SESS REPORT 2020
SUMMARY FOR STAKEHOLDERS

The State of Environmental Science in Svalbard – an annual report

SIOS
SVALBARD INTEGRATED ARCTIC EARTH OBSERVING SYSTEM

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in Svalbard – an annual report

Marta Moreno-Ibáñez, Jon Ove Methlie Hagen,
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Foreword

Svalbard Integrated Arctic Earth Observing System (SIOS) is an international multidisciplinary research infrastructure in and around Svalbard. SIOS focuses on long-term monitoring of key variables in the Arctic to observe, attribute and describe the effects of global environmental and climate change. SIOS entered into the operational phase in 2018 with a mission to develop an efficient observing system; to share technology, experience, and data; to close knowledge gaps, and to decrease the environmental footprint of science. The annual SESS report is one tool to fulfil this mission.

The SESS report is a way to guide development of the observing system; the recommendations in the SESS reports are used to identify research needs, gaps in observations, and new techniques and methods that can improve and optimise the research infrastructure. This is the third SESS report. Like its forerunners, it is based on multifarious contributions from different disciplines within Earth System Science. The reports' recommendations are already being implemented, either at the initiative of the SIOS Knowledge Centre or by SIOS members as a direct result of collaborating to write a SESS chapter or within SIOS in general. During the coming year, we will synthesise the recommendations from the first three reports and develop a roadmap for their implementation.

The year 2020 has been overshadowed by the global COVID-19 pandemic. The Svalbard community, which is quite dependent on tourism and research, was also hit hard. The nationwide lockdowns in many countries, quarantine regulations, and restrictions on travel to and within Svalbard led to field work being postponed or cancelled. Meetings, workshops, and conferences were all moved online. This is foreseen to continue at least for the first half of 2021.

SIOS reacted swiftly to this new situation with various initiatives. The SIOS Knowledge Centre, with help from the working groups, organised possibilities to patch gaps in field data with satellite or airborne remote sensing, coordinated remote access to research instrumentation, and also intensified the social aspects of SIOS by gathering the community virtually for coffee breaks, webinars and conferences. None of these things would have happened without members' and the SIOS Knowledge Centre's dedication. In some ways, it might be said that the pandemic has made the SIOS community more tightly knit by bringing them together – if only virtually – to share knowledge, solve problems and ensure research continuity.

There is a lot to learn for the future. How will the "new normal" look? How much we will change our behaviour? Will we continue or even expand our use of digital technology to interact with each other? Will we increasingly rely on remote and virtual access to keep measurements running and gather samples? Only time will tell how much of today's on-site fieldwork will be replaced by remote sensing tools and innovative approaches. SIOS will certainly continue to strive to be at the forefront of developing new methodologies that ensure high quality observations in the Arctic.

I would like to express my appreciation for the editorial board; it was a pleasure to work with such an enthusiastic team. I am deeply grateful to the reviewers for their input on this SESS report; reviewing is hard work, and I thank you. I also acknowledge my colleagues here at SIOS Knowledge Centre. These have been strange times, but we managed to support each other and make the best of a challenging situation.

Longyearbyen, December 2020

Heikki Lihavainen

Director, SIOS

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Executive Summary

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The State of Environmental Science in Svalbard (SESS) report 2020 aims to document the state of the Artic environment in and around Svalbard, and highlight research conducted within SIOS. Given its remote but accessible location, Svalbard constitutes a privileged place to observe the Arctic environment in general, including, more specifically, the causes and consequences of climate change in the Arctic.

The Arctic is currently undergoing significant changes due to global warming. The IPCC Special Report on the Ocean and Cryosphere in a Changing Climate (2019)[1] was a wake-up call for climate change action. Over the last two decades, the Arctic has warmed more than twice as fast as the global average. The Arctic sea-ice extent has declined and will continue to decline in the future. For a stabilised global warming of 2°C, there is a 10-35% risk of a sea ice free September occurring at the end of the 21st century.

Svalbard, as the Arctic in general, has undergone substantial changes in near-surface temperature, precipitation and sea-ice extent in response to the warming over the last few decades, and these trends are projected to continue in response to future climate change. The future increases in temperature and precipitation in the Arctic and in Svalbard are expected to be significantly larger than the global mean increase in those variables. Thus, Svalbard is well-suited as an observational supersite for the Arctic (SvalCLIM).

Knowledge of the spatio-temporal distribution of snow in the Arctic is key to understanding the snow–atmosphere feedbacks involved in Arctic amplification. Long time-series of snow cover from a wide variety of observational platforms provide information at different spatial and time scales. For instance, satellite monitoring over 1982-2015 has shown an earlier onset of snow-melting in Svalbard, and shortened duration of summer snow cover with the most pronounced decrease in valleys, by 1-2 days per year (SvalSCESIA) . A comparison between satellite-derived snow cover data and the output from several hydrological snow models revealed significant differences in the geographical distribution and the timing of snow cover, which are likely explained by inaccurate inputs to the snow models (SATMODSNOW). Satellite observations are limited by their relatively low temporal resolution, and they can be affected by cloud cover. In contrast, terrestrial photography is characterised by high temporal resolution and is less affected by the weather; therefore, it can provide a continuous ground-truth for validating remotely sensed observations of snow cover in Svalbard (PASSES). Integrating these three methodologies allows for a multi-scale approach to snow cover observations and modelling (SnowCover).

Depending on their composition, aerosols can contribute to warming or cooling of the Arctic atmosphere. The reduction of cooling sulphate aerosol due to air quality legislation in Europe and North America since the 1980s has been proposed to be responsible to a significant part of Arctic warming. Knowledge about the long-term trends of aerosol concentration and composition is therefore essential to understand their role in Arctic warming. A significant increase in aerosol concentration in the Arctic troposphere occurs in winter–spring (Arctic Haze), and has mainly an anthropogenic origin. The Gruvebadet and Zeppelin observatories, in Ny Ålesund, provide long-term data on sulphate and ammonium, two central components of

1 IPCC (2019) Technical Summary. In: Pörtner H-O, Roberts D C, Masson-Delmotte V, Zhai P, Poloczanska E, Mintenbeck K, Tignor M, Alegría A, Nicolai M, Okem A, Petzold J, Rama B, Weyer N M (eds.) IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. In press.

Arctic Haze. Long-term trends of those compounds are analysed (HAZECLIC).

In general, an increase in water runoff has been observed from glacierised catchments due to increased melt of the glaciers. However, over the last decades, there has been a decrease in freshwater fluxes from some small glacierised catchments due to rapid shrinking of glacier area and volume. In contrast, water discharge has increased in rainfall-dominated watersheds due to increased precipitation. The boundaries of the hydrological year have shifted to earlier onset of snowmelt in the spring and later freeze-up in the autumn. The current long-term monitoring of evaporation and condensation, as well as of precipitation change with elevation is sparse and needs to be upgraded (SvalHydro).

One of the Arctic ecosystems that is directly and indirectly impacted by global warming is the coast. Climate change-induced stressors such as reduction of land and glacier ice, altered wind and wave energy, increased precipitation, thawing permafrost and changes of surface runoff all affect environmental conditions in the coastal waters. Global warming also contributes to more intense human activity in the Arctic (e.g., tourism, natural resources exploration). More comprehensive monitoring of physical, geochemical and biological parameters is necessary to detect, understand and mitigate changes in Svalbard's coasts (SvalCoast).

