SESS REPORT 2021

The State of Environmental Science
in Svalbard – an annual report

SIOS
SVALBARD INTEGRATED ARCTIC
EARTH OBSERVING SYSTEM

SESS REPORT 2021

The State of Environmental Science in Svalbard – an annual report

Josefine Feldner, Christiane Hübner,
Heikki Lihavainen, Roland Neuber,
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The State of Environmental Science in Svalbard
– an annual report

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Foreword

Another year under the shadow of the COVID-19 pandemic has passed. With vaccinations, the world started to open up. Scientific field work was possible to some extent, and it was a pleasure to meet scientists visiting the SIOS office again. We have learned to use virtual tools but also miss meeting people in real life. The Arctic Circle Assembly and the Svalbard Science Conference were the first events I attended in person after the start of the pandemic. Indeed, meeting people face-to-face is an all-embracing experience all in all and virtual tools cannot fully replace it. Even as I write this, restrictions are being reintroduced due to increasing numbers of COVID-19 cases. It is not over yet, but we are also learning a new way of life.

The first funding phase of the host contribution from Norway to support SIOS Knowledge Centre ended last year and new funding has been secured until the end of 2026. I would like to acknowledge the Research Council of Norway for their continuous support for our endeavour. The renewed funding is also a sign that we as a SIOS community have succeeded and are seen as an important actor, not only in Svalbard, but also in the Pan-Arctic and in the landscape of European Environmental Research Infrastructures. Nevertheless, there is still lot to accomplish and for the new funding period we have also renewed the strategy of SIOS.

One of the key strategic objectives is the construction of a roadmap for optimisation of the observing system. The roadmap is built on the renewal of the research infrastructure optimisation report, the SIOS core data process and a synthesis of the recommendations provided by the SESS reports. The SESS report thus plays an important role in the development of the observing system. The SIOS science wheel is a concept showing the development of the SESS report and the associated call for activities. The teeth of the cogwheels that drive SIOS forwards are the working groups and task forces deployed by the governing bodies of SIOS. The science wheel is driven mainly through bottom-up processes such as the SESS report, but is regularly aligned through top-down decisions.

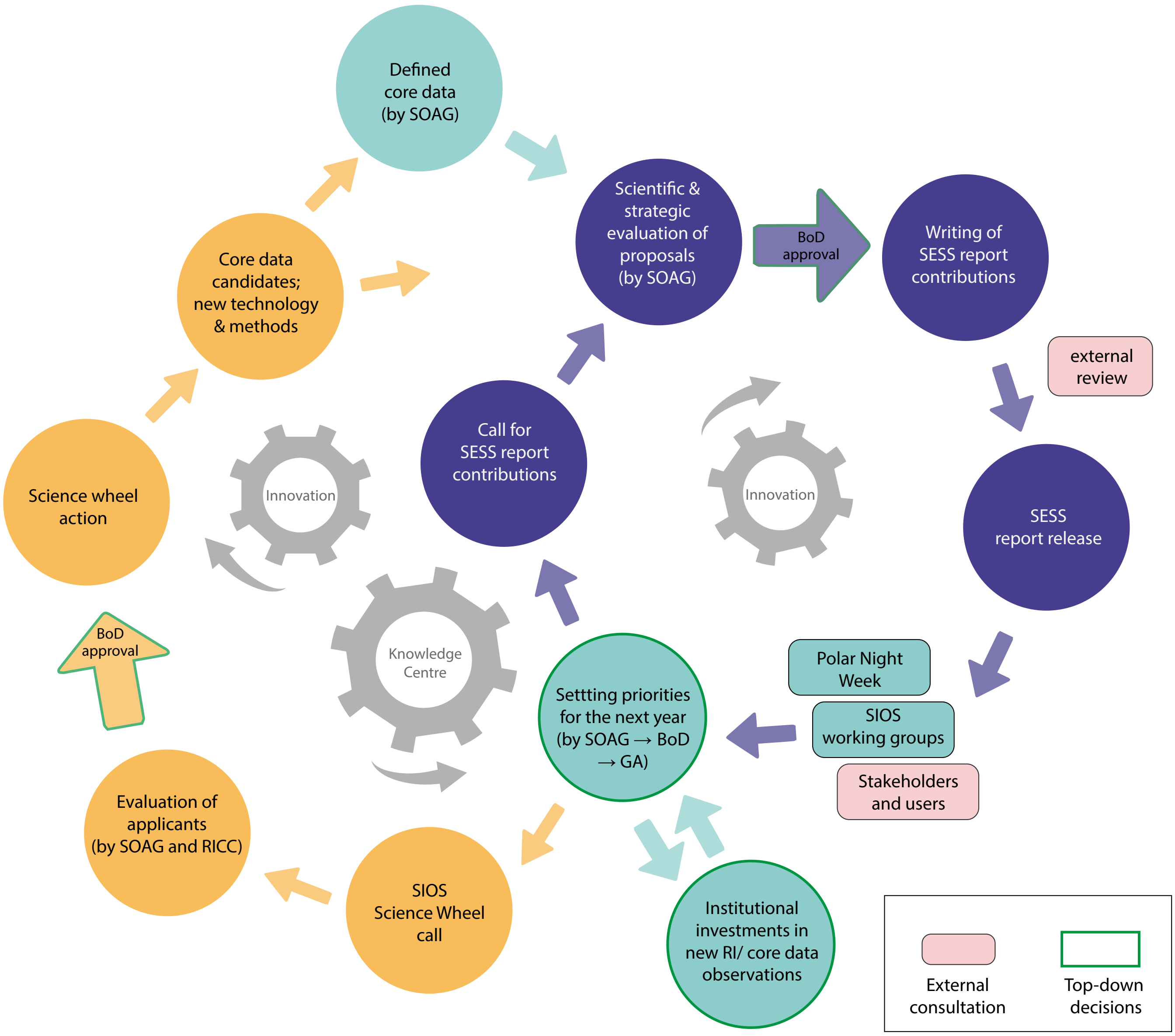
After three published SESS reports containing a total of 147 recommendations for developing the observing system, we felt a need to shift gears in the SIOS science wheel to better synchronise the machinery's cogwheels. Slowing down the SIOS science wheel means that new SESS report chapters are accepted only every other year while update chapters are accepted every year. This issue will be the first containing solely update chapters. The strengthened focus on updating previous chapters will help fine-tune the existing parts of the machinery with new insights and updated recommendations. Thus the science wheel can advance SIOS, guided by the roadmap and fuelled by new concrete recommendations, and we can adapt our work by adding new horizons as the need arises.

My sincere thanks go to Agata Zaborska, Josefine Feldner and Roland Neuber for their engagement as the editorial board. I would also like to acknowledge the person who keeps the SESS threads together, our information officer Christiane Hübner; her task is hard but at the same time delicate. I thank the anonymous reviewers for their efforts. I am grateful to the rest of the SIOS-KC crew for their energy and for being an endless source of fresh ideas. And, of course, thanks to the authors of the SESS report 2021.

Longyearbyen, December 2021

Heikki Lihavainen

Director, SIOS



The SIOS science wheel

The SIOS science wheel concept to optimise the observing system, showing the development of the State of Environmental Science in Svalbard report (blue) and the SIOS science wheel call (yellow). Other elements within SIOS that influence the processes are shown in turquoise. SESS = State of Environmental Science in Svalbard report; GA = General Assembly; BoD = Board of Directors; SOAG = Science Optimisation Advisory Group; RICC = Research Infrastructure Coordination Committee; RI = Research Infrastructure.

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Executive Summary

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The State of Environmental Science in Svalbard (SESS) report 2021 together with its predecessors contributes to the documentation of the state of the Arctic environment in and around Svalbard, and highlights research conducted within the Svalbard Integrated Arctic Earth Observing System (SIOS). Climate change is a global problem, but many of its impacts are being felt most strongly in the Arctic. Given its remote but accessible location, Svalbard constitutes an ideal place to study the Arctic environment in general, including, more specifically, the causes and consequences of climate change.

The Arctic Climate Change Update (2021)[1] emphasised the severity of global climate change for ecosystems across the Arctic. They are undergoing radical changes regarding their structure and functioning, affecting flora, fauna and livelihoods of Arctic communities. Oceanic ecosystems and food webs are directly and indirectly altered by the warming and freshening of the Arctic Ocean. A prolonged open water period and the expansion of open water areas caused by declining sea ice affect under-ice productivity and diversity. These changes have cascading effects through ecosystems and impact the distribution, abundance and seasonality of a variety of marine species.

Svalbard is located at one of the key oceanic gateways to the Arctic. This land–ice–ocean transition zone is a system particularly vulnerable to environmental changes. Svalbard's environment is influenced by maritime processes; thus extensive observation of the ocean system is nowadays necessary. The chapter on the iMOP project reports seawater temperature and salinity variability over the last decades and indicates changes of Svalbard fjord seawater properties. The chapter highlights the role of a collaborative and supportive network of observatory operators and encourages joint planning and maintenance of future marine observatories.

Arctic vegetation plays a key role in land–atmosphere interactions. Alterations can lead to ecosystem–climate feedbacks and exacerbate climate change. Extreme precipitation events are already becoming more frequent. Together with an increasing rain-to-snow ratio they impact the structure and functioning of terrestrial ecosystems.

Dynamics in Arctic tundra ecosystems are expected to undergo fundamental changes with increasing temperatures as predicted by climate models. To detect, document, understand and predict those changes, COAT Svalbard provides a long-term and real-time operational observation system through ecosystem-based terrestrial monitoring. The observation system consists of six modules comprising food web pathways as well as one climate-monitoring module and focuses on two contrasting regions in Svalbard to allow for intercomparison. To date, the project has done an initial assessment of tundra ecosystems in Norway and will now begin with the long-term ecosystem-based monitoring.

For remote regions such as the Svalbard archipelago, terrestrial photography is a crucial addition to satellite imagery, because land-based cameras offer high temporal resolution and insensitivity towards varying weather conditions. PASSES provides an overview of cameras operating in Svalbard managed by research institutions and private companies. The survey revealed difficulties and knowledge gaps preventing the full potential

1 AMAP, 2021. Arctic Climate Change Update 2021: Key Trends and Impacts. Summary for Policymakers. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. 16 pp

of the terrestrial photography network in Svalbard from being used. Therefore, PASSES recommends the creation of a Svalbard camera system network.

