earth observing data (e.g., MODIS imagery), though still challenging, could help improve their performance. Finally, model predictions should be validated with remote sensing data (e.g., Malnes et al. 2021). A digital twin concept for the extended water cycle in Svalbard could be a reasonable framework for achieving this.

Improve the assimilation of Earth observations and use interpolated, gridded meteorological forcing data in detailed snow process models (e.g., SURFEX/CROCUS).

Harmonizing snow research across focal research sites

Several of the challenges and recommendations we delineate above are specific to the respective fields of snow research. However, many research needs are, in fact, common to most of the fields, particularly those related to physical properties of snow and aspects of resolution and scale of measurements.

Snow and snow-cover properties have large spatial variability, and well-established tools and emerging technologies are used to investigate these properties at scales ranging from field campaigns and ground-based measurements to airborne instruments and satellites. It is important to apply these tools in an integrated approach to serve research, calibration and validation activities, and models with adequate and quality ensured data. Examples are better knowledge of representativeness of area-averaged retrieved values in gridded satellite products, catchment-scale studies to calibrate and test models and improvement of these tools by validation at smaller scales and/or new methods.

Snow distribution and SWE are the most commonly measured variables for mass balance, climate models and remote sensing, at scales varying from a few 100 m to several km. LWC and ROS are critical for ecosystem interactions and need to be properly addressed at the necessary scales for vegetation observation and snow modelling possibilities.

There is also a clear overarching need for standardized protocols. For instance, snow sampled for studies of impurities, chemistry and microbiology needs to be treated in a standardized manner during sampling, storage, processing and transport to ensure comparability of data. Likewise, consistent and well-documented protocols are needed both for snow physical information and content analyses of the snowpack. The development of such protocols should draw on those that already exist (e.g., Leppänen et al. 2016; Gallet et al. 2018; Meinander et al. 2020), and in so doing dovetail with initiatives to harmonize snowpack measurement protocols across Europe (Pirazzini et al. 2018; Haberkorn 2019).

There are several ongoing initiatives to harmonize monitoring and research activities across Svalbard. Examples are the organization of research and monitoring activities in Ny-Ålesund in four integrative flagships (Ny-Ålesund Research Station 2023) and the work conducted by SIOS to foster cooperation between institutions and nations towards common protocols and sharing of data.

To further advance knowledge of current and future snow conditions across Svalbard, we advocate a dedicated programme of harmonized snow observations while building on the existing facilities and initiatives. The observations should be conducted across a network of focal research sites suitable for long-term monitoring, alongside multi-site, multi-scale and multi-platform integrative studies (Fig. 4). The most feasible sites to start developing such a network are the four research nodes on the west coast of Spitsbergen: Ny-Ålesund, the Kapp Linné/Grønnfjorden area, Longyearbyen and Hornsund (Fig. 1). These sites are easily accessible by air and/or boat and have established research infrastructure, existing scientific cooperation and collaborations amongst scientists, power supply and means of communication allowing for data transfer. Snow monitoring has already been established at several of these sites using harmonized methods, including time-lapse cameras to validate satellite retrievals of snow-cover extent and ground-penetrating radar measurements to quantify SWE. The sites span a gradient of climate conditions, from warmest/wettest in Hornsund to coldest in Ny-Ålesund and driest in Longyearbyen (Hanssen-Bauer et al. 2019), and during the cold season, they are surrounded by snow-covered environments ranging from coastal tundra to mountain glaciers (see SIOS 2021 for details).

The development of this network of focal sites will facilitate the calibration, validation and integration of snow-cover retrieval data by different spaceborne sensors. The sites are spread across areas of Svalbard with different relief and ground cover, ensuring that they capture the spatial heterogeneity of snow-cover properties across the archipelago's complex landscapes. This will help to define site-specific thresholds for snow-cover detection and quantification by different satellite sensors under different local conditions. The focal sites will allow for testing new methods for monitoring snow wetness and detecting basal ice layers from ROS events, and for integrating snow-cover extent data acquired by optical sensors across different spatial resolutions, with the aim of harmonizing observations limited by the overpass frequency of individual satellites and cloud cover. In addition, the derived snow-cover distribution maps can be optimized for spatial resolution and areal coverage across the archipelago. Such data harmonization efforts can be supported and accelerated using internet cloud-based data processing services, such as the Copernicus Data Information Access Services, the Virtual Laboratory Platform, the ESA's Thematic Exploitation Platforms, Google Earth Engine and Amazon Web Services.

Furthermore, we strongly recommend that measurements be expanded to the uplands of central and northern Spitsbergen, as well as Nordaustlandet, representing a colder and dryer climate. Conducting snow monitoring activities in these areas is challenging because they are difficult to access logistically, protected (with increased difficulty of obtaining field permits for conventional research activities) and logistically expensive. The development of new field sensor technologies with remote power and communication solutions should be prioritized with the aim to establish automated instrumented sites in underrepresented areas.

Lastly, an interdisciplinary field campaign should be developed to visit regions outside the focal sites to investigate research topics beyond the range of pure snow physical parameters.