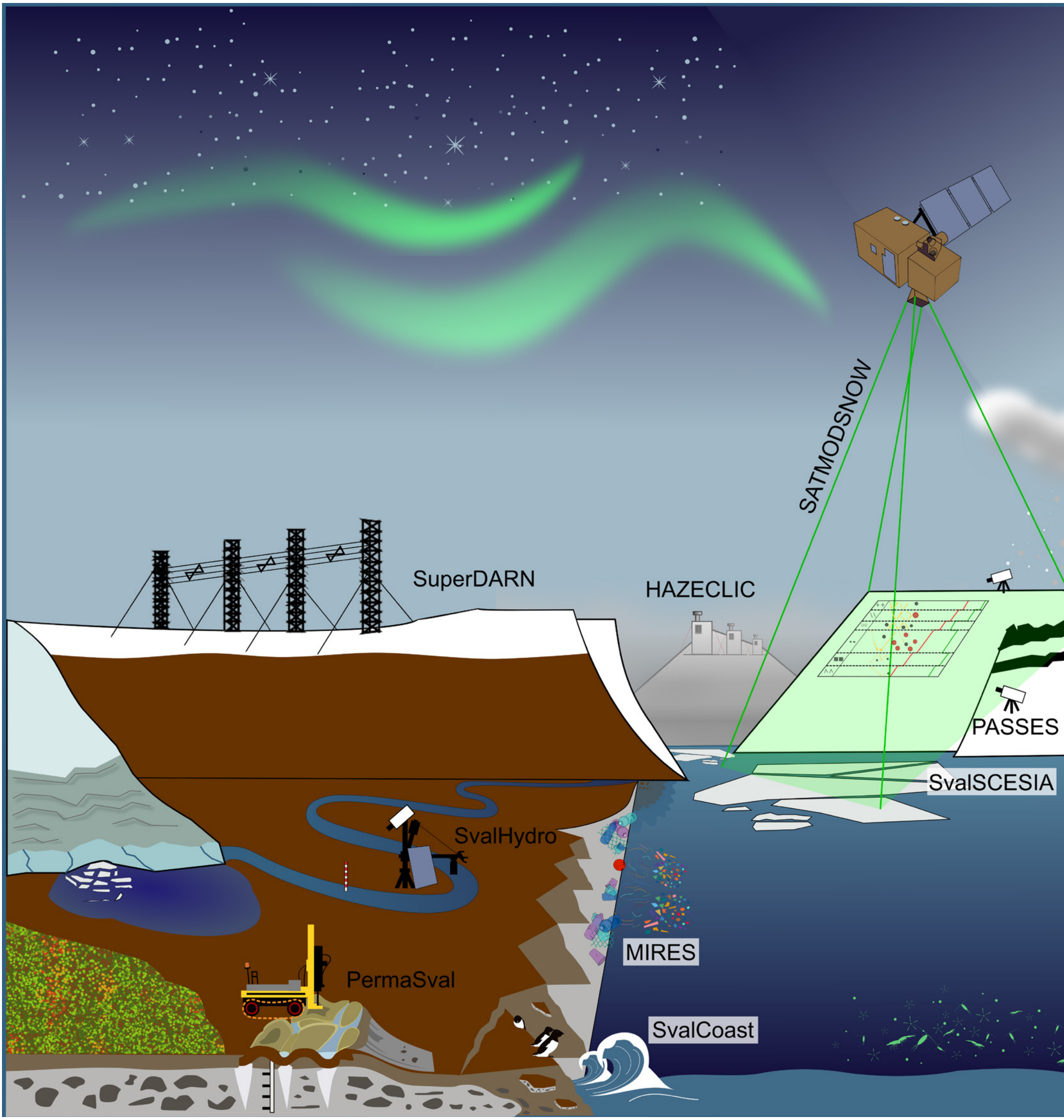
Climate change in the Arctic can also lead to an increase in the risks to human populations, such as geohazards. In permafrost landscapes, the thawing of ground ice often leads to ground instability and subsidence. Current knowledge about ground ice in Svalbard is focused on coastal lowlands, valley bottoms and periglacial landforms, while research on ground ice in slope deposits is currently limited. Temperature and pore water pressure sensors in boreholes in slopes could improve our understanding of slope sensitivity to climate change and enable preparedness for geohazards (PermaSval).

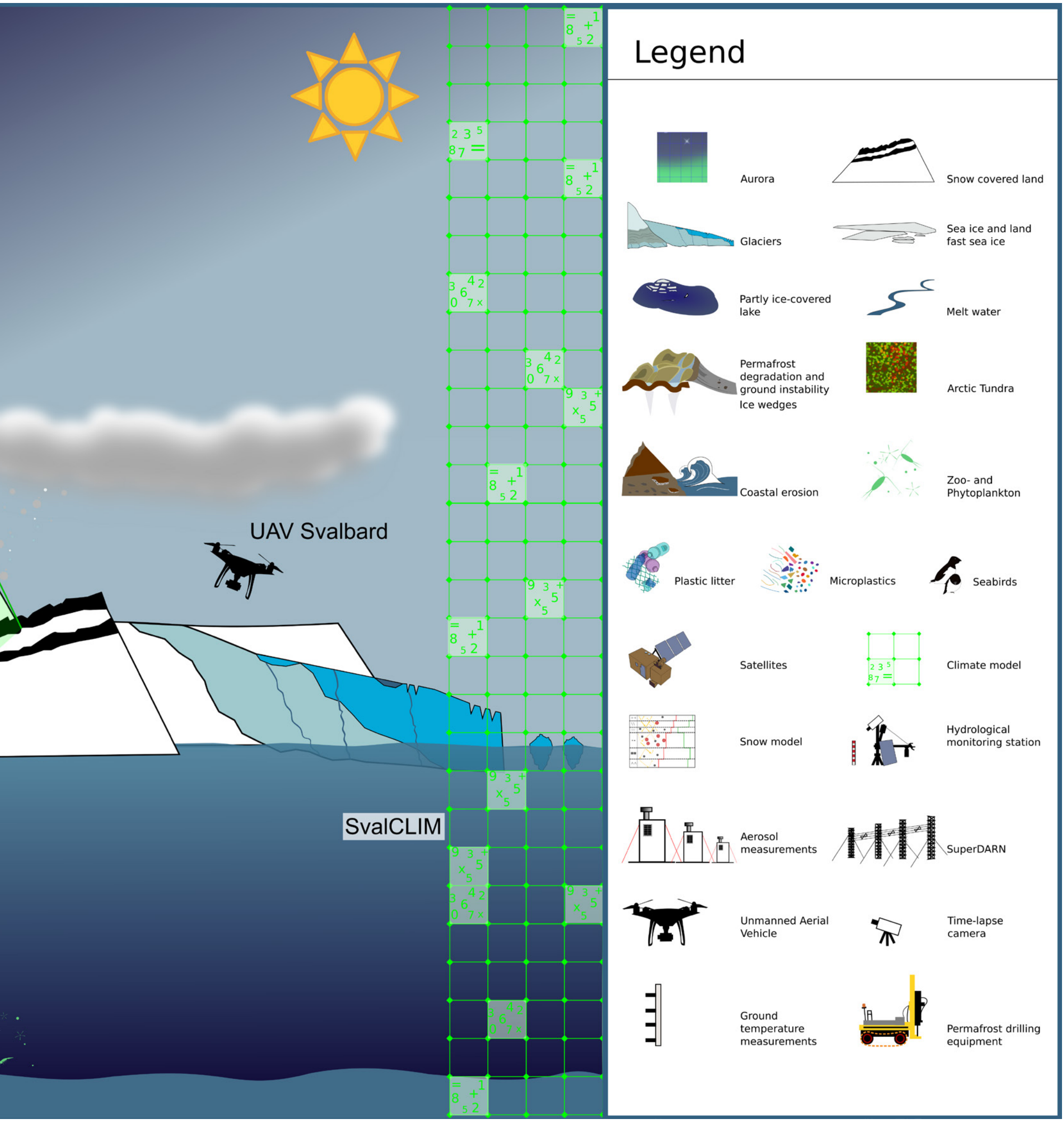
Climate change is not the only problem of anthropogenic origin affecting Svalbard. The archipelago is also affected by plastic waste, which is an emerging global issue. Microplastics are plastic fragments (1 µm to 5 mm in size) that originate from both primary (e.g. cosmetics) and secondary (fragmentation of plastic products) sources. Microplastics debris has been found in sea ice, snow, water, sediment and biota samples from Svalbard. A holistic view of the microplastics status is crucial for evaluating and communicating the significance of prevention and reduction of plastic pollution in the Arctic (MIRES).

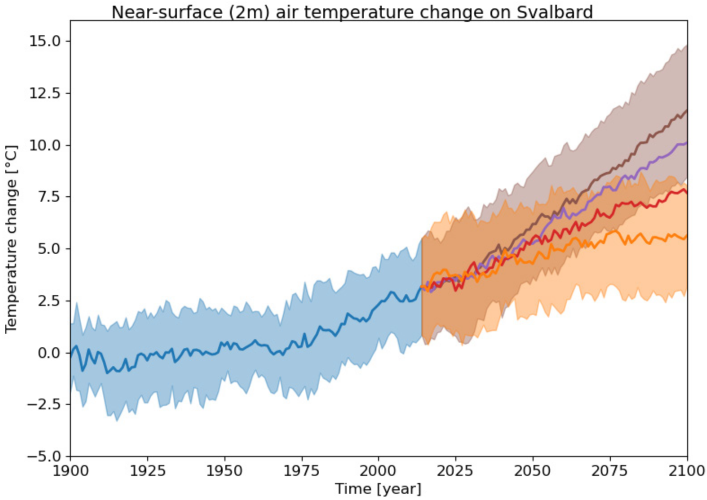
Developing an integrated Arctic Earth observing system is of utmost importance if we aim to better understand the numerous environmental challenges faced by the Arctic. Among the observational platforms available, unmanned aerial vehicles (UAVs) can provide valuable observations around the Svalbard region. To increase collaboration and to allow establishing long-term monitoring datasets, a system to log past, existing, and planned projects with UAVs in Svalbard should be developed (UAV Svalbard). Svalbard is also home to space physics infrastructure, including a wide range of optical and radio instruments. The Svalbard SuperDARN radar is part of a global network of high frequency radars that provide information on the structure and dynamics of the Earth's ionosphere. Among other uses, SuperDARN could support space weather monitoring by providing real-time observations. Unfortunately, SuperDARN was damaged by a severe ice storm in 2018, but it will be rebuilt in 2021 (SuperDARN).