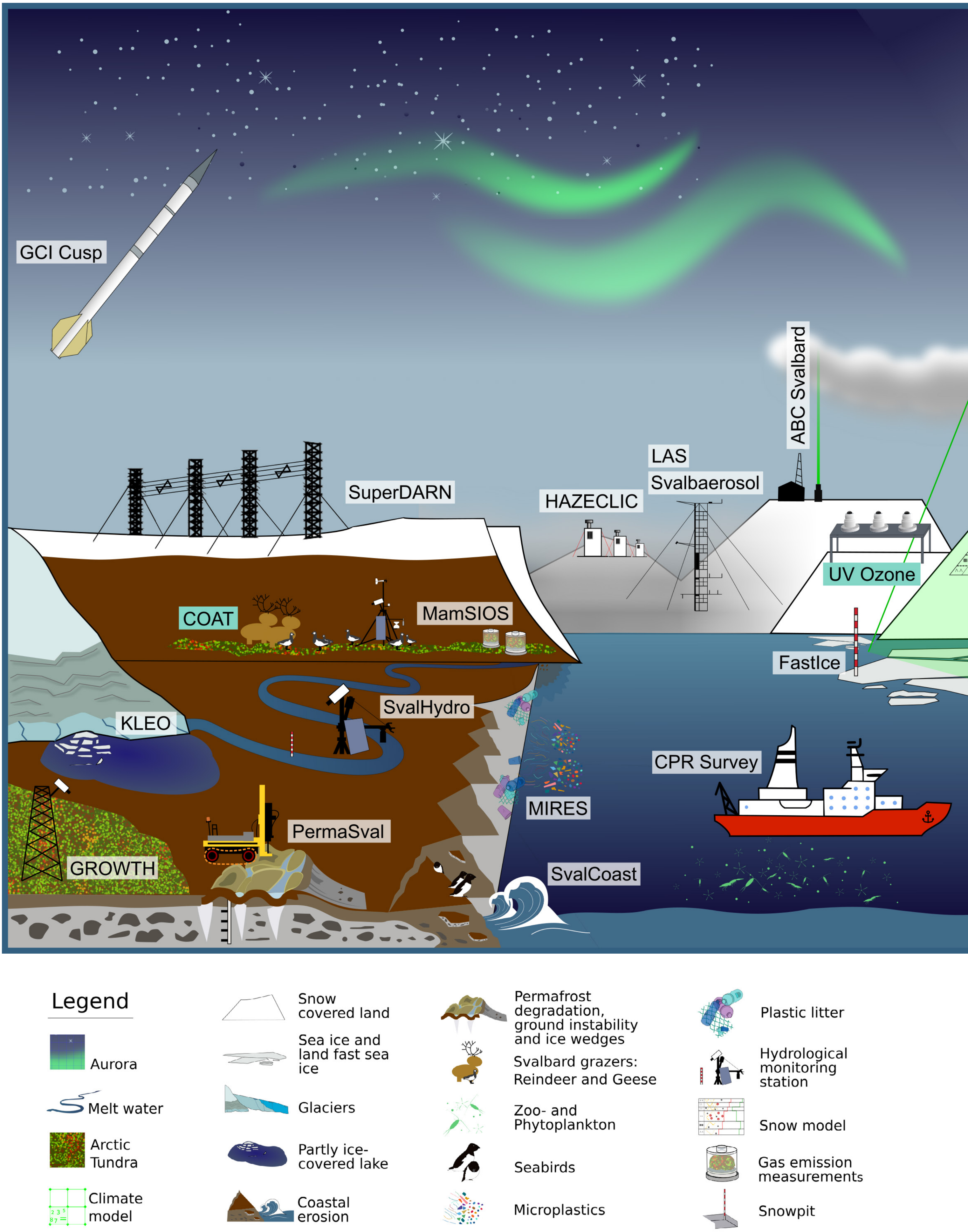
The effects of climate change contributed to a specific anomaly of the springtime Arctic atmosphere, namely a pronounced depletion of stratospheric ozone during March and April 2020, which can be called an Arctic ozone hole. In Svalbard, the amount of ozone loss was recorded by ground-based dedicated spectroscopic instruments measuring the total ozone column as well as the UV irradiance (EXAODEP-2020, an update of UV Ozone). The latter is important for effects on the biota. Corresponding erythemal daily doses for spring 2020 show a doubling compared to previous years with less or no ozone depletion. While the correspondence between ozone loss and increase in UV doses follows a well-known relationship, the possible later consequences of the observed springtime increase of UV doses on Svalbard's environment need to be further studied.

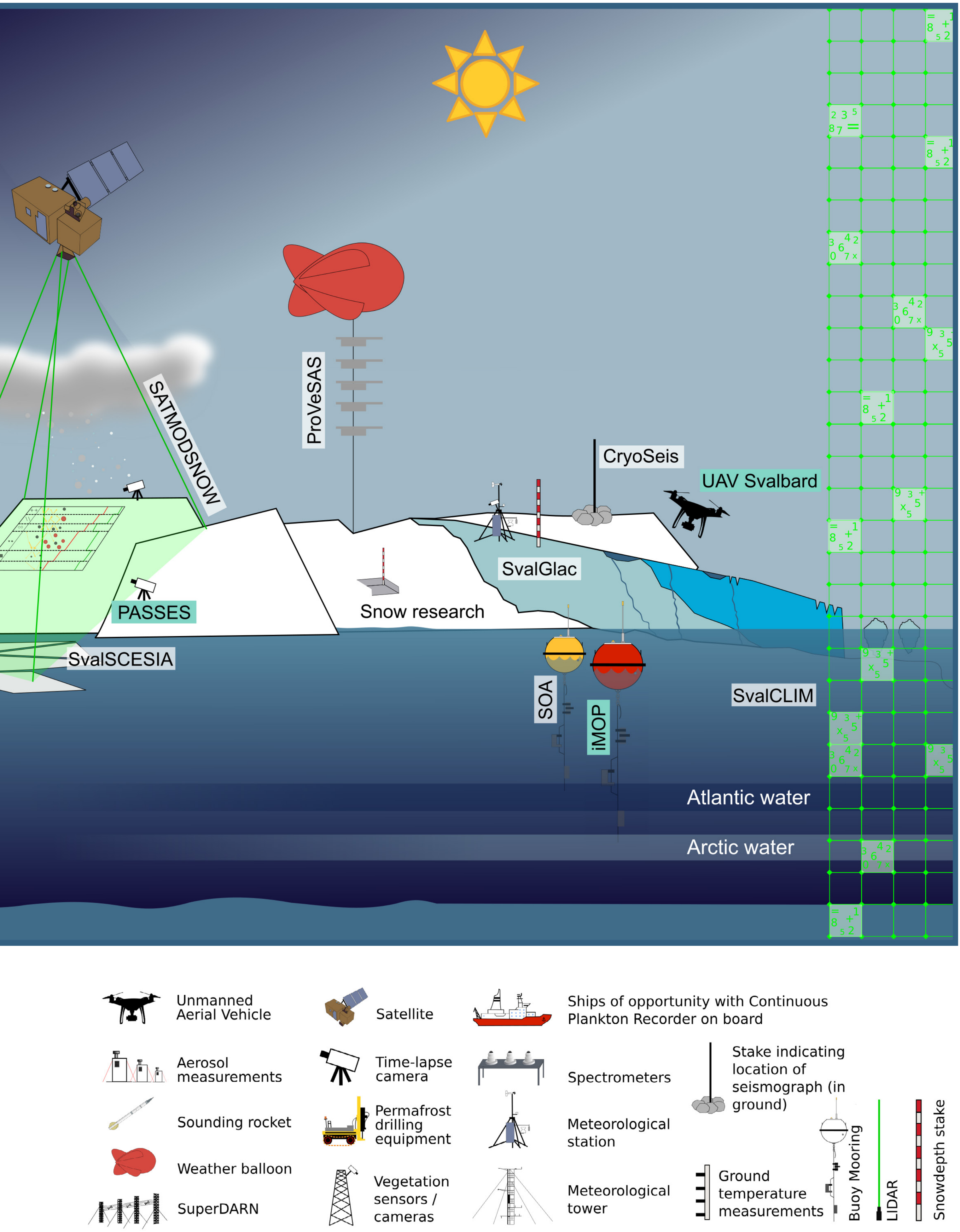
A particular method to observe the Svalbard environment, which has seen a very strong increase in usage during recent years, is the application of unmanned airborne or marine vehicles. The update on recent publications using these devices (UAV Svalbard) reveals that especially conventional remotely operated aerial vehicles (drones) with camera equipment are now widely used. It is recommended to SIOS to foster interdisciplinary communication among the multitude of drone users to establish exchange of information and data. New EU regulations for drone operations are being put in place from 2022 onwards also in Svalbard.

Climate services are receiving more and more attention from Arctic countries, because they translate data into relevant and timely information, thereby supporting governments, societies and industries in planning and decision-making processes.

SIOS contributes to climate services by providing research infrastructure with an overarching goal to develop and maintain a regional observational system for long-term measurements in and around Svalbard. The SIOS Core Data (SCD) consists of a list of essential Earth System Science variables relevant to determine environmental change in the Arctic. SCD is developed to improve the relevance and availability of scientific information addressing ESS topics for decision-making. SIOS Core Data providers have committed to maintain the observations for at least five years, to make the data publicly available, and to follow advanced principles of scientific data management and stewardship.

Arctic climate change is posing risks to the safety, health and well-being of Arctic communities and ecosystems. Still, there remain gaps in our understanding of physical processes and societal implications. The authors of the SESS chapters have highlighted some unanswered questions and suggested concrete actions that should be taken to address them. The editors would like to thank the authors for their valuable contributions to the SESS Report 2021. These chapters illustrate how SIOS projects contribute to ensure the future vitality and resilience of Arctic peoples, communities and ecosystems.


GCI Cusp
ABC Svalbard
LAS
Svalbaerosol
HAZECLIC
SuperDARN
UV Ozone
COAT
MamSIOS
FastIce
SvalHydro
KLEO
CPR Survey
MIRES
PermaSval
GROWTH
SvalCoast
Legend
Aurora
Melt water
Arctic Tundra
Climate model
Snow covered land
Sea ice and land fast sea ice
Glaciers
Partly ice-covered lake
Coastal erosion
Permafrost degradation, ground instability and ice wedges
Svalbard grazers: Reindeer and Geese
Zoo- and Phytoplankton
Seabirds
Microplastics
Plastic litter
Hydrological monitoring station
Snow model
Gas emission measurements
Snowpit



The Earth System in Svalbard as described in the first three SESS reports. Acronyms of all original chapters are shown, the chapters updated in this issue have a green background (Figure: Floor van den Heuvel).

CHAPTER 1

RV *Helmer Hanssen* operating in the Svalbard fjords (Photo: Finlo Cottier)

Temperature and salinity time series in Svalbard fjords – 'Integrated Marine Observatory Partnership (iMOP II)'

Click here for full chapter

HIGHLIGHTS

- Svalbard's west-facing fjords show increasing temperatures in the warmest and coldest periods of the year
- The inner part of Kongsfjorden has a slight cooling trend in the last decade
- Rijpfjorden shows no trend in temperature
- Outer Kongsfjorden has increased salinity at a rate of 0.1 per decade

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We show temperature records from five marine observatories located around the fjords of Svalbard – Kongsfjorden (3 observatories), Isfjorden and Rijpfjorden. We have analysed the records from these observatories (the shortest is 5 years, the longest is 18 years) to determine trends in the water temperature. We investigated trends in the warmest part of the year (September to November) and the coldest part (March to May).

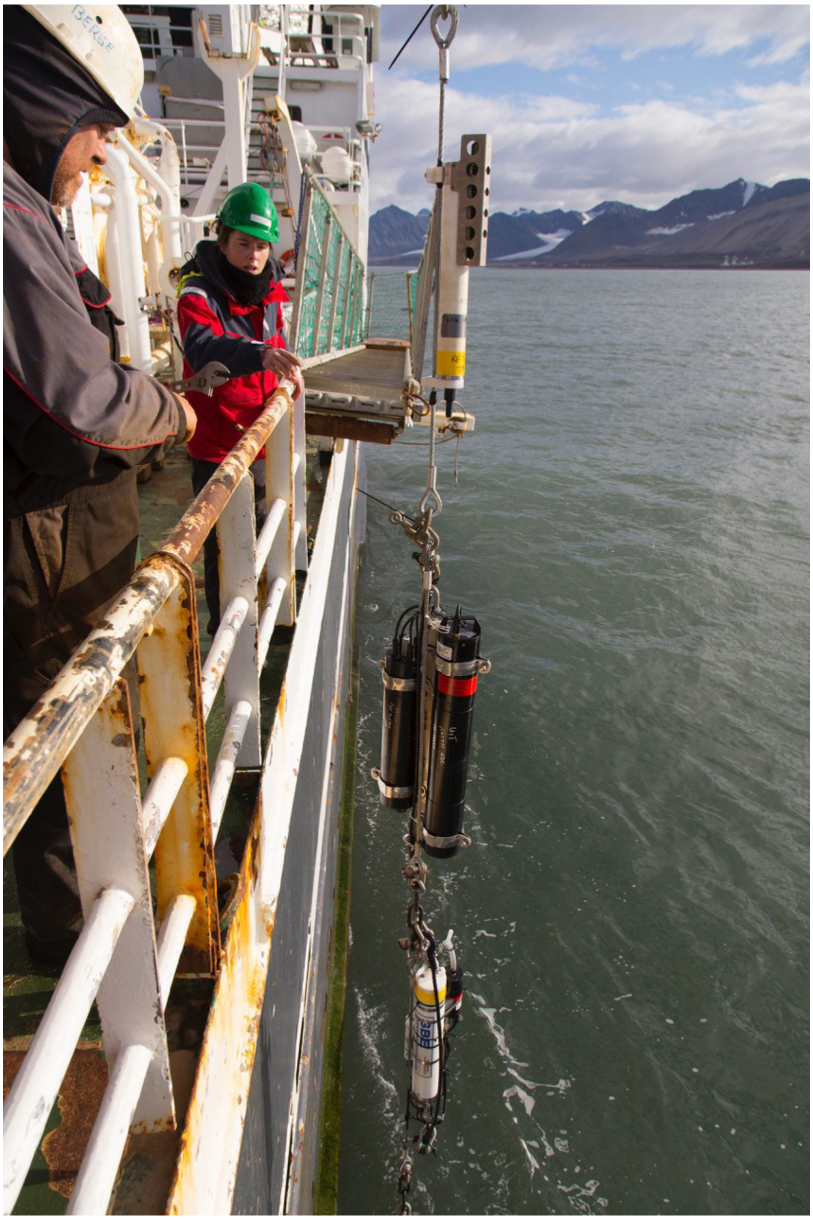
In those fjords facing west towards the Fram Strait we typically see increasing temperatures, the maximum rate being 1.5°C per decade for the coldest period of the year in Kongsfjorden. This has resulted in much less sea ice in these western fjords. In the far northeast, Rijpfjorden shows no signs of warming at any point in the year.