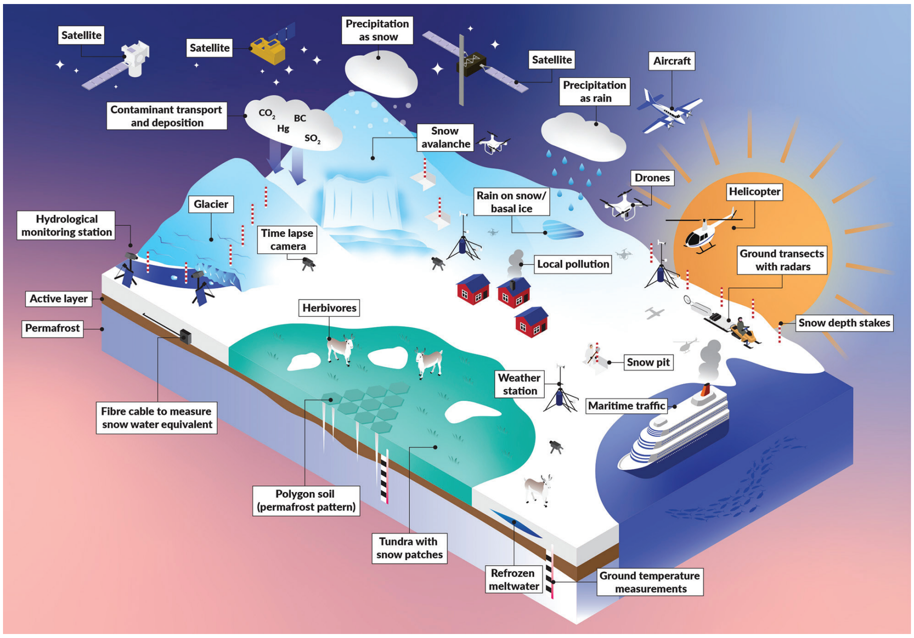

Fig. 4 Conceptual diagram illustrating various snow-covered environments of Svalbard, some of the external factors that affect them (e.g., weather and pollution) and the components of a multi-platform, multi-scale snow monitoring system advocated for the archipelago.

The combination of focal sites, automatic monitoring stations and coordinated interdisciplinary field campaigns would provide a robust long-term snow monitoring programme, greatly benefitting the snow science community and related Earth system science in Svalbard.

Acknowledgements

Many experts contributed to the SIOS workshop report on which this paper is based. The authors would like to thank James Bradley (Queen Mary University of London), Elisabeth Cooper (UiT The Arctic University of Norway), Mangesh Deshpande (Symbiosis International University), Biagio Di Mauro (Institute of Polar Sciences, National Research Council of Italy), Markus Eckerstorfer (Norwegian Research Centre AS), Josef Elster (Centre for Polar Ecology, University of South Bohemia), Rune Engeset (Norwegian Water Resources and Energy Directorate), Lara Ferrighi (Norwegian Meteorological Institute), Simon Fihol (University of Oslo), Øystein Godøy (Norwegian Meteorological Institute), Holt Hancock (University Centre in Svalbard), Ingrid Hunstad (National Institute for Geophysics and Volcanology, Rome), Dariusz Ignatiuk (SIOS Knowledge Centre and University of Silesia), Hans-Werner Jacobi (Institute for Geosciences and Environmental Research, Université Grenoble Alpes), Shridhar Jawak (SIOS Knowledge Centre), Inger Jennings (SIOS Knowledge Centre), Krystyna Kozioł (Gdansk University of Technology), Catherine Larose (Centre National de la Recherche Scientifique, École Normale Supérieure de Lyon), Pierre-Marie Lefeuvre (Norwegian Polar Institute and University Centre in Svalbard), Lu Li (Norwegian Research Centre AS), Maarten Loonen (University of Groningen), Bartłomiej Luks (Institute of Geophysics, Polish Academy of Sciences), Outi Meinander (Finnish Meteorological Institute), Kjetil Melvold (Norwegian Water Resources and Energy Directorate), Luca Mortarini (Institute of Atmospheric Sciences and Climate, National Research Council of Italy), Adam Nawrot (Institute of Geophysics, Polish Academy of Sciences), Geir Nævdal (Norwegian Research Centre AS), Christina Pedersen (Norwegian Polar Institute), Veijo Pohjola (Uppsala University), Tuomo Saloranta (Norwegian Water Resources and Energy Directorate), Roberto Salzano (Institute of Atmospheric Pollution Research, National Research Council of Italy), Andrea Spolaor (Institute of Polar Sciences, National Research Council of Italy), Monica Sund (Norwegian Water Resources and Energy Directorate), Jonas Svensson (University of Grenoble-Alpes and Finnish Meteorological Institute), Ward van Pelt (Uppsala University), Igor Vasilevich (Arctic and Antarctic Research Institute), Angelo Viola (National Research Council of Italy), Vito Vitale (Institute of Polar Sciences, National Research Council of Italy), Zhiyong Xie (Helmholtz Center Geesthacht) and Jie Zhang (Uppsala University) for their valuable contribution. The

SIOS community and especially SIOS Knowledge Centre initiated this work and gave support through organization of the consultation workshop and task force meetings, as well as manpower.

Disclosure statement

The authors report no conflict of interest.

Funding

The work on this agenda paper was supported by the Research Council of Norway through the projects 291644 and 269927 and the Norwegian Space Agency (contract no. 74CO2116). All lead authors were supported by their home institutions.

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