Based on research conducted within the framework of SIOS, the authors of the SESS chapters have highlighted the gaps in our knowledge about the Earth system and suggested concrete actions that should be taken to address these gaps.

The editors would like to thank the authors for their valuable contributions to the SESS Report 2020. Together, these chapters show how SIOS projects contribute to the advancement in the knowledge of the Svalbard region's role in the Earth system.


SATMODSNOW
SuperDARN
HAZECLIC
PASSES
SvalSCESIA
SvalHydro
MIRES
PermaSval
SvalCoast


UAV Svalbard
SvalCLIM
Legend
Aurora
Snow covered land
Glaciers
Sea ice and land fast sea ice
Partly ice-covered lake
Melt water
Permafrost degradation and ground instability
Ice wedges
Arctic Tundra
Coastal erosion
Zoo- and Phytoplankton
Plastic litter
Microplastics
Seabirds
Satellites
Climate model
Snow model
Hydrological monitoring station
Aerosol measurements
SuperDARN
Unmanned Aerial Vehicle
Time-lapse camera
Ground temperature measurements
Permafrost drilling equipment



Model results showing near-surface temperature change, averaged over the globe and the year. Lines show the mean, and shading shows the spread of the historical period and four future projections by an ensemble of 23 models. Results for historical runs (1900-2014) are presented in blue. Orange, red, purple, and brown colours present results based on best-case to worst-case scenarios for the future.

How representative is Svalbard for future Arctic climate evolution? An Earth system modelling perspective (SvalCLIM)

HIGHLIGHTS

- Svalbard displays stronger warming than the Arctic as a whole for the period 1980–2014.
- Over the same period, sea ice melts faster around Svalbard than in the whole Arctic.
- In the worst-case future scenario, winter precipitation and winter temperatures rise less in Svalbard than in the whole Arctic.

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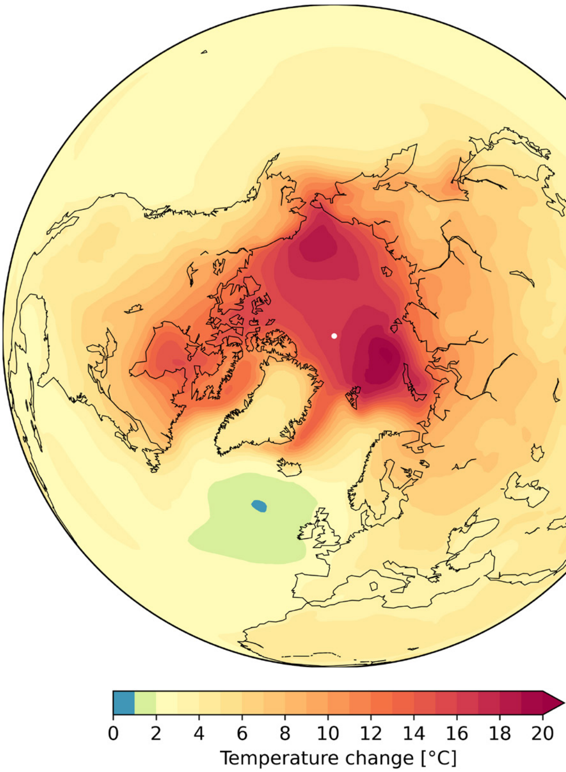
Situated in the Arctic and in a region with relatively pristine conditions, Svalbard is a very important and interdisciplinary observational supersite for the Arctic. In this SESS chapter, we investigate how representative Svalbard is for the Arctic region as a whole using data from numerical simulations with climate models.

In our study comparing model predictions of how temperature, precipitation, and sea-ice extent develop over time, we found that the changes in Svalbard resemble those in the Arctic as a whole, both during the warming period of the past few decades and during projected future climate change. However, some important differences were found (see highlights).

Predicting and characterising climate change in Svalbard will be increasingly important in the 21st century as changes in near-surface air temperature, precipitation and sea-ice extent seem to occur at an extremely high pace in Svalbard, even higher than in the rest of the Arctic. Closer collaboration between experimentalists, observationalists, and the modelling community could help us understand the mechanisms underlying differences between observed and modelled climate changes. SIOS is in a unique position to coordinate and facilitate such collaborative research.

RECOMMENDATIONS

- To cooperate with the Norwegian national Earth System Modelling infrastructure INES to build the modelling tools needed to integrate new SIOS data and explore where comparisons between data from models and observations can provide meaningful answers to questions related to Arctic amplification, abrupt changes, and climate feedbacks.
- To foster e-science tools (and education) so that young researchers working in Arctic climate science can efficiently analyse results from model ensembles, such as CMIP6.
- To initiate and strengthen collaboration with existing pan-Arctic research initiatives and institutions to assemble temporal trends of physical climate variables.
- To identify and document the most efficient international means of cooperation to foster joint understanding of forthcoming Arctic climate changes, possible abrupt climate transitions, and the drivers for such changes.



Projected change in near-surface air temperature in winter (Dec–Jan–Feb) from the baseline (1951–1980) to 2071–2100. The figure shows the ensemble-mean change from 23 CMIP6 models. The future forcing scenario used for these projections represents weak action on mitigating climate change and reducing emissions, shown in purple in figure to the left.

CHAPTER 2

The Svalbard SuperDARN radar, situated at Breinosa. (Photo: Mikko Syrjäsuo / UNIS)

Space Physics in Svalbard: A study of the energy input into the polar ionosphere using SuperDARN

HIGHLIGHTS

To understand, predict and model the upper atmospheric response to energy input from the Sun, we need continuous, long-term observations from many types of instruments. In Svalbard, these data are provided by a wide range of optical and radio instrumentation, including the Svalbard SuperDARN Radar.

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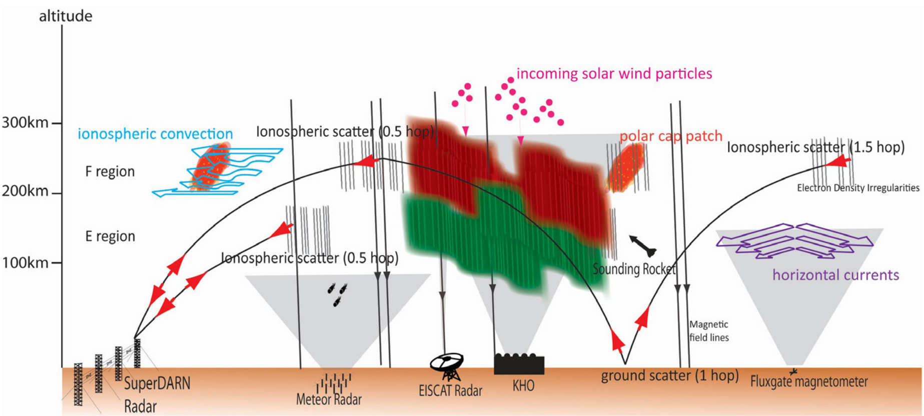
The chapter provides an overview of Norwegian space physics infrastructure in Svalbard (owned either individually or through collaborations) with a particular focus on the Svalbard SuperDARN (Super Dual Auroral Radar Network) radar. This new radar, located on Breinosa near the Kjell Henriksen Auroral Observatory (KHO), is the only Norwegian-owned radar in a global network of more than 30 radars. They are designed for studying flows and turbulence in the upper atmosphere (100-300 km altitude), driven by interactions between the magnetic fields of the Sun and the Earth. The Svalbard SuperDARN radar fills an important gap in the spatial coverage of SuperDARN and complements the other research infrastructure mentioned in the report. The radar operated continuously from October 2016 – October 2018, before being damaged by a large ice storm. It will be rebuilt in 2021. The report highlights the important scientific achievements of the radar, with an emphasis on localised upper atmospheric processes and studies of a more global nature.