We also investigated the salinity of the bottom water in the outer part of Kongsfjorden and show that the salinity peaks in October and that there is a gradual increase in salinity since 2003 at a rate of 0.1 per decade.

Finally, the proportion of Atlantic-type water in Kongsfjorden has been very high since 2014.

RECOMMENDATIONS

- Continue to develop a collaborative and supportive network of observatory operators to encourage joint planning and maintenance of future marine observatories. This can be done through the SIOS Marine Infrastructure workshops and Kongsfjorden Flagship meetings.
- Undertake a community analysis of temperature records from all long-term inshore moorings and, where possible, include an analysis of water salinity to capture the rates and locations of change around Svalbard.
- Metrics to quantify the changes in Atlantic-type water should be developed and applied to all moorings with salinity and temperature data. Such a widespread analysis could be undertaken to find evidence for the greater occurrence of Atlantic-type water in Svalbard fjord systems. This could be done in conjunction with analysis of offshore moorings.
- Efforts should be made to identify similar long-term marine records (e.g. zooplankton or fish populations) and for other Earth System processes (e.g. meteorology and glaciology) and undertake coupled analyses.



Mooring recovery
(Photo: Unknown)

CHAPTER 2

COAT Svalbard (2016-2021) has established a variety of research infrastructure related to data collection, field logistics and data management solutions. Implementation of new technology and techniques, such as drones, herbivore exclosures, camera traps, sound stations and GPS-collars on reindeer and foxes complements and enhances traditional monitoring techniques (Photos from upper left to lower right: I. Eischeid, S. Thomson, V. Ravolainen, E. Fuglei, image captured by the Reconyx camera trap, V. Ravolainen, F. Samuelsson, N. Lecomte and E. Fuglei)

Climate-Ecological Observatory for Arctic Tundra (COAT) — Adaptive system for long-term terrestrial monitoring

Click here for full chapter

HIGHLIGHTS

COAT:

- provides scientifically robust systems for ecosystem-based long-term real-time observation of climate impacts on Arctic tundra ecosystems;
- provides new infrastructure to collect and manage data;
- assessed ecological condition of low and high Arctic tundra ecosystems in 2021;
- is entering the operational phase of the long-term ecosystem-based monitoring.

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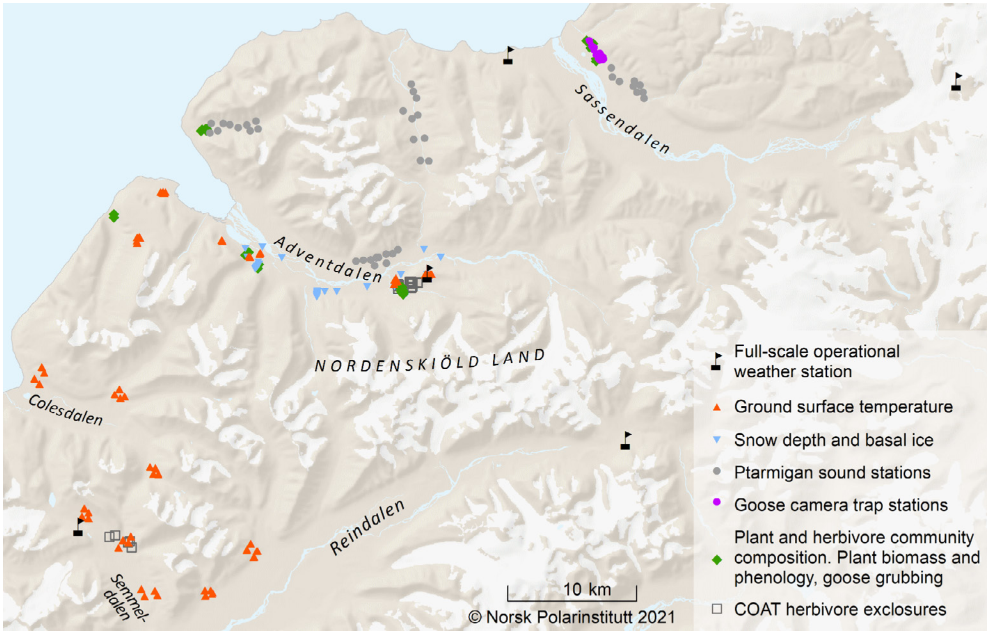
Predicted temperature increases in the Arctic are expected to fundamentally alter tundra ecosystem dynamics. The Arctic's extreme year-to-year and place-to-place variability make long-term monitoring challenging, yet essential for environmental conservation, management and policy making. COAT has developed a framework that addresses these complex issues using a holistic, ecosystem-based adaptive approach. This is achieved by integrating data on the state of various characteristics of the ecosystem measured at relevant sites and relevant times to reach clearly defined goals and targets for monitoring the terrestrial food web. For this reason, COAT Svalbard is an essential component of the Svalbard Integrated Arctic Earth Observing System (SIOS).

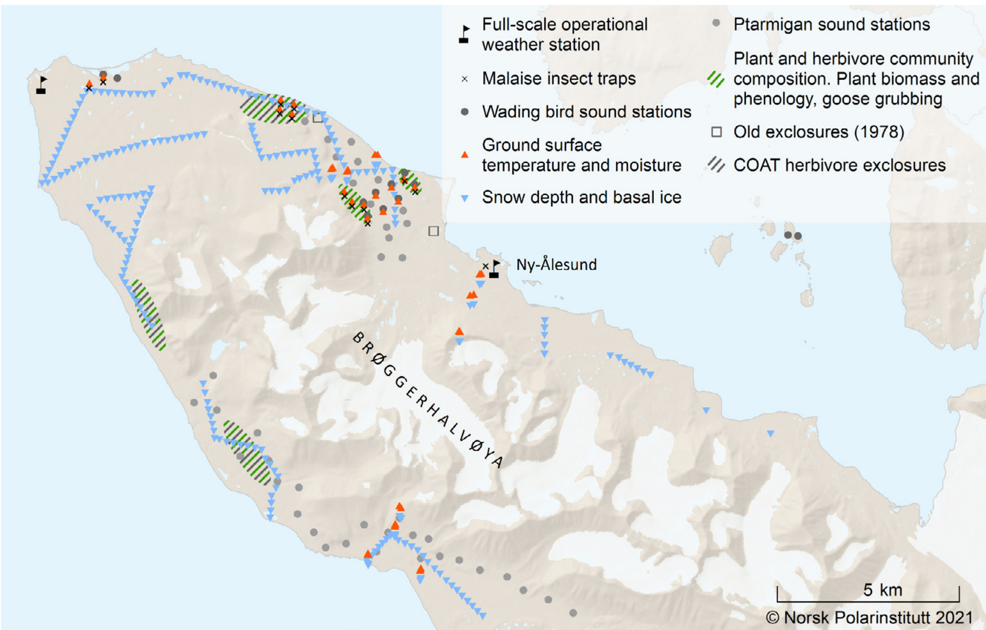
COAT Svalbard contains six monitoring modules, with study sites in two contrasting regions in Svalbard, Nordenskiöld Land (inland) and Brøggerhalvøya (coastal). Five of the modules focus on the Svalbard food web — vegetation, Arctic fox, geese, ptarmigan and reindeer. The sixth module, a climate-monitoring network with full-scale operational weather stations and associated infrastructure, has now been fully implemented.

Svalbard's tundra ecosystems have undergone rapid and substantial changes in climatic conditions — manifested particularly as rising surface temperatures, longer and warmer growing seasons, shortening of the snow-covered season and rising permafrost temperatures. Currently, monitored vertebrate populations appear to be stable or increasing in these regions. Long-term monitoring of vegetation communities is being implemented and will enhance understanding of bottom-up processes in the terrestrial food web.

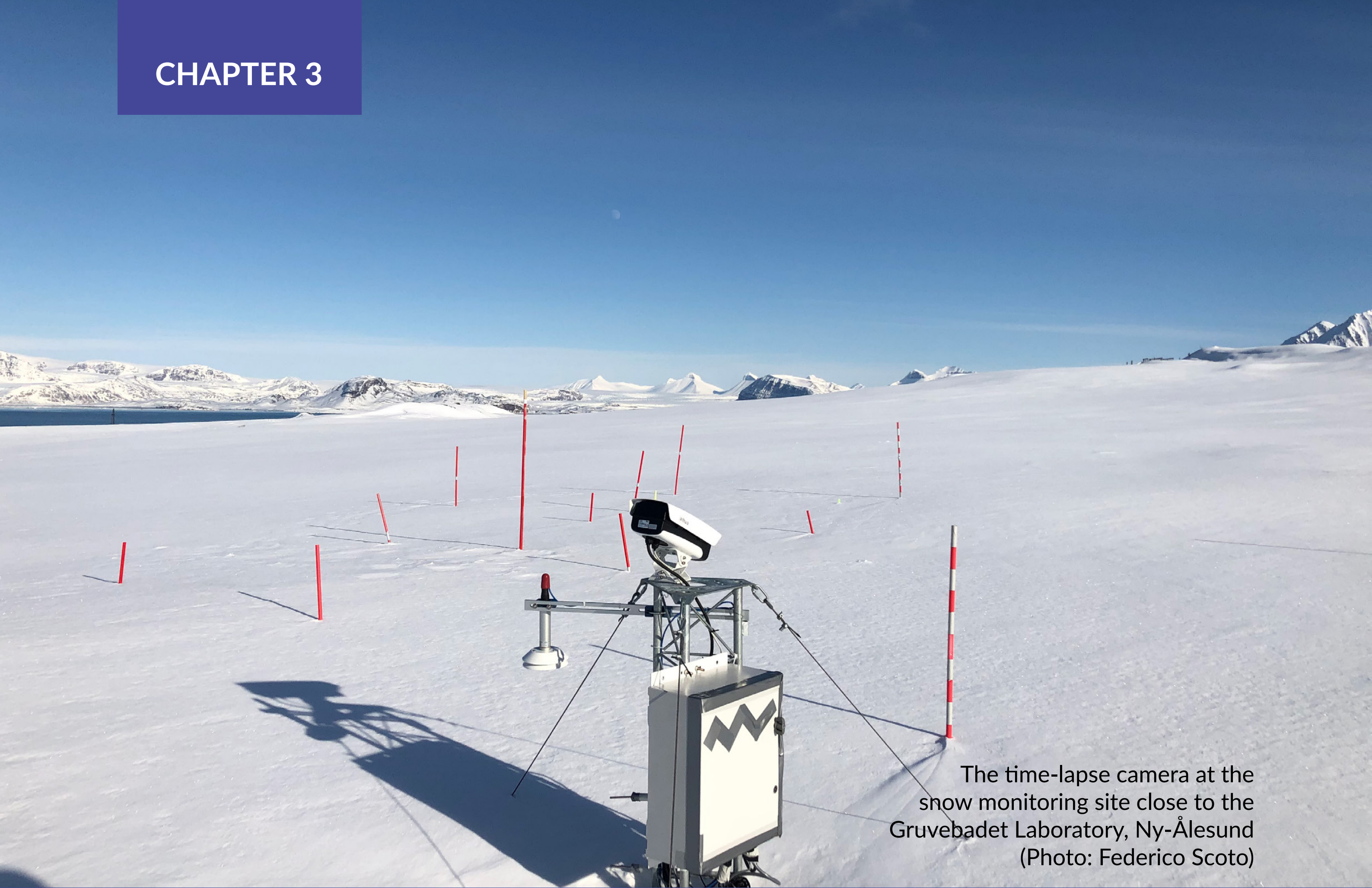
RECOMMENDATIONS

The COAT Svalbard observation system is an integral part of the SIOS land module. This offers opportunities for multidisciplinary studies, integration of ecologically relevant state variables at comparable spatial and temporal scales, and opportunities to develop products and modelling approaches that are based on a variety of data sources. We recommend further focus on: 1) climatic drivers of ecosystem change and multi-model development, 2) new methods and technologies to improve the spatial and temporal coverage of monitoring efforts and 3) cooperation with end-users.