Construction of the Svalbard SuperDARN radar. (Photo: Mikko Syrjäsuo / UNIS)

RECOMMENDATIONS

1. Rebuild the Svalbard SuperDARN radar, and secure ongoing funding for maintenance and operational costs.
2. Designate the area on Breinosa (which currently includes the SuperDARN and EISCAT radars and KHO) as a research infrastructure zone, and limit land rental costs. Excessive costs unnecessarily deplete research budgets and divert funding away from core research.
3. Construct a second SuperDARN radar on the same site as the current radar, with a field of view covering the region southwest of Svalbard. This would cover the flight path of sounding rockets from Ny-Ålesund and complement the fields of view provided by existing All-Sky Cameras and any newly developed SuperDARN radars in Iceland.
4. Develop a collaboration between Norway and North America to build the real-time space weather monitoring capability of SuperDARN, including tracking of space weather disturbances across the polar cap, and monitoring HF radio absorption.
5. Support an extension to the Longyearbyen meteor radar to allow 2-D measurements of the atmospheric velocities and temperatures in the mesosphere. This would provide a complementary dataset to the higher altitude SuperDARN dataset.

A schematic showing some of the of space physics phenomena and the instrumentation used to study them from Svalbard. (Illustration: Lisa Baddely / UNIS)



CHAPTER 3

Drone operations in front of Nordenskiöldbreen. (Photo: Richard Hann)

Scientific Applications of Unmanned Vehicles in Svalbard (UAV Svalbard)

HIGHLIGHTS

- We reviewed the scientific usage of unmanned vehicles in Svalbard.
- Off-the-shelf drones are most common, followed by fixed-wings, and marine vehicles.
- We recommend giving SIOS partners access to more platforms and services.
- Long-term data storage and open access to data should be facilitated.

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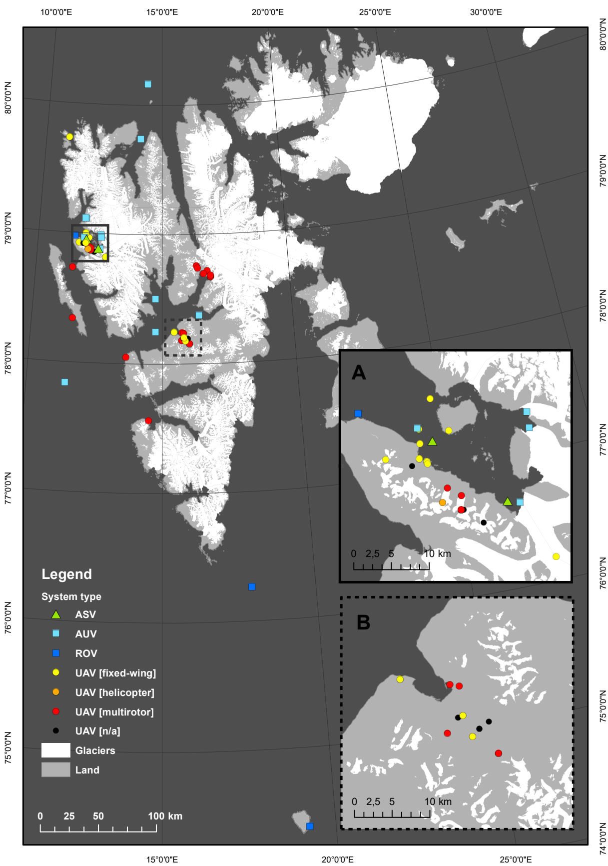
The polar regions are among the most sensitive areas of the Earth and changes in the Arctic have global consequences. Therefore, more and better Arctic research is needed, and unmanned vehicles are an important tool in this research. This report provides a review of research conducted with unmanned vehicles in Svalbard. That includes vehicles that travel in air, on water and underwater. The main focus is on unmanned aerial vehicles (UAVs). UAVs are well-suited for Arctic research for several reasons. The Arctic regions lack high vegetation and big settlements, making them ideal for aerial observations. UAVs can access glaciers, mountains, and other difficult areas. They are cheaper and have a lower environmental impact than manned flights. Svalbard has an international research infrastructure and frequent flight connections, making it a hotspot for Arctic research. However, there are several challenges to the use of unmanned vehicles in the Arctic. These include magnetic interference, low temperatures, harsh weather conditions, and wildlife. Most optical sensors cannot be used during the dark season between October and February. This review shows that the researchers using unmanned vehicles in Svalbard can be divided into two groups: basic and advanced users. The majority of researchers today are basic users. They use off-the-shelf UAVs to enhance their fieldwork. The most common application is mapping. A minority of the researchers are advanced users. This group includes users of unmanned marine vehicles and fixed-wing UAVs.

RECOMMENDATIONS

We suggest both increasing the number of basic users, as well as encouraging mature basic users to become advanced users. To achieve this, we have four main recommendations:

1. Establishing an outreach and experience transfer program for SIOS partners to train them in the use of unmanned vehicles.
2. Giving SIOS partners access to more platforms and piloting services, as well as providing consultation on regulations.
3. Developing best-practice standards that include data collection methods, processing methods, specification of sensors and systems, access to raw data, and data formats.
4. Facilitating long-term data storage and open-access sharing of data to make the projects more relevant for long-term monitoring.



Overview of unmanned vehicle activities in Svalbard. Location of study sites: A: Kongsfjorden region; B: Adventdalen region; ASV - Autonomous Surface Vehicle, AUV - Autonomous Underwater Vehicle, ROV - Remotely Operated Vehicle, UAV - Unmanned Aerial Vehicle

CHAPTER 4

Gruvebadet and Mt Zeppelin observatories. (Photo: Mirko Severi)

Arctic haze in a climate changing world: the 2010-2020 trend (HAZECLIC)

HIGHLIGHTS

Arctic haze is relevant in controlling the Arctic atmosphere. Long-term studies reveal change in the extent and composition of the haze. Sulphate and sulphate:ammonium ratios were analysed at two altitudes in Ny-Ålesund. Sulphate levels have declined in the first decade of the 21st century.

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The phenomenon of Arctic haze was studied in Ny-Ålesund at two observatories close to each other but at different altitudes (Gruvebadet and Mt Zeppelin, 50 m and 700 m a.s.l.). The sites are influenced by a different mix of sources and transport processes: mainly long-range sources and free troposphere at Mt Zeppelin and short-range inputs at Gruvebadet. These two complementary sites offer a way to better understand advection of polluted air masses to Svalbard at continental and local-to-regional scale. The data series from Mt Zeppelin covers the last 27 years while the Gruvebadet data series begins in 2010. Here we present the first comparison of the available data on chemical tracers for this potentially harmful phenomenon (sulphate and ammonium), to be developed further by taking into account other tracers. Sulphate concentrations in the atmosphere have been decreasing in the Arctic since the 1990s


Walking to Gruvebadet observatory during a day with Arctic haze. (Photo: Rita Traversi)

RECOMMENDATIONS

To confirm the trends described here about sulphate concentration and acidic/alkaline character of the atmosphere, continuous long-term measurements are needed at Gruvebadet and Zeppelin, particularly during winter/early spring (Arctic haze months).

Analysis of the chemical composition (sulphate, ammonium, nitrate, organic and black/elemental carbon) of the particulate matter collected will allow more accurate discrimination between natural and anthropogenic sources.

A thorough comparison between the data series from the two sites is needed to better constrain the impact of the haze and identify a "local" and "long-range" signature in Svalbard.

(in line with falling SO2 emissions). Our data show continued decreases at roughly the same rate also in the first decade of the 21st century. Moreover, we find that this decrease is particularly intense during Arctic haze months (winter and early spring), whereas in autumn the concentrations are constant or slightly rising. Decreases in sulphate may have opposing fallouts on climate, environment and human health in Svalbard, since the atmosphere is becoming poorer in sulphuric acid, favouring an additional warming of the atmosphere (lower scattering effect on incoming solar radiation) and modifying the chemistry of the atmosphere (towards a more alkaline character, richer in ammonia).


Trained personnel checking aerosol cut-off devices on the roof of Gruvebadet observatory. (Photo: Rita Traversi)

CHAPTER 5

Photo: Jon Aars

Microplastics in the realm of Svalbard: current knowledge and future perspectives (MIRES)

HIGHLIGHTS

The findings of microplastics in sea ice, snow, water, sediment, and biota samples in Svalbard show that the archipelago is not isolated from pollution generated in other parts of the world and plastic pollution in the region must be monitored.

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Plastic pollution is an increasing problem worldwide including in Svalbard and the Arctic more widely. This includes microplastics (MPs) i.e. the fraction of plastic smaller than 5 mm. MPs are ingested by a wide range of organisms like zooplankton, crustaceans, fish, seabirds and mammals. Once ingested, MPs can potentially affect the organisms either by obstruction and abrasion, by releasing the associated chemicals and adsorbed contaminants (plasticisers, persistent organics pollutants), or by adverse effects of the particles themselves. Humans are exposed to MPs, amongst other pathways, by consuming contaminated food.

We find MPs in sea ice, snow, water, deep-sea sediment, beaches and organisms (amphipods, fish) at different locations

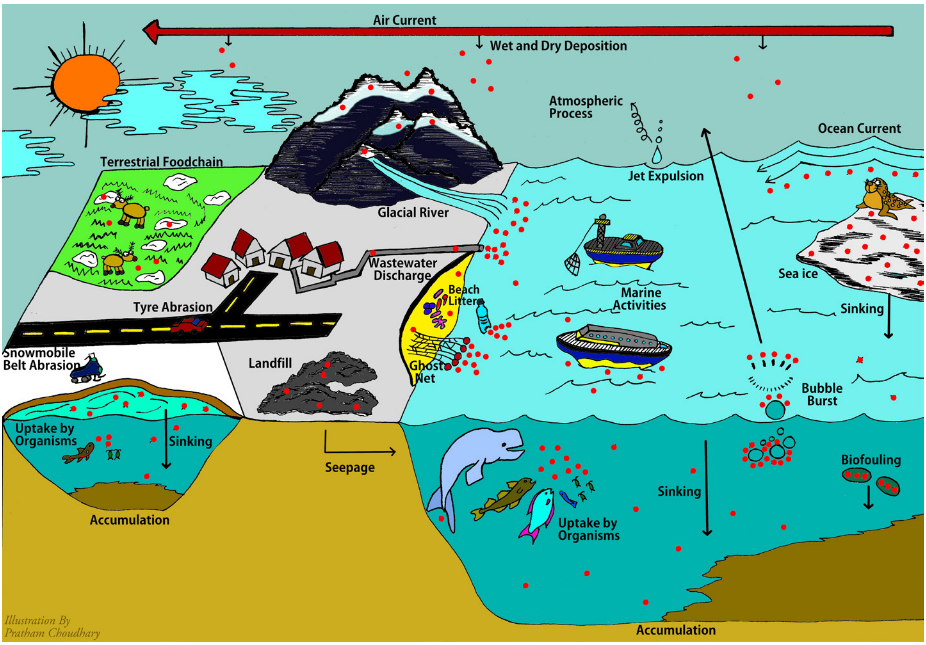
Photo: Susanne Kühn

in Svalbard. The best available evidence gathered by monitoring and research suggests that MPs pollution is likely to have negative effects in Svalbard, at least at long time scales. A good view of MPs status based on our current understanding and adopting a future perspective is crucial for evaluating and communicating the significance of preventing and reducing plastic pollution in the Arctic.

RECOMMENDATIONS

- **Harmonising methodologies:** A workshop is needed to facilitate agreements among international MPs experts on how to start monitoring MPs at Svalbard's four observatories (Hornsund, Barentsburg, Longyearbyen, Ny-Ålesund). The work currently being finalised by AMAP on MPs monitoring will be highly valuable.
- **Long-term monitoring:** A monitoring programme should be designed to consider societal needs such that science can provide advice regarding plastic use in Svalbard, wastewater treatment, effects of cruises and other tourism activities, and fishing.
- **Mapping:** MPs in the unexplored parts of Svalbard, which include terrestrial and marine biota, need to be mapped to establish a proper risk assessment for both the environment and human consumers.
- **Collaboration:** A Svalbard plastics task force should be formed and meet regularly to develop methods and monitoring recommendations, to ensure that there is a concerted effort to fill the identified knowledge gaps.
- **Experiments:** Experimental studies of Arctic key species and the possible trophic transfer of MPs under Arctic conditions should be set up.

Potential sources and pathways of microplastics in Svalbard. (Illustration: Pratham Choudhary)



CHAPTER 6

Since 2005 a five-fold increase in the macroalgal cover has been observed in western Spitsbergen. In northern and eastern Svalbard, most rocky shores are still barren due to sea ice scouring. (Bohemanneset. Photo: Josef Wiktor, IOPAN)

Environmental status of Svalbard coastal waters: coastscapes and focal ecosystem components (SvalCoast)

HIGHLIGHTS

- First coastscape mapping of Svalbard
- Recent warming and sea-ice loss has increased intertidal species richness and biomass in western Svalbard
- Ecological losers include cold-adapted species that rely on sea ice
- The next decade's greatest environmental changes are expected in northeastern Svalbard

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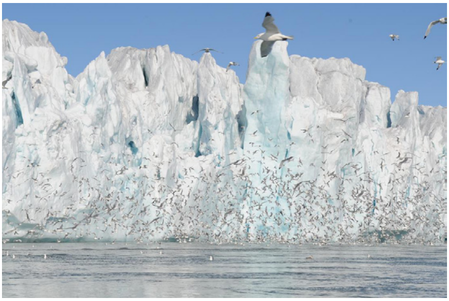
Coastal waters are among the most productive regions in the Arctic. These nearshore waters are critical breeding and foraging grounds for many invertebrates, fish, birds, and marine mammals and provide a host of ecosystem services, from private outdoor activities to large-scale tourism and fisheries. Arctic nature coast types (= coastscapes)

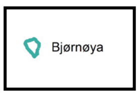


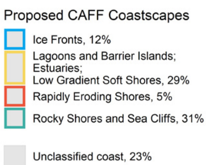
Tidewater glacier fronts are important feeding areas for seabirds and marine mammals. The Ice Front coastscape is particularly vulnerable to climate change. (Photo: Kit M Kovacs and Christian Lydersen, NPI)

RECOMMENDATIONS

- Monitor environmental and ecosystem trends in both warm and cold regions in Svalbard
- Improve international coordination and cooperation to develop and maintain the infrastructure and activities required to achieve a more holistic coastal observatory in Svalbard
- Generate a list of Svalbard-specific standard coastscapes (i.e. nature types)
- Agree on a list of essential focal ecosystem components (e.g. bio-indicators) to be monitored in these coastscapes
- Adopt new methods (e.g. molecular methods) and technology (e.g. autonomous observatories, remote sensing) to secure cost-efficient long-term data series

and biodiversity are under growing pressure as climate change and human activities increase in the region. More data on the rates of change in the physical, chemical and biological environments in these highly dynamic and heterogeneous coastscapes are urgently needed. Svalbard is warming more rapidly than anywhere else in the Arctic, and the Arctic is warming at 2-3 times the rate of other areas globally. Svalbard experiences steep climate gradients due to being situated at the interface between warm Atlantic and cold Arctic waters. Warming is creating a huge potential for increased colonisation by boreal species, with potential negative impacts on "native" species assemblages and food webs. Changes in physical drivers and biodiversity patterns must be documented to predict upcoming challenges and opportunities as the Arctic changes. This synopsis is the first joint effort across nations, institutes, and disciplines to address current gaps in knowledge and monitoring of Svalbard's coast – a result of the international workshop Svalbard Sustainable Coasts in Longyearbyen, February 2020. Another important task of this synthesis work was to look into the applicability of the defined coastscapes and biodiversity tools in the Arctic Coastal Monitoring plan, initiated by the Arctic Council's Conservation of Arctic Flora and Fauna (CAFF, www.caff.is), for Svalbard.





The first mapping of Svalbard's coastscapes as defined by CAFF's Arctic Coastal Biodiversity Monitoring Plan, is based on aerial photos of 77% of Svalbard's coastline (8 739 km) taken by the Norwegian Polar Institute (1987-1991). (Map: Norwegian Polar Institute)

CHAPTER 7

An example of a braided river in a glacierised catchment. Adventelva inflow into Adventfjorden. (Photo taken by A Nowak in August 2019)

From land to fjords: The review of Svalbard hydrology from 1970 to 2019 (SvalHydro)

HIGHLIGHTS

Hydrological response to ongoing environmental revolution in the Arctic is the most important research topic, yet long-term monitoring is sparse. Dramatic warming forces us to rethink water balance. Not all catchments are delivering increasing amounts of water to the polar ocean.

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Svalbard was long seen as a canary in the coalmine for climate change. Now this early warning system has suffered irreparable damage. Svalbard has warmed 2-6 times faster than the rest of the world, and we can expect further increase in air temperature (by 4–7°C), precipitation (by 45–65%) and more frequent heavy rainfall and floods.

Contrary to predictions from regional climate models, freshwater fluxes from some glacierised catchments have steadily decreased for over a decade. Yet in rainfall dominated watersheds, water discharge has been increasing. To understand the implications, we must improve hydrological research in Svalbard.