CHAPTER 3



The time-lapse camera at the snow monitoring site close to the Gruvebadet Laboratory, Ny-Ålesund (Photo: Federico Scoto)

Improving terrestrial photography applications on snow cover in Svalbard with satellite remote sensing imagery (PASSES 2)

Click here for full chapter

HIGHLIGHTS

- Time-lapse cameras are an efficient and economically advantageous way to observe changes in Svalbard's environment.
- Snow cover monitoring with time-lapse cameras is an inherently multidisciplinary approach.
- Terrestrial photography is a vital ground truth for satellite remote sensing.

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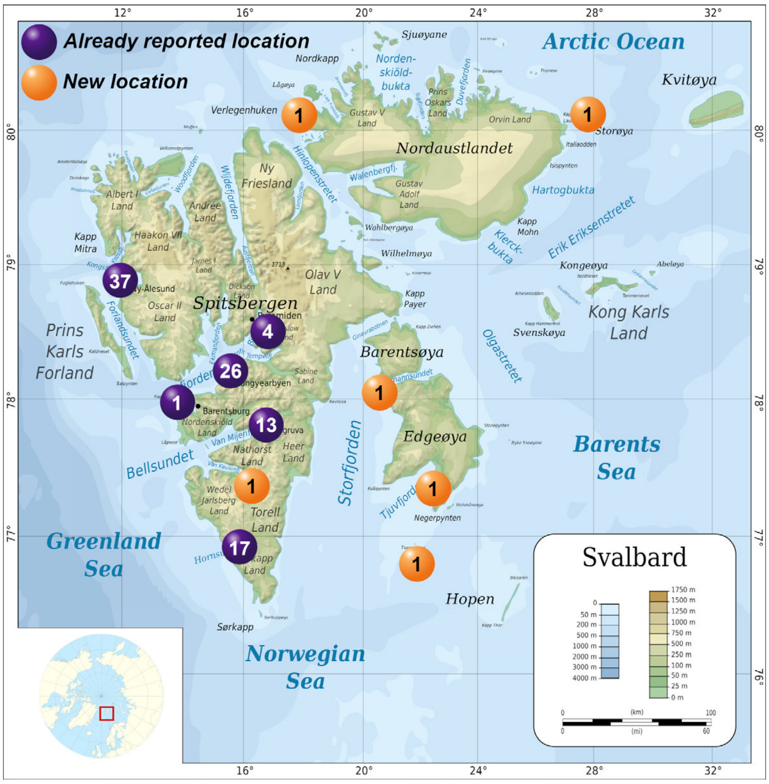
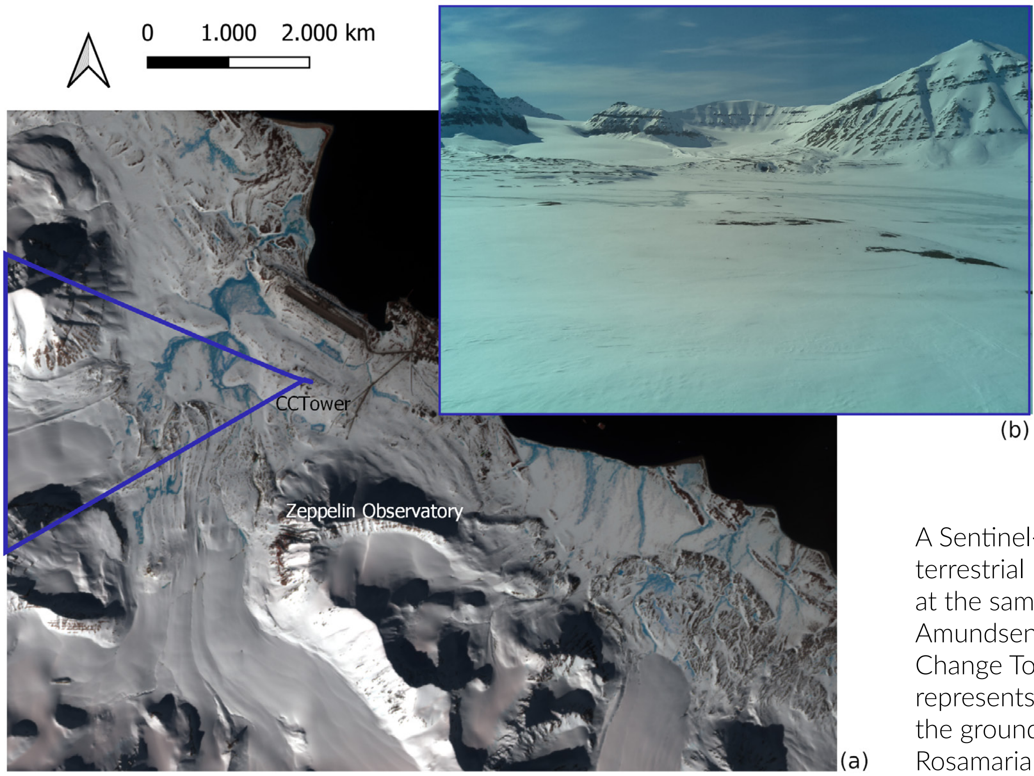
Three actions are required to improve terrestrial photography applications in Svalbard, according to the SESS report recommendations. The first one is focused on maintaining the dataset on terrestrial photography applications in Svalbard, widening the range of involved disciplines. The second one is aimed at defining a harmonised protocol based on established experience and describing guidelines for developing novel applications with a network perspective. Finally, exploring integration with remotely sensed data, it is possible to highlight potential ways of solving multi-scale gaps by combining ground based and remotely sensed data. This novel knowledge highlights even more the need for a strategic network of terrestrial cameras located in key locations where different disciplines could benefit from the description of snow cover evolution during the melting seasons.



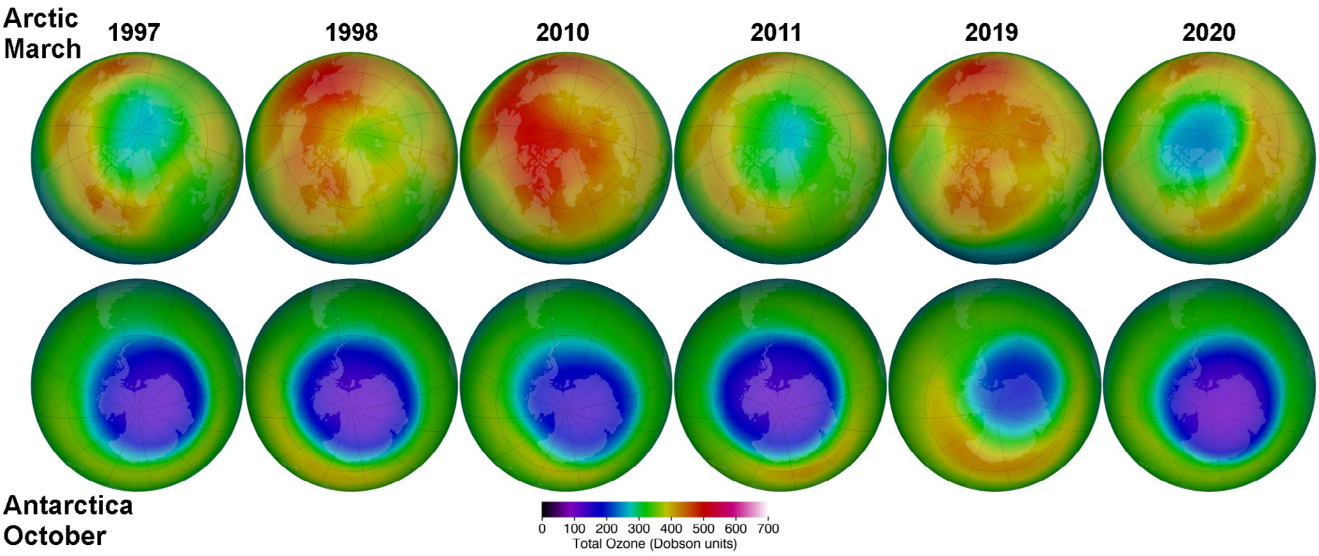
Locations of terrestrial photography applications identified in the Svalbard archipelago. The numbers denote how many camera(s) are available at each location (Photo: Riccardo Cerrato)

RECOMMENDATIONS

- Promote actions and projects that use time-lapse cameras, especially in the more remote areas of Svalbard. Cameras with a field of view covering higher-elevation terrain should be particularly encouraged.
- Stimulate the creation of a Svalbard-wide camera system network. There is a need to create a common and easy to apply algorithm for processing large quantities of images from different devices for snow cover applications.
- Further integrate terrestrial photography and satellite remote sensing since this is a promising strategy for extending in situ observations to improve regional monitoring.
- Encourage the use of time-lapse cameras by different disciplines where high time-resolved information can be retrieved for different purposes (glaciology, hydrology, plant and animal ecology, coastal processes, sea ice tracking, satellite cal/val).



A Sentinel-2 image and a terrestrial photograph taken at the same time from the Amundsen-Nobile Climate Change Tower. Blue triangle represents the field of view of the ground-based camera (Photo: Rosamaria Salvatori)



Comparison between Arctic and Antarctic ozone reductions in spring. The upper row shows the ozone distribution over the Northern Hemisphere in March of the years indicated. The lower row shows ozone distributions in the Southern Hemisphere in the austral spring (October) of the same years. The colours represent total ozone (in Dobson Units): blue indicates low values while red indicates high values. Images downloaded from the NASA website https://ozonewatch.gsfc.nasa.gov/NH.html and https://ozonewatch.gsfc.nasa.gov/SH.html.

The extreme Arctic ozone depletion in 2020 as was observed from Svalbard (EXAODEP-2020)

Click here for full chapter

HIGHLIGHTS

Strong springtime decreases in ozone have been seen in the Arctic in the past decades. The strongest episode took place in 2020. It was studied by using data from instruments based in Svalbard. The ozone reduction episode caused a twofold increase of solar ultraviolet irradiance vs normal conditions.

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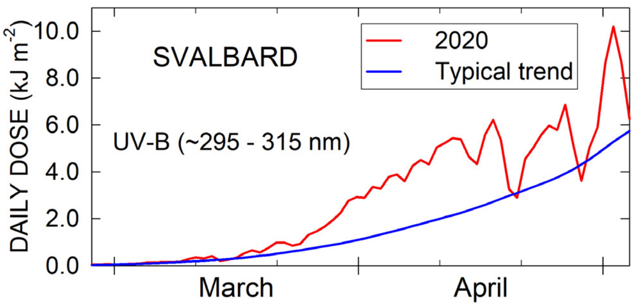
Strong stratospheric ozone reductions during the spring months were first observed in Antarctica in the early 1980s. Follow-up ozone monitoring showed that such reductions occurred annually to a varying extent, mainly in the Southern Hemisphere. However, similar events were occasionally observed also in the Northern Hemisphere; these Arctic ozone reductions were especially pronounced in 1996, 1997, 2011 and 2020. Ozone distribution maps for March (Arctic spring) clearly show the strength of these episodes and how they contrast with the usual Arctic ozone behaviour. Comparison with the ozone distribution during the Antarctic spring (October) in the same years reveals that the extremely strong 2020 Arctic episode was comparable to the ozone depletion events in the Antarctic. According to current knowledge, these phenomena are triggered by the specific dynamics in the atmosphere over the polar regions in late winter and early spring when an extremely large vortex forms in the stratosphere and closes off a certain volume of the air from external impacts. That leads to a deep cooling and the formation of clouds in the low stratosphere. Heterogeneous chemical reactions taking place on the particles within these clouds form active chlorine species which destroy ozone. Usually, the Arctic polar vortex is much less intensive than the Antarctic one and is unable to create the conditions for a strong ozone reduction, which explains the differences between hemispheres.

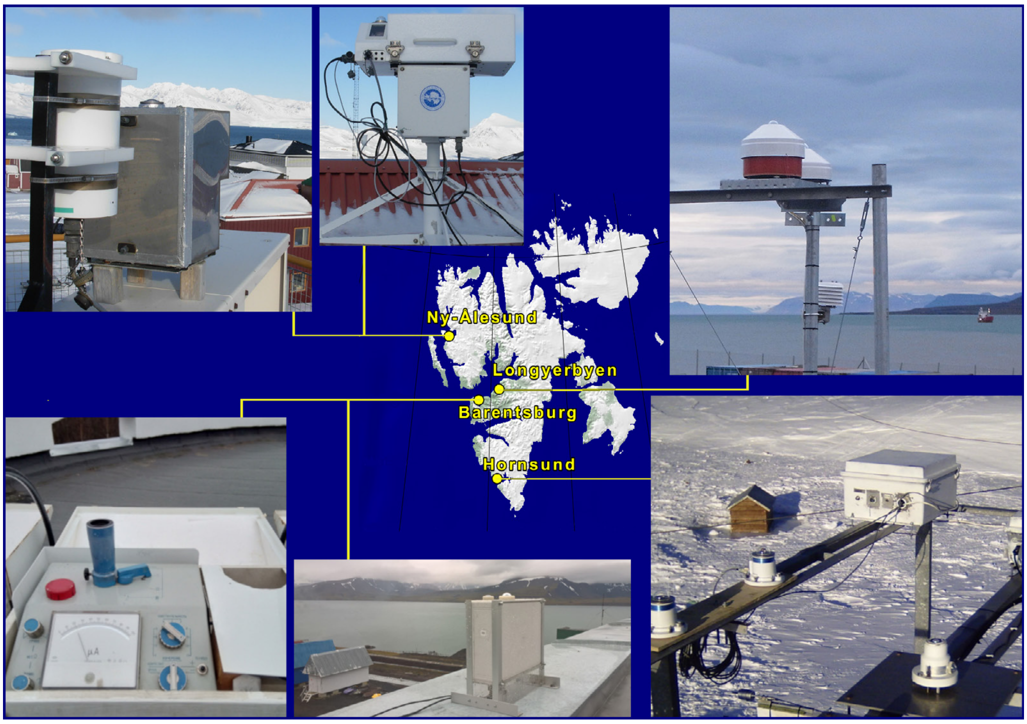
This report presents total ozone levels and solar ultraviolet (UV) radiation during the 2020 episode as measured from Svalbard. The stratospheric ozone reduction in spring 2020 nearly doubled the amount of UV-B radiation that reached the ground. This could significantly stress organisms adapted to a certain level of UV-B irradiance.

RECOMMENDATIONS

- All instruments operating in Svalbard should ultimately be coordinated in a regional network to ensure reliable and coherent data over most of the archipelago. In particular, the coverage of UV spectral observations should be improved.
- The solar UV observation network should be extended across the Fram Strait to Eastern Greenland.
- The effects of climate change on the frequency of ozone reductions must be taken into account in future studies.



The development of the daily amounts of solar UV-B radiation (doses) in the early spring of 2020 compared with the typical annual course determined from nearly 20 years of observations.



Instruments based at four Svalbard stations provided data for the present study (see main text). Ny-Ålesund has filter radiometers (left) and a Brewer spectroradiometer. Longyearbyen station is equipped with a Kipp & Zonen UVS broadband radiometer. A filter ozonometer M 124 operates at Barentsburg (on the left), where a UFOS spectroradiometer (on the right) was also recently established. The Kipp & Zonen UVS broadband radiometer at Hornsund can be seen at the lower right.

CHAPTER 5

An off-the-shelf drone (DJI Phantom 4) being used to monitor changes in the coastline of Recherchefjorden, Bellsund (Photo: Piotr Zagórski)

Update to Scientific Applications of Unmanned Vehicles in Svalbard (UAV Svalbard Update)

Click here for full chapter

HIGHLIGHTS

- This year, 15 articles using unmanned systems in Svalbard were published, vs 51 publications in 2007-2020.
- Basic operations with off-the-shelf multirotor drones are most common.
- New EU drone regulations apply from 1 January 2022.
- We show what this means for Norwegian and non-Norwegian drone operators.

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Unmanned systems are an emerging technology adding value to an increasing number of research fields. The previous SESS report presented the first inventory of all the research work in Svalbard that utilised marine or aerial unmanned vehicles. In this update, we found that since last year's report, 15 new articles that used unmanned systems for research in Svalbard have been published. Compared to the 49 publications that were identified in the previous review period of 2007-2020, this is a clear indication that unmanned systems have a growing importance for scientific applications in Svalbard. We identified that most research is performed using unmanned aerial vehicles (commonly called drones) with quite basic operational missions. Mostly, commercial off-the-shelf multirotor drones are used.

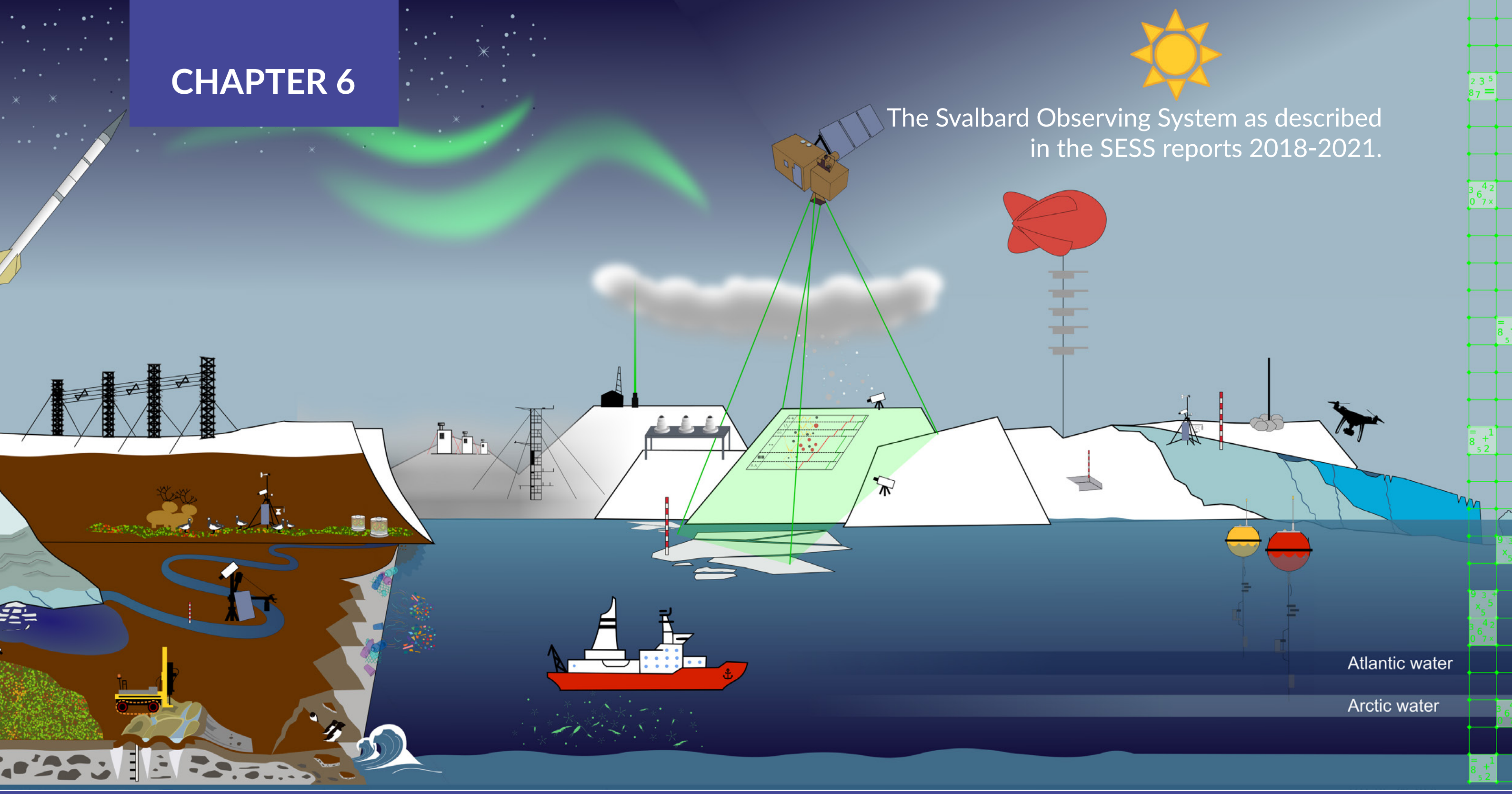
In this report, we also examine the new EU drone regulations that will be applicable in Svalbard from 1 January 2022. We give an overview of the most relevant operational categories for scientific drone operations in Svalbard and their requirements. Furthermore, we discuss the most significant differences from the old Norwegian drone regulations and give instructions on how pilots can be certified within the new rules. The information is aimed at Norwegian and non-Norwegian drone pilots.

RECOMMENDATIONS

In addition to the four recommendations from the previous SESS report we suggest the following additional three:

- Develop national standard operational scenarios (NSTS) for drone operations in Svalbard. Such scenarios should include operations with extended visual line of sight and altitudes higher than 120m, as long as they are performed with small drones in remote and uninhabited areas.
- Disseminate information about the new EU drone regulations. This will help new drone users get started and support users in adapting their operations to the new rules.
- Establish an interdisciplinary communication platform. The scientific drone community in Svalbard would greatly benefit from a platform to share experiences and develop common best practice guidelines for safe and sustainable drone operations.

A commercial off-the-shelf drone is used for counting reindeer in Svalbard (Photo: Richard Hann)



SIOS Core Data (SCD)

Click here for full chapter

HIGHLIGHTS

- A process to identify SIOS core data is in place
- For the first set of SIOS core data, 51 variables have been identified
- The SIOS Data Access Portal provides access to datasets covering 29 of the identified SCD, with the number increasing
- Members are committed to providing SIOS core data

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Svalbard Integrated Arctic Earth Observing System (SIOS) is an international consortium of currently 26 member institutions which develops and maintains a regional observing system in Svalbard and surrounding waters. SIOS brings together the infrastructure and data of its members into a multidisciplinary network dedicated to answering Earth System Science (ESS) questions related to global change. The 'SIOS Core Data' (SCD) are composed of long-term data series collected by SIOS partners, fulfilling defined criteria: (1) relevant to answer key ESS questions, (2) available to interested parties according to advanced ('FAIR') data management principles and (3) data collection to be guaranteed by members for a minimum of 5 years.

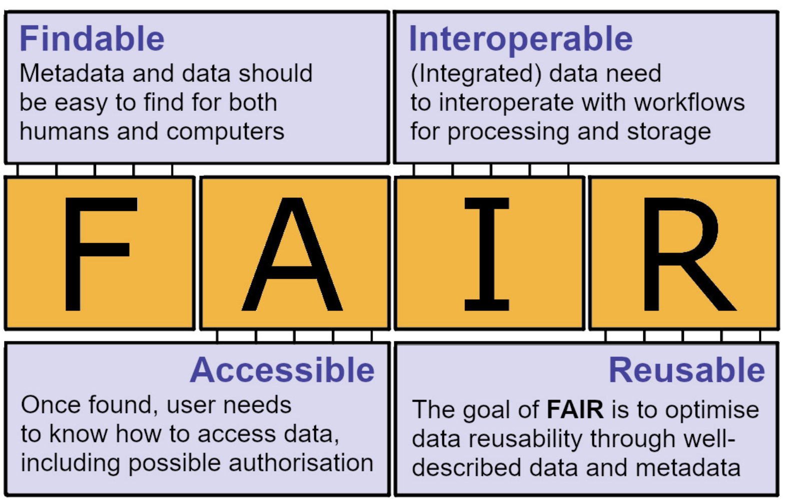
The first set of SCD variables has been identified by the Science Optimisation Advisory Group in cooperation with the Research Infrastructure Coordination Committee and scientific experts.

Many SCD variables are derived from the list of Essential Climate Variables defined by the Global Climate Observing System and are described using WMO standards and the Global Change Master Directory keywords, thus following earlier standardisation efforts. SCD variables are critical for characterising the climate system and its changes in the Arctic, and answering key ESS research questions prioritised by the SIOS community. SIOS activities related to SCD are in line with Sustaining Arctic Observing Networks' (SAON) Roadmap for Arctic Observing and Data Systems process.