Ground newly uncovered by receding glaciers develops permafrost when exposed to harsh Arctic winters. Simultaneously, permafrost thaw produces new

UNIS students performing maintenance of a hydrological monitoring station in Adventdalen during flood. (Photo: A Nowak)

water sources and flowpaths. Current hydrogeological models do not account for such complexity.

The boundaries of the hydrological year have shifted due to earlier onset of snowmelt, and later freeze up.

Other weaknesses in hydrological research come from scarcity of long-term monitoring, outdated methods and data for evaporation and condensation and a lack of data on precipitation change with elevation.

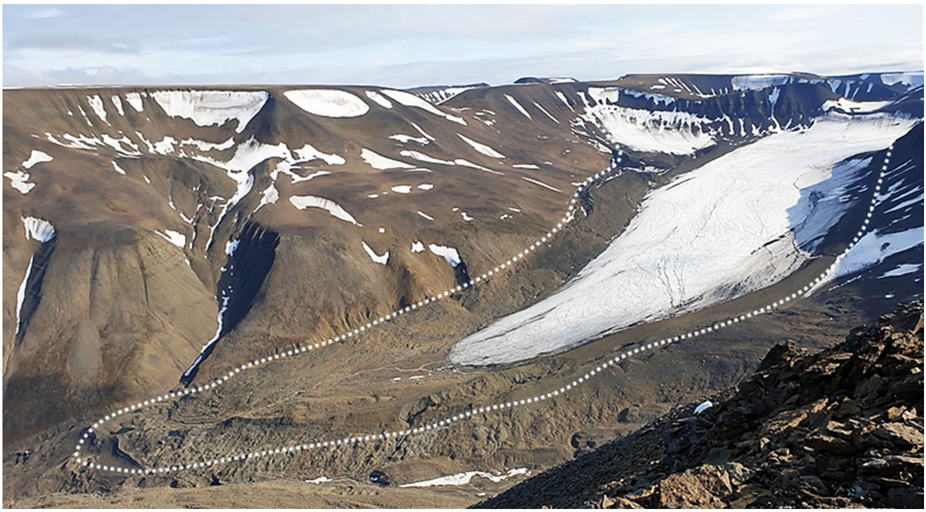
RECOMMENDATIONS

We must close the water budget for the Norwegian High Arctic. We recommend upgrading existing sites (Hornsund, Grøndalen, Adventdalen, DeGeerdalen, Kaffiøyra, Ny-Ålesund) and establishing new supersites for hydrological research. The main action points are:

- **Establish long-term hydrological monitoring** yielding easily accessible data:
- **Autonomous meteorological and hydrological monitoring** on:
  - Svalbard's east coast e.g. Væringsdalen or Eistradalen
  - Northern Svalbard e.g. Svartdalen, Mosselhalvøya
- Permanent hydrological monitoring in Endalen and Gruvedalen (Longyearbyen's drinking water)
- **A network of meteorological stations across a range of elevations** (Longyeardalen, Hornsund, Ny-Ålesund, Svalbard's east and north coasts)
- **Set up time-lapse cameras** in catchments to capture onset of snowmelt
- **Measure water flux in the active layer**
- **Use multi-sensor remote sensing** to obtain water balance data from inaccessible places and improve spatial coverage in monitored areas.

As every new broken record reminds us, it is more urgent than ever to understand Svalbard's hydrology.

Fleinisen, a valley glacier in the process of recession. Dashed line represents the extent of the glacier in the 1920s. (Photo taken by A Nowak in August 2019)



CHAPTER 8

Snow field campaign on Longyearbreen 2018. (Photo: Rolf-Ole Jenssen)

Satellite and modelling based snow season time series for Svalbard: Inter-comparisons and assessment of accuracy (SATMODSNOW)

HIGHLIGHTS

We compared six time series of snow cover from satellite and models for Svalbard between 1957-2020. The significant differences between datasets could in part be explained by differences in spatial resolution. Future work should lead to better integration of models and improved reanalysis of historical snow data over Svalbard.

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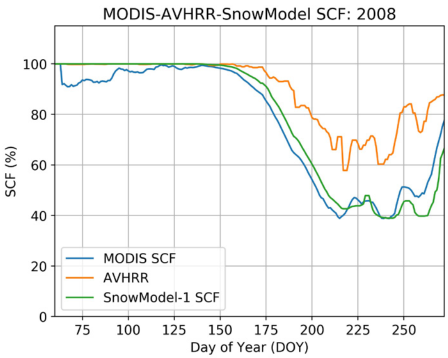
We document differences and similarities between three satellite-based and three model-based snow cover datasets, showing the geographical distribution and amount of snow across Svalbard for several periods from 1957 to 2020. The study shows that the datasets have many differences and that work needs to be done to accurately represent the snow cover in Svalbard. Low resolution datasets tend to predict longer winters than higher resolution datasets.

We studied differences between the datasets and suggest methods to improve each dataset. Satellite data have been available since 1978, but early sensors had low resolution, and can only provide correct information over larger areas. Current sensors, available since 2016, have high resolution. Older low-resolution data may be improved by utilising overlapping time-series of high- and low-resolution data since local snow distribution patterns recur annually with a time-shift depending on average temperature and precipitation during the winter.

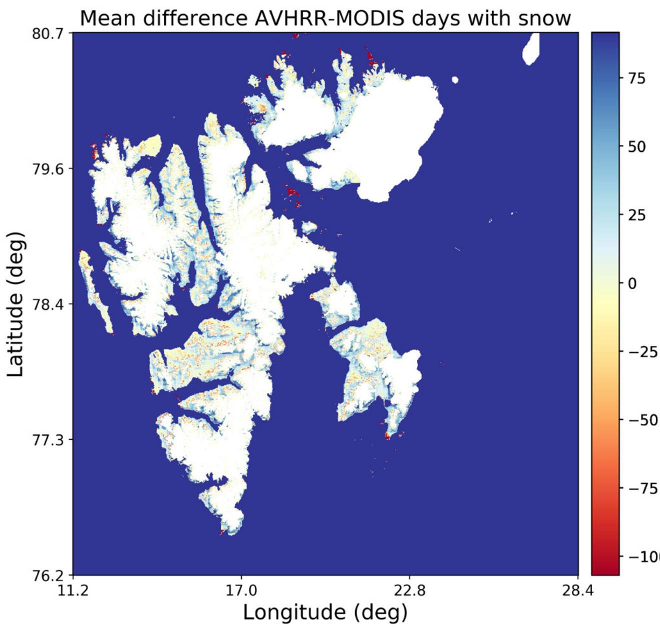
The snow models predict in general the amount of snow (Snow Water Equivalent or SWE), but the timing of snow disappearance predicted by the models can be compared with estimates from satellite snow cover observations. Since the snow models depend on uncertain models of precipitation and temperature to estimate SWE there is potential to integrate satellite data to improve the models for snow in the future.



Comparison of the average snow cover fraction (SCF) for entire Svalbard for 2008 based on satellite data from MODIS (moderate resolution) and AVHRR (high resolution) and on predictions by the model from Uppsala University. Note that AVHRR overestimates snow cover during summer, whereas MODIS and SnowModel are in good agreement.

RECOMMENDATIONS

- Combine efforts from snow cover models and Earth Observation (EO) data to compile a long-term time series of snow cover data that covers the period 1978-2020 with as high spatial resolution as possible
- Future efforts should integrate multi-source EO data (in situ, airborne and satellite observations) with new techniques (e.g., AI and data assimilation) to further improve the characterisation of snow cover and SWE in Svalbard
- Hydrologists should utilise EO data from remote sensing to improve hydrological models in order to capture snow cover distribution and simultaneously improve SWE estimates
- Future datasets from EO should be compared with corresponding layers from modelling (e.g. liquid water content)
- Snow measurement infrastructure in Svalbard needs improvements for providing more calibration and validation data for both models and EO datasets



Average difference for the period 2000-2015 in number of snow days between satellite data from MODIS (moderate resolution) and AVHRR (high resolution). AVHRR frequently underestimates snow cover fraction in lowlands and overestimates it in highlands as compared to MODIS.

On-site measurements of the snowpack are performed annually to monitor and analyse its physical properties over time and space, their inter-annual variability and long-term trends. These measurements cover the main ecological and climatic gradients from the outer fjord areas to the inner part of the valley. (Photo: Ketil Isaksen, from March 2019 at Platåberget outside Longyearbyen, view towards Isfjorden)

Svalbard snow and sea-ice cover: comparing satellite data, on-site measurements, and modelling results (SvalSCESIA)

HIGHLIGHTS

Satellite monitoring over 1982-2015 shows earlier onset of snow melt in Svalbard. The most pronounced shift is in valleys, where the ground is snow-free 1-2 days more every year during summer. Snow cover variability in lowlands correlates with the variability of sea ice in the adjacent seas, especially in June.