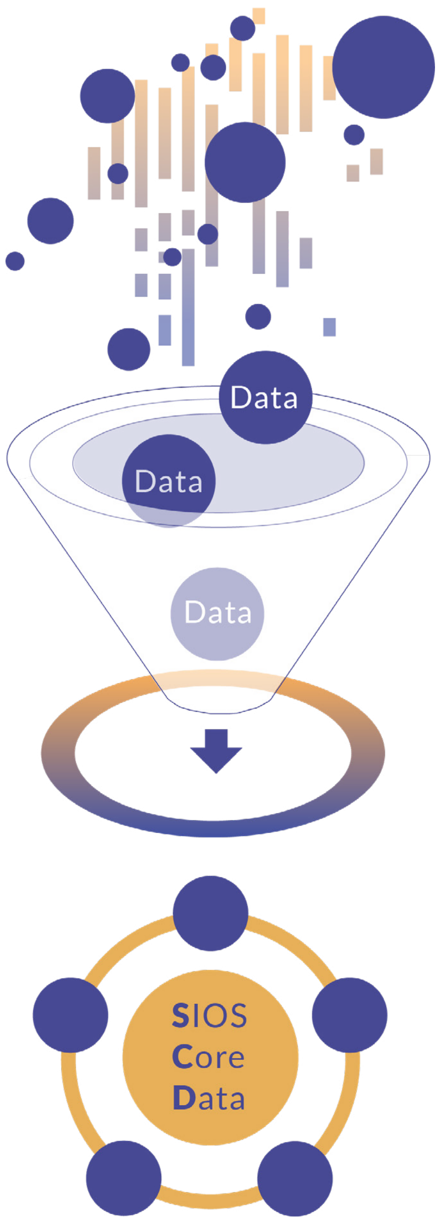
SIOS core data are made freely available through the SIOS Data Access Portal. The datasets cover mainly physical entities like geophysical, meteorological, or oceanographic data. They allow for example the determination of mass and energy flows across Svalbard, which enables better understanding of the archipelago's role within the Earth System.

RECOMMENDATIONS

- Facilitate transformation of SCD-candidates to SCD and verification of previously reported SCD-candidate variables
- Prioritise defining and harmonising measurement protocols and data protocols for SCDs
- Do an annual evaluation of variables on the SCD list to ensure their significance and reusability
- Activate hidden data from multi-year monitoring efforts that are currently not available in any database that meets the FAIR data principles
- Share knowledge, expertise, and experience of the SCD definition process in international projects



The 'FAIR guiding principles for scientific data management and stewardship' were published in 2016 by Wilkinson et al. in Scientific Data (https://doi.org/10.1038/sdata.2016.18). The principles emphasise machine-actionability, meaning that there should be minimal human intervention required in finding and accessing data.



A diagram illustrating the processes of selection and harmonisation of SIOS core data state variables from among all the SIOS Earth System Science data. The datasets collected in Svalbard are selected as core data candidates based on their importance for assessing the state of the environment in Svalbard (shown as funnel). To become full SIOS core data, they must additionally fulfil certain criteria and be in a FAIR format (shown as circle).

Temperature and salinity time series in Svalbard fjords – ‘Integrated Marine Observatory Partnership (iMOP II)’

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Update of chapter 4 in SESS report 2018

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1. Introduction

The Svalbard Archipelago is located at one of the key oceanic gateways to the Arctic. Its environment is heavily dominated by its maritime location and many of the processes occurring in the region are strongly influenced by the state of the ocean and ice (Ellis-Evans and Holmen 2013). There are extensive networks of marine observations around the Arctic to observe processes and change in this data-sparse region (Smith et al. 2019) and autonomous technologies are becoming increasingly prevalent as a mean of capturing data on appropriate spatial and temporal scales (Sørensen et al. 2020). Svalbard Integrated Arctic Earth Observing System (SIOS) makes an important contribution to this international effort for monitoring the Arctic through the placement of observatories in selected fjord locations. These observations have relevance to both marine processes and the broader connections to atmospheric and glaciological systems.

Many of the marine observations that are made in Svalbard are biased towards summer and autumn, though in recent years there has been an increased effort on marine observations during the polar night (Berge et al. 2015, Berge et al. 2020, Lønne et al. 2015). Due to intense seasonality in Arctic regions, this bias in observations can skew our understanding or, at worst, present a misleading picture of rates and processes that are active in the marine environment. Moored observatories have the capacity to make year-round measurements of key physical, geochemical and biological properties (Hauri et al. 2018, Henley et al. 2020, Hop et al. 2019a). In this report, we define an observatory or mooring to mean an arrangement of sub-surface instrumentation, fixed to a vertical wire or rope, that take regular measurements throughout in the water column to examine physical, geochemical or biological parameters over timescales that span at least one season.

In the first SESS report in 2018 (Cottier et al. 2019) – hereafter referred to as SESS-18 – we reported on four marine observatories in Svalbard and the scope of the report was limited to temperature only (Cottier et al. 2019). In this updated report we also introduce one of the longest seasonally resolved salinity records. Salinity is a key parameter in marine systems particularly in Arctic waters where it is the primary factor determining water density. Coastal and fjord oceanography is dominated by the existence of strong vertical and horizonal density gradients (Sundfjord et al. 2017) such that salinity is one of the primary determinants of the fjord circulation (Cottier et al. 2010, Davison et al. 2020). Further, the gradual warming of Arctic waters through the process of 'Atlantification' has been extensively reported for the Barents Sea region of the Arctic (Årthun et al. 2012, Barton et al. 2018) and for the West Spitsbergen fjords (Promińska et al. 2017, Skogseth et al. 2020, Tverberg et al. 2019) where the warm, high salinity water masses are a signature of enhanced Atlantic influence. In this update we:

1. Extend the temperature series for 4 observatories previously reported in SESS-18
2. Include an additional time series of temperature from a mooring located in the inner part of Kongsfjorden, giving a more glacial-proximate environment
3. Report on the salinity characteristics in the bottom water of the outer part of Kongsfjorden

2. The state of Marine Observatories

There have been many mooring deployments in the waters around Svalbard over the last decades and there exists a rich network of observatories around the Svalbard Archipelago and adjacent shelf seas (Bensi et al. 2019, Hop et al. 2019a, Renner et al. 2018, Skogseth et al. 2020). Historically, many of the observatories were located within the fjord systems and were operated for just a few years to support short-term projects. More recently, both coastal and offshore moorings have been established as part of more extensive observational networks and many have been maintained for multiple years, providing key insights into interannual variability.

The iMOP project has focused exclusively on inshore observatories (within fjords). The work does not include all inshore observatories and does not consider any of the existing offshore time series observations. The criteria for inclusion in this report and in SESS-18 were as follows:

- Observatories that are currently deployed in fjords around Svalbard
- Observatories that have a minimum of three years of continuous operation
- Observatories which are likely to be maintained for another three years

With these criteria, we are then able to focus on time series that are likely to contribute to future SESS reports rather than short-term, process oriented observations. The observatories that were considered are listed in Table 1. Two of the moorings presented herein (outer Kongsfjorden and Isfjorden) are implemented in the Norwegian infrastructure project SIOS-InfraNor[1], which in effect will ensure that these two moorings will both be coordinated and in operation until 2027.

2.1. Temperature

We follow the same methodology for temperature analysis as described in SESS-18. In summary, temperature data recorded on mooring sensors were interpolated onto a regular grid of 10-m vertical resolution and 6-hour time resolution.

Table 1: Summary of the four observatories that collected temperature data for this report. Precise distribution and the instrumentation on each mooring is documented within the cited literature. Derived from (Hop et al. 2019a).

Location	Start	Latitude*	Longitude*	Water Depth (m)	Institution and point of contact
Isfjorden	2005**	78°03.64’ N	013°31.44’ E	205	UNIS Ragnheid Skogseth
Kongsfjorden (inner)	2010***	78°54.86’ N	12°15.53’ E	105	CNR Italy Stefano Aliani
Kongsfjorden (middle)	2014	78°56.4’ N	12°6.00’ E	193	NCPOR Divya David
Kongsfjorden (outer)	2002	78°57.75’ N	011°48.30’ E	230	SAMS/UiT Finlo Cottier/Daniel Vogedes
Rijpfjorden	2006****	80°18.08’ N	022°17.44’ E	236	UiT/SAMS Daniel Vogedes/Finlo Cottier

* Positions are approximate as over the course of many years of deployment the moorings will have been in slightly different positions. Nevertheless, the positions are sufficiently similar to make realistic assessments of interannual change.

** No deployment between Feb 2008 and Sep 2010.

*** Analysis for this SESS report only started in 2012 when at least three temperature sensors were deployed on the mooring

**** No deployment between Sep 2008 and Sep 2009

1 https://sios-svalbard.org/InfraNor

Temperature values from 50 m and deeper (to avoid seasonal surface warming effects) were then reduced to a single depth-average value for each time step. The following metrics were then derived from each time series:

Monthly mean temperature: A single value representing the depth mean for each calendar month.

Maximum mean temperature: A single annual value representing the mean value for the months which climatologically show the warmest depth-mean temperatures (September/October/November).

Warmest 5-day temperature: An annual value for the warmest depth-mean temperature recorded across a series of 5-day periods.

Minimum mean temperature: A single annual value representing the mean value for the months which climatologically show the coldest depth-mean temperatures (March/April/May).

Coldest 5-day temperature: An annual value for the warmest depth-mean temperature recorded across a series of 5-day periods.

Note that we do not make reference to the terms 'summer' and 'winter' as these are a) generally defined inconsistently and b) the climatological extremes do not coincide with the perception of summer and winter being warmest, and coldest respectively.

2.2. Salinity

The salinity time series under analysis is from the SAMS/UiT mooring in the outer part of Kongsfjorden. This has been in operation since 2002, though it was not deployed September 2002 to September 2003 and there were no salinity sensors in the deployment September 2004 to September 2005. We focus on the bottom sensor at a depth of approximately 180-200 m depending on the deployment location but typically 10-15 m from the seabed. This choice of salinity record was motivated by it yielding the longest record (mid-depth sensors were only used in the later half of the deployment period) and salinity changes recorded in the bottom water are not associated with transient wind-driven displacements of the halocline (Cottier et al. 2005) giving a more consistent record of the water mass evolution with time.

The underlying methodology was similar to that used for temperature with the salinity data interpolated onto a regular 6-hour resolution time coordinate. From this, the mean annual cycle of salinity was derived by calculating the mean salinity value for each month from all years. From this we establish that the highest salinities are centred around October (aligning in time with the highest temperatures) and represent the period of maximum penetration of water masses of Atlantic origin, either Atlantic Water (AW: salinity >34.9 and temperature >3°C) or the modified form of Atlantic Water called Transformed Atlantic Water (TAW: salinity >34.7 and temperature >1°C) – water mass definitions from Tverberg et al (2019). To look at the long term evolution of salinity, the mean salinity for the period August to November each year was calculated as the best estimate of salinity during the period when the presence of Atlantic-origin water in Kongsfjorden was greatest. Finally, the proportion of AW and of the combined Atlantic Water types (AW +TAW) present in the bottom water for each year was calculated as a fraction of the entire year.

2.3. Results

2.3.1. Temperature

The updated temperature records are shown in Figure 1. Taking each location in turn we report specifically on the updated trends and comment on the additional data. Due to the variable mooring designs, duration of operation and data gaps, the trends reported are indicative in nature rather than a full statistical linear model of temperature change in the fjords.

Kongsfjorden (outer): This mooring failed during the period 2019 to 2020. As reported in SESS-18, the trends for temperature for the full monthly record and for both the warmest and coldest periods exceed a rate of warming of 1°C per decade, though the new additional data show a slightly cooler period towards the end of the record. 2006 was regarded as an anomalously warm period when it was first reported (Cottier et al. 2007) and we see in the temperature record for the coldest part of the year an increase from typically sub-zero pre-2006 to around +1°C in 2006. The trend line for the coldest period exceeded +1°C in 2014 and is currently around +2°C as typical value for the coldest period. Consequently, temperature values in 2006 that were considered anomalously warm are now considered cooler than normal.