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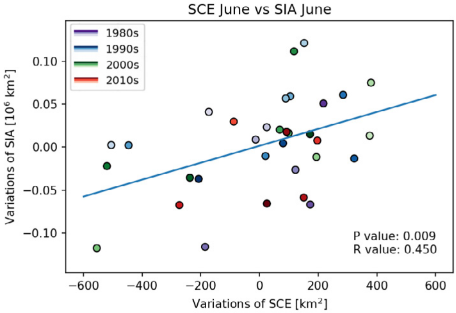
Fundamental knowledge gaps and scaling issues hamper efforts to determine how changes in snow cover and snow distribution affect ecosystems. The presence of snow cover has huge impact on Arctic ecosystems, human activities, atmospheric processes and Earth's surface energy balance. Mapping snow cover over large regions is challenging because of its variability over time and space. Also, the small number of weather stations that measure snow cover contributes to a poor observational base. Svalbard is located on the border between the ice-covered Arctic Ocean and the warmer North Atlantic, which means the sea is a controlling factor for Svalbard's climate. By using remote sensing monitoring it is possible to get a better overview of snow conditions on land. This information can be compared with on-site observations of snow, output from snow models, and evaluated in relation to the sea-ice extent in the adjacent sea. A 34-year satellite data record for snow cover indicates that snow now starts melting more than a week earlier. The total number of snow-free days in summer is increasing fastest in regions dominated by lowland valleys and coastal plains. Most noticeable are the trends centred near the large valleys of Nordenskiöld Land. Negative trends dominate the extent of the sea ice as well. There is significant and positive correlation between sea-ice area and snow-cover extent at elevations up to 250 m in June, the month when snow melt begins. Snow melt, again, is probably strongly affected by ocean–air interactions and energy exchange when warm (or cold) winds from an open (or ice-covered) ocean come in over land.

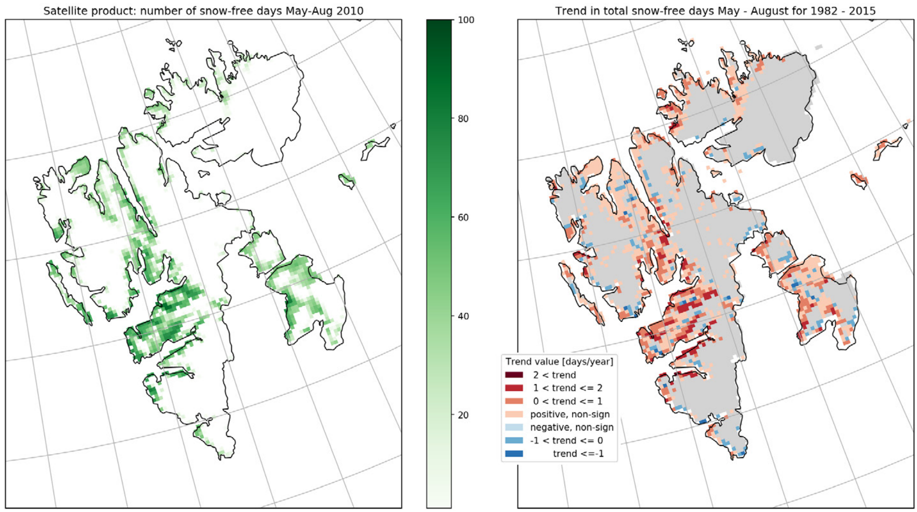
RECOMMENDATIONS

The ecosystem impact of changing snowpack properties in a warming climate is an important arena for interdisciplinary research between ecology and geophysics. Besides co-location of research infrastructure, there is a need to develop a system that merges available observational datasets on snow properties with state-of-the-art, high-resolution (1-to-500-metre scale), physically based snow models. The goal of this data–model fusion system is to create accurate datasets that have good spatial distribution and evolve with time. Such datasets can be used to better understand relationships between ecosystem processes.



The correlation between sea-ice area (SIA) and snow-cover extent (SCE) for June. Each dot represents a year during 1982-2015. The line illustrates the positive correlation between the two.

The left panel shows the number of snow-free days during May–August 2010. The right panel shows the trend in total snow-free days during May–August over the period 1982–2015. Reds indicate trends toward more snow-free days and blues toward fewer snow-free days.



CHAPTER 10

Time-lapse camera at the summit of Fugleberget in Hornsund. (Photo: Daniel Kępski)

Terrestrial photography applications on snow cover in Svalbard (PASSES)

HIGHLIGHTS

Time-lapse cameras are important sources of data, offering an efficient and economically advantageous way to observe changes in the Svalbard environment. For snow cover monitoring using cameras, it is important to identify potential image providers, archived imagery, and processed datasets.

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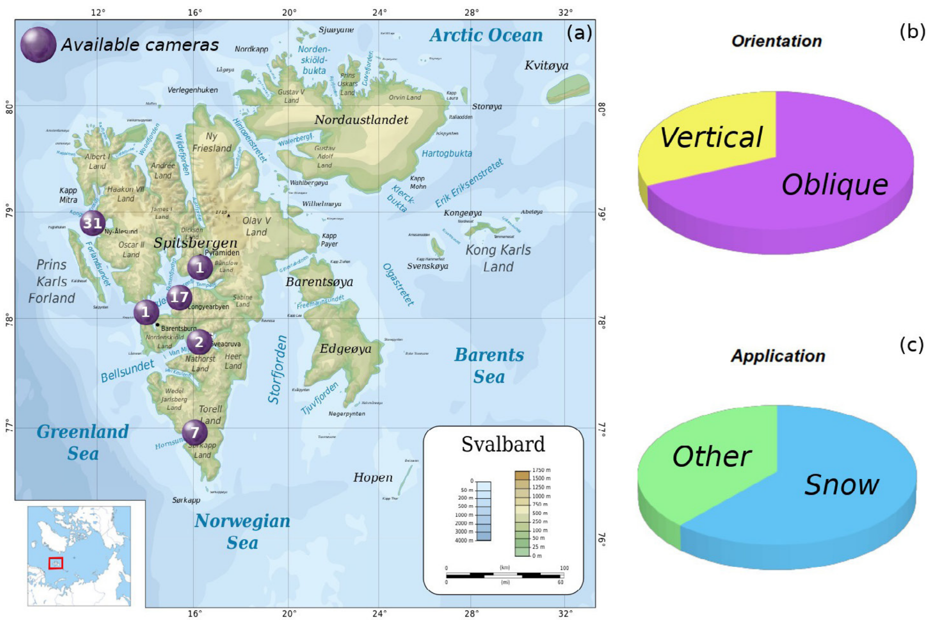
Ground-based observations are critical requirements for many disciplines that are trying to monitor climate change in a remote environment such as the Svalbard archipelago. This overview of cameras operating in Svalbard has been compiled by searching for specific applications that monitor the snow cover and by collecting information about images that can be accessed on the internet, including those not solely dedicated to cryospheric research. The survey identified 43 cameras operating in the region that are managed by research institutions and private companies. These cameras include facilities operated by different nationalities. The datasets vary, but the feasibility of using them to determine fractional snow cover is generally limited. Identifying the key metadata necessary to survey the available devices revealed problems and knowledge gaps that prevent using the full potential of terrestrial photography networks in Svalbard.

Time-lapse cameras at the Climate Change Tower in Ny-Ålesund. (Photo: Roberto Salzano)

RECOMMENDATIONS

The usefulness of time-lapse camera networks for snow cover monitoring and related studies can be enhanced through:

1. Promoting actions and projects based on using time-lapse cameras, especially in the more remote areas of Svalbard. Most terrestrial photography setups focus on Spitsbergen's shores, close to settlements. There are no cameras that cover terrain at higher elevation. Monitoring such areas is crucial for calibration and validation of satellite snow products.
2. Stimulating the creation of a Svalbard camera system network. Although all cameras provide valuable scientific data, it is currently difficult to use all the data collectively for one scientific purpose. There is a need to establish a common approach for processing images obtained by devices aimed at snow cover applications.
3. Creating a space on the SIOS website that gathers information about actively maintained camera systems in Svalbard.
4. Promoting the estimation of the fractional snow-covered area from images obtained by time-lapse cameras not specifically devoted to snow studies. This will facilitate the involvement of local communities in participatory forms of science.
5. Stimulating the use of time-lapse cameras by different disciplines where high resolution information can be retrieved for various purposes.