Kongsfjorden (middle): The temperature record from this mooring is now 5 years long yet the trend for the monthly data series actually shows a small decrease of around 0.07°C per year – an important contrast to the outer part. The positive summer trend is also relatively small but the winter trend is similar in magnitude and sign to the trend in the outer part of Kongsfjorden at +0.15°C per year.

Kongsfjorden (inner): This is a new record included in this report. This mooring is located to the south-east of Ny-Ålesund at a water depth of around 100 m. Thus this mooring is not only the most glacial-proximate location of all the Kongsfjorden moorings but also located shallower than the outer and middle mooring locations and near a sill separating the main body of the fjord from the inner basin. Water temperatures in this location are rather steady over time, and actually show a slightly decreasing trend in the coldest period in contrast to the other locations in Kongsfjorden.

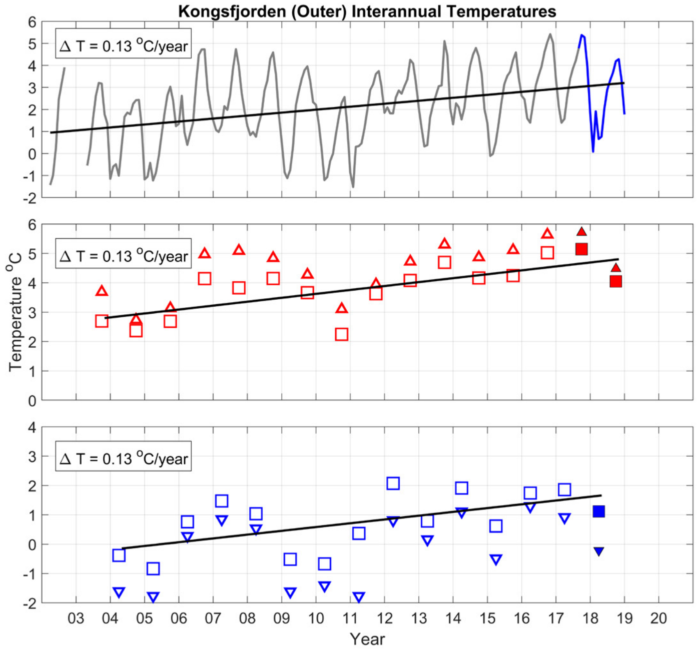
Isfjorden: The new data added to this series include some relatively cold years resulting in a slight decrease in the temperature trend over the duration of the record. Nevertheless, the data continue to show a positive increase with time, most marked in the warmest period where there is an increase of +1.5°C per decade similar to the outer and middle locations of Kongsfjorden.

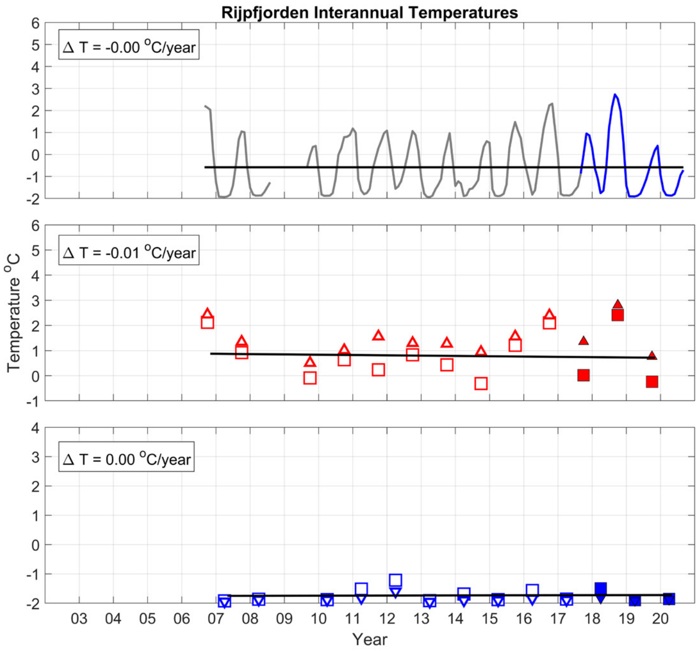
Rijpfjorden: The new data provide a very consistent record of temperatures which show zero trend in temperature for any of the derived parameters. The only perceivable change is an increase in the interannual variation in temperature in the warmest periods during the last four years, but this can't be confirmed statistically due to the short data record. Nevertheless, it could represent an early indication of oceanic change in Rijpfjorden which has previously shown to be relatively stable.

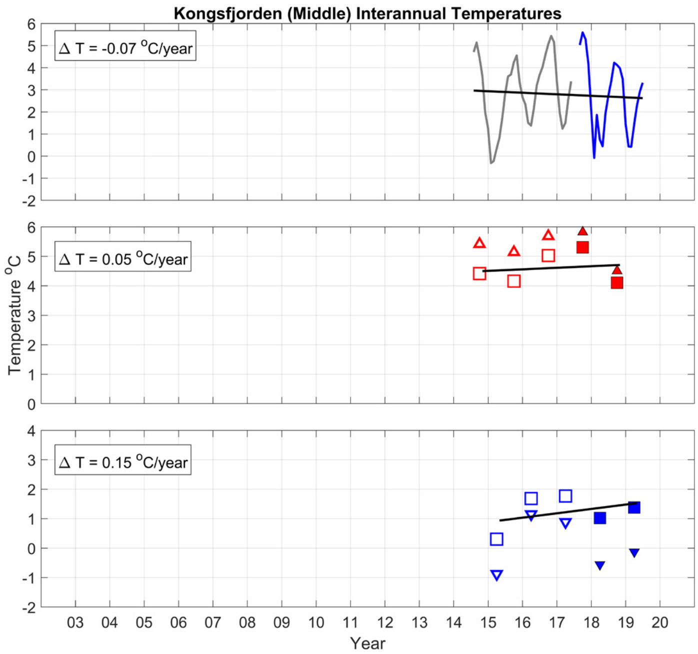
2.3.2. Salinity

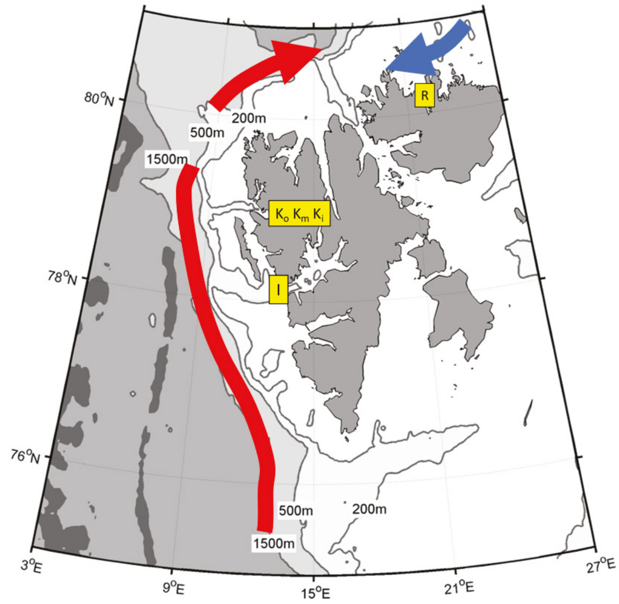
The data for the bottom water salinity from the outer part of Kongsfjorden is shown in Figure 2. The annual cycle shows highest salinity in October (S=34.90) and lowest salinity in January (S=34.75). This corresponds to the occurrence of warm and saline AW at the end of each summer. Looking at the time series of mean salinity during the months August to November we see that there has been a steady increase in salinity at a rate of around 0.1 per decade. This rate of increase is similar to increases in salinity found for Isfjorden of 0.21 per decade (January-May for the period 1999-2017) and 0.07 per decade (July-September for the period 1987-2017) from profiling CTD data (Skogseth et al. 2020). Since 2014 the mean bottom salinity in Kongsfjorden for August-November has regularly exceeded the criteria for AW (S=34.9). Similar observations in the Isfjorden system since 2003 found the greatest salinity in the bottom water in 2014 (Bloshkina et al. 2021). However, in longer records (Skogseth et al. 2020) we note occurrence of high bottom salinities in 1988, 1990 and 1994) though there is still a decadal trend of increasing salinity. The increase in AW occupation in Kongsfjorden is seen in the lower panel of Figure

Figure 1: Multipanel figure showing the temperature time series of depth-averaged water column temperature (50 m > bottom) at five locations in Svalbard: Kongsfjorden outer (K_o), middle (K_m) and inner (K_i) basins, Isfjorden (I) and Rijpfjorden (R). Each location data comprises three panels. Upper panel: monthly temperature values (grey reported in SESS-18, blue updated or new data), middle panel (red markers) is warmest months (Sep/Oct/Nov) mean (square) and the peak temperature values in the season (triangle) – open shapes are values reported in SESS-18 and filled shapes are new data, lower panel (blue markers) is coldest months (Mar/Apr/May) mean (square) and the minimum temperature values in the season (triangle).


Kongsfjorden (Outer) Interannual Temperatures
Δ T = 0.13 °C/year
Δ T = 0.13 °C/year
Δ T = 0.13 °C/year
Temperature °C
Year


Rijpfjorden Interannual Temperatures
Δ T = -0.00 °C/year
Δ T = -0.01 °C/year
Δ T = 0.00 °C/year
Temperature °C
Year


Kongsfjorden (Middle) Interannual Temperatures
Δ T = -0.07 °C/year
Δ T = 0.05 °C/year
Δ T = 0.15 °C/year
Temperature °C
Year


80°N
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K$_o$ K$_m$ K$_i$
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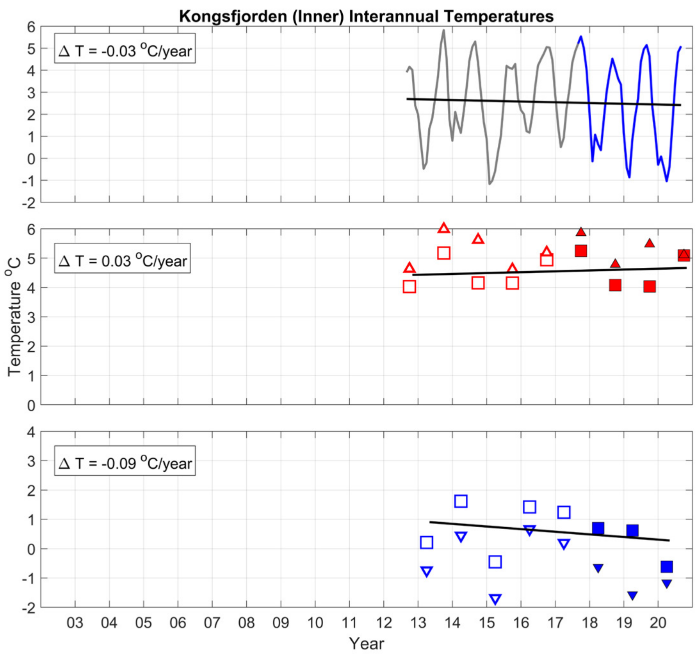
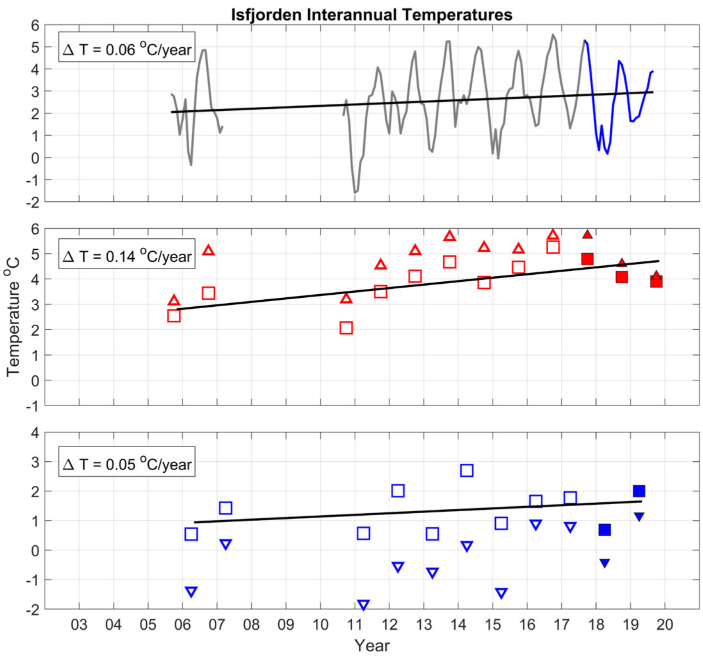
21°E
27°E