First survey of time-lapse cameras available in Svalbard (a). Fraction of cameras with vertical versus oblique setups (b) and fraction that show snow cover (c). (Figure: Roberto Salzano)

CHAPTER 11

Photo: Dariusz Ignatiuk

A multi-scale approach on snow cover observations and models (SnowCover)

HIGHLIGHTS

Long time-series on various snow parameters are crucial to many disciplines, including climate research.

Arctic snow cover can be monitored precisely but locally (*in situ* measurements), or broadly but at low resolution (satellite imagery).

Combined, these methods complement and enhance each other.

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Data on snow properties such as cover fraction, depth, water equivalents, and melt date are important *per se*, but also as input in various models, and to verify model results. Earth observation (EO) gathers information on these parameters. Different EO methods for snow have different strengths. Manual measurements and locally deployed sensors give precise data, but only at individual sites. Satellite-based methods give huge amounts of data covering vast areas, but at lower resolution, and only when the satellite passes over relevant sites.

Three SIOS projects attempt to bridge the spatial and temporal gaps between remote sensing data and point measurements of snow cover.

PASSES gathers information about time-lapse cameras already deployed around Svalbard for research or other purposes.

Most of them show snow-cover extent on an intermediate scale (10 m^2 to 10 km^2), with good temporal resolution. Some have been in place for 20 years, providing a valuable historic record.

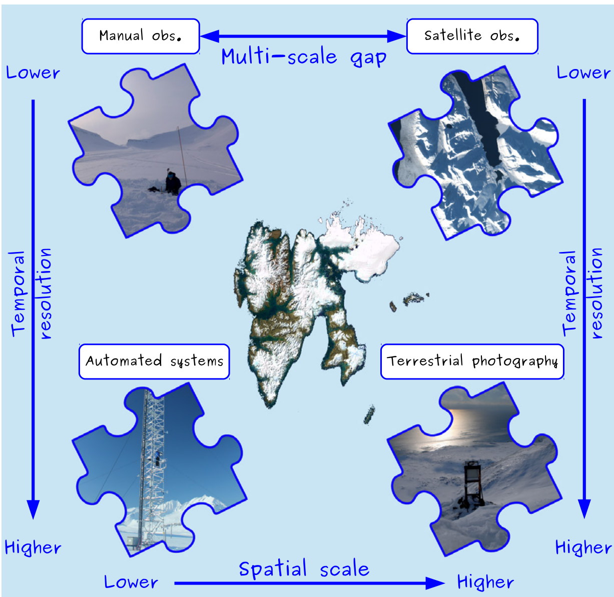
SATMODSNOW finds that discrepancies between satellite data and model results arise from weaknesses in how the models handle precipitation and temperature. Since snow cover disappears in similar patterns every year, with a time shift depending on precipitation and temperature, close examination of satellite observations offers a way to refine hydrological snow models.

SvalSCESIA compares satellite data on both sea-ice area and snow cover against ground-based monitoring data and snow model output. They find major shifts in the duration of summer snow-free periods, especially in valleys and lowlands. Snow cover also correlates with the ice cover in adjacent seas, indicating a strong effect of energy exchange between land and sea.

Integration and intercomparison of EO data obtained with different methods and on different scales will likely improve snow models.

RECOMMENDATIONS

- Compare and inter-calibrate snow products covering spatial scales from 4 km to <1 m to better understand melt patterns.
- Establish a SIOS super-site containing snow-related remote sensing data and ground measurements of snow, for calibration/validation activities.
- Create and maintain an inventory of existing EO monitoring systems for snow cover in Svalbard.
- Investigate ways to incorporate EO data into snow-related models.



The representation of a multi-scale strategy aimed at solving the gap existing between in situ measurements and satellite observations: the snow cover observed from different perspectives. The gaps between different spatial and temporal scales need to be bridged using sensors in the intermediate scale range (e.g., airborne sensors) to understand and remove uncertainties in long-term snow time series based on coarse-scaled satellite data and modelling.

CHAPTER 12

Ice-rich permafrost at 150 cm depth from the Endalen borehole site. The darkest parts are ice lenses, while the rest are cobbles and sediment. (Photo: Ullrich Neumann)

Ground ice content, drilling methods and equipment and permafrost dynamics in Svalbard 2016-2019 (PermaSval)

HIGHLIGHTS

In 2016-2019 the top permafrost cooled and permafrost at 10-20 m continued warming slightly at most Svalbard observation sites. Active layer thicknesses decreased but doubled at a blockfield site. Permafrost ice content is largest in valley bottom sediments up to 160%, but typically below 15% in bedrock.

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The observed mean annual permafrost temperature data for the period 2016-2019 at 10-20 m depths show a range from no warming in the Adventdalen, Ny-Ålesund and Barentsburg areas, up to 0.15°C/yr warming in inner Adventdalen at Janssonhaugen. This shows that there is still a response to the general warming that Svalbard has seen over the last decades. During the observation period, the mean annual air temperature declined by 0.6°C, with a particular cooling in the autumns. There was a clear reduction in the amount of precipitation of 100 mm. This caused the top permafrost temperature to decrease at all observation sites ranging from 0.2°C/yr at Kapp Linné to 0.6°C/yr in Barentsburg.

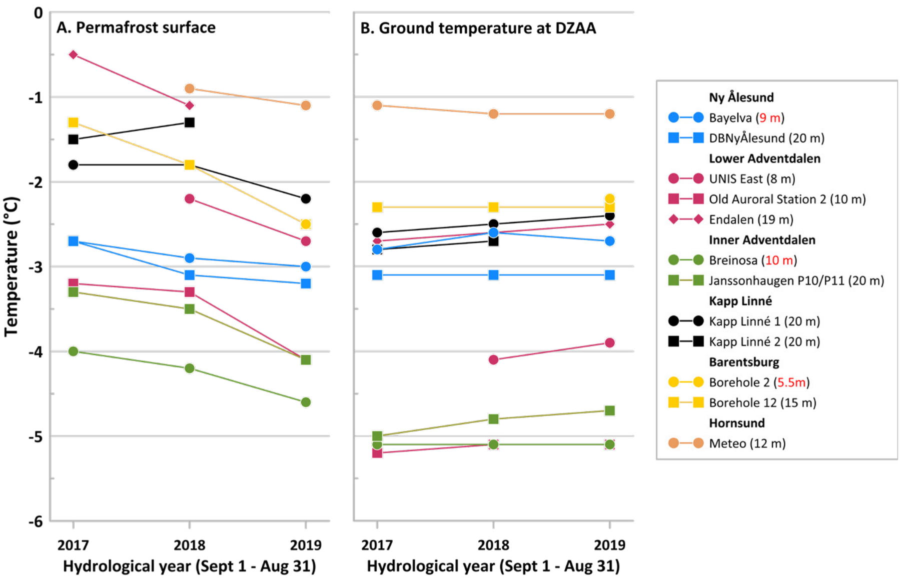
The active layer has mostly decreased slightly in thickness over the 2016-2019 period from 1 cm/yr in Ny-Ålesund to 6.5 cm/yr in Adventdalen, while two sites had small increases, 1 cm/yr at Kapp Linne and 3.5 cm/yr at Janssonhaugen. In the blockfield at Breinosa the active layer doubled to 98 cm, while in raised marine sediments in Barentsburg the active layer thinned by 18.5 cm/yr from summer 2017 to summer 2019.

The ground ice content in the Svalbard permafrost observation boreholes is largest in the permafrost in valley bottom sediments, up to 160% (relative to dry weight), with much less ice in the bedrock sites, typically below 15%. In Adventdalen the permafrost has a much higher content of ground ice, reaching 150% in the top 1-3 m, where terrestrial sediments such as loess and solifluction sediment dominate, and clearly lower ice content ~25-30% in the fluvial and marine sediments below.

RECOMMENDATIONS

- Always collect ground ice and stratigraphy data from long-term permafrost observation sites
- Consider expanding the permafrost observation network
- Perform ground ice studies on slopes
- Get more permafrost Essential Climate Variables and SIOS Core Data operational and online

The overview of the drilling equipment demonstrates clearly that Svalbard is now well-equipped for drilling boreholes with a range of equipment, allowing creation of both deep and shallow boreholes. The review of the drilling methods used for the existing observation boreholes shows that most of them, even though made for permafrost observation, did not collect cores, and some do not even have any stratigraphical record.



Mean annual ground temperature development as recorded at (A) the permafrost surface and (B) the depth of zero annual amplitude (DZAA) or deepest sensor, for the hydrological years 2016-2017 to 2018-2019. DZAA (black text) or location of the deepest sensor (red text) is given in brackets beside each borehole in the legend.

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