Kongsfjorden (Inner) Interannual Temperatures
Δ T = -0.03 °C/year
Δ T = 0.03 °C/year
Δ T = -0.09 °C/year
Temperature °C
Year


Isfjorden Interannual Temperatures
Δ T = 0.06 °C/year
Δ T = 0.14 °C/year
Δ T = 0.05 °C/year
Temperature °C
Year

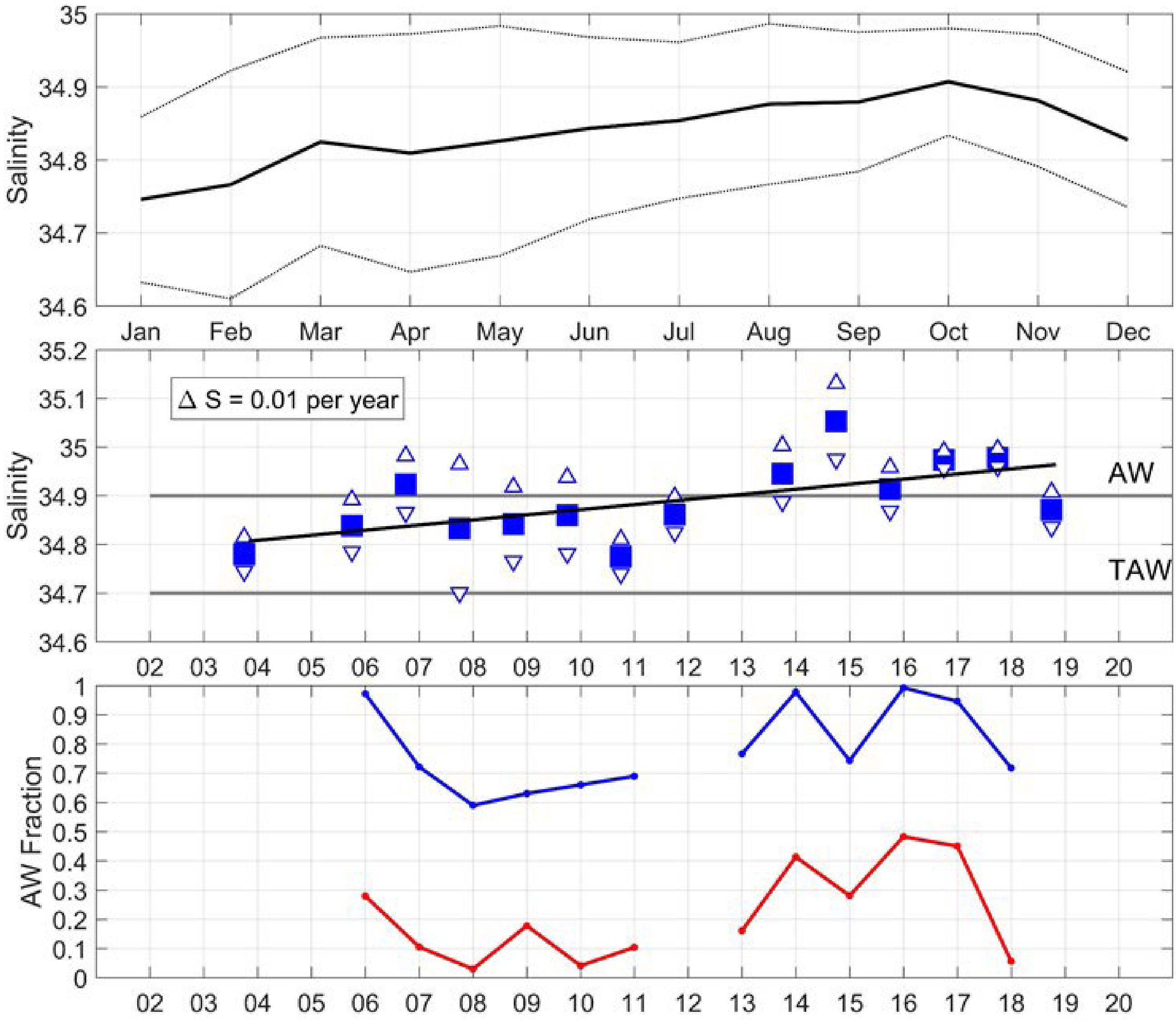


Figure 2: Multipanel figure for salinity parameters measured at the bottom of the outer part of Kongsfjorden. Upper panel shows the annual cycle of salinity by month with standard deviation (dotted line). Middle panel shows the mean salinity (blue squares) with standard deviation (triangles) by year for those months with highest salinity (Aug-Nov) with an indicative linear trend marked in black and the salinity boundaries for Atlantic Water (AW) at 34.9 and Transformed Atlantic Water (TAW) at 34.7 indicated by horizonal grey lines. Lower panel shows the proportion of the year when AW is recorded in the bottom water (red) and when any form of Atlantic Water (AW or TAW) is recorded (blue) for each year of mooring operation.

2, peaking at 50% of the year in 2016. Taking both Atlantic water types into account (AW and TAW), we note that in 2006 as well as 2014 and 2016 Kongsfjorden was fully occupied with either AW or TAW. We note an increase in the fraction of AW with little additional TAW, such that the total contribution of Atlantic-type water does not rise substantially in 2009. Data for 2018 shows a decrease in Atlantic water types for Kongsfjorden. Nevertheless, this pronounced increase in occurrence of Atlantic water types since 2014 has been reported for both Kongsfjorden and Isfjorden (Skogseth et al. 2020, Tverberg et al. 2019).

3. Unanswered questions

1. The extent to which oceanographic changes are driving zooplankton communities around Svalbard has received some attention previously (Daase and Eiane 2007, Dalpadado et al. 2016). There are observations that inter-annual variations in the mesozooplankton community composition and abundance are strongly related to hydrographic fluctuations

in Kongsfjorden (Hop et al. 2019b) leading to changes in the energy flow to higher trophic level (Vihtakari et al. 2018). In the colder, more sea ice-dominated Rijpfjorden, studies have shown a delay in the spring developmental stages of zooplankton compared to the warmer Kongsfjorden (Weydmann-Zwolicka et al. 2021). However, there is an overall lack of monitoring of long-term changes of marine biological communities with high seasonal resolution, coordinated with equivalent ocean timeseries, to enable studies of how the observed changes in oceanic conditions across the archipelago affect the coastal and fjord ecosystems.

2. We lack a full integration of the many data series to assess systematically how oceanic conditions are changing in Svalbard fjords. There are well-resolved time series of change for Isfjorden (Bloshkina et al. 2021, Pavlov et al. 2013, Skogseth et al. 2020), a series of annual sections of temperature and salinity for Hornsund (Promińska et al. 2017), extensively documented hydrography of Kongsfjorden (Promińska et al. 2017, Tverberg et al. 2019) and time series of sea ice conditions in selected fjords (Gerland et al. 2020, Johansson et al. 2020, Muckenhuber et al. 2016, Pavlova et al. 2019) . But there are other fjord locations, notably Storfjorden which is an important region of local water mass modification, where we don't have a clear picture of long term variability. Such a coordinated assessment of the coastal and fjordic conditions should consider the wider system of Atlantic inflow, meteorological forcing, run-off etc. for both inshore and offshore conditions through the many excellent projects addressing aspects of this.

3. To what extent the fjord conditions are coupled with meteorological factors and/or offshore oceanographic conditions is not well understood. Neither do we have a full understanding of the role that ocean forcing is playing on glacial dynamics in the regions. A much greater level of integration could be achieved between disciplines.

4. Recommendations for the future

In SESS-18 we recommended to further develop the network of operators to encourage collaboration, communication and planning of future marine observatories. Initiatives are developing through SIOS Marine Infrastructure workshops and Kongsfjorden Flagship meetings and these efforts should be continued. In practice, we are seeing operational collaboration between nations, e.g. Italian group assisting mooring operations for IndARC. The SIOS-funded mooring operations in Kongsfjorden and Isfjorden provide a long-term platform for mooring operations and provide a basis for many science campaigns and should be continued.

We recommend conducting a community analysis of temperature records of all long-term inshore moorings and to include, where possible, an analysis of water salinity to capture the rates and locations of change around Svalbard. This should be ongoing with an agreed protocol for how data should be analysed for each mooring.

There are moorings elsewhere in Svalbard which we have not been able to include in this report. However, the inclusion of the CNR-Italy mooring has demonstrated a quite different character to the temperature trend even within one fjord. We present an analysis of seasonally resolved salinity for Kongsfjorden and demonstrate the increasing prevalence of Atlantic Water; a similar pattern is reported for Isfjorden (Skogseth et al. 2020). A more widespread analysis could be undertaken to find evidence for Atlantification of Svalbard fjord systems. Related to this, we recommend an extensive analysis of offshore moorings; this should be the focus of a distinct SESS report.

In addition, an effort should be made to identify similar long-term marine records (e.g. zooplankton or fish populations) and for other Earth System processes (e.g. records of meteorology or glaciers) and undertake coupled analyses.

5. Data availability

Dataset	Parameters	Period	Location	Metadata access (URL)	Dataset provider
Oceanographic mooring	Temperature Salinity Chlorophyll fluorescence Currents	2002 – present (not present Sep 2002-Sep 2003 and mooring failure 2019-20)	Kongsfjorden outer basin	https://archive.sigma2.no/welcome.xhtml and https://arctic-observatories.webs.sigma2.no/	Jørgen Berge (UiT) Jorgen.berge@uit.no Daniel Vogedes Daniel.vogedes@uit.no
Oceanographic mooring	Temperature Salinity Currents	2014 – present	Kongsfjorden middle basin	http://data.ncaor.gov.in/newhtml	Divya David divya@ncpor.res.in
Oceanographic mooring	Temperature Salinity	2010 – present	Kongsfjorden inner basin	http://iadc.cnr.it/cnr/index.php	Leonardo Langone leonardo.langone@cnr.it
Oceanographic mooring	Temperature Salinity	2005 – present (not 2008-09 and 2009-10)	Isfjorden mouth	https://data.npolar.no/dataset/?filter-links.rel=data&q=Mooring%20Isfjorden%20South%20(I-S)	Ragnheid Skogseth ragnheids@unis.no
Oceanographic mooring	Temperature Salinity Chlorophyll fluorescence Currents	2006 – present (not present 2008-09)	Rijpfjorden	https://archive.sigma2.no/welcome.xhtml and https://arctic-observatories.webs.sigma2.no/	Jørgen Berge (UiT) Jorgen.berge@uit.no Daniel Vogedes Daniel.vogedes@uit.no

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Climate-Ecological Observatory for Arctic Tundra (COAT) – Adaptive system for long-term terrestrial monitoring

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1. COAT in a 'nutshell'

The Climate Ecological Observatory for Arctic Tundra (COAT) is a response to urgent international calls for the establishment of scientifically robust observation systems enabling long-term and real-time detection, documentation, understanding and predictions of climate impacts on Arctic tundra ecosystems (Christensen et al. 2020). COAT aims to be a fully ecosystem-based, long-term, adaptive monitoring programme, based on a food-web approach (Ims et al. 2013; Ims and Yoccoz 2017; Appendix 1). The focus is on two Norwegian Arctic regions, the low-Arctic Varanger peninsula and high-Arctic Svalbard, that provide pertinent contrasts in ecosystem complexity, climatic conditions and management regimes. COAT Svalbard is an essential component of the Svalbard Integrated Arctic Earth Observing System (SIOS) and serves to optimise and integrate the ecosystem-based terrestrial monitoring.

In 2016, COAT Svalbard started to implement research infrastructure related to data collection, field logistics and data management solutions. To cover the range of existing variation in climatic and management contexts, the data sampling systems are geographically distributed over Svalbard. Seven full-scale operational weather stations form the core infrastructure, essential for quantifying key climatic variables along a coast-inland gradient (Appendix 2). In addition, 32 herbivore exclosures, networks of camera traps and acoustic sensors, telemetric devices on animals, drones, and networks of small instruments that log climate parameters at the ground level have been established (Figure 1). The COAT programme is now entering the operational phase of the long-term ecosystem-based monitoring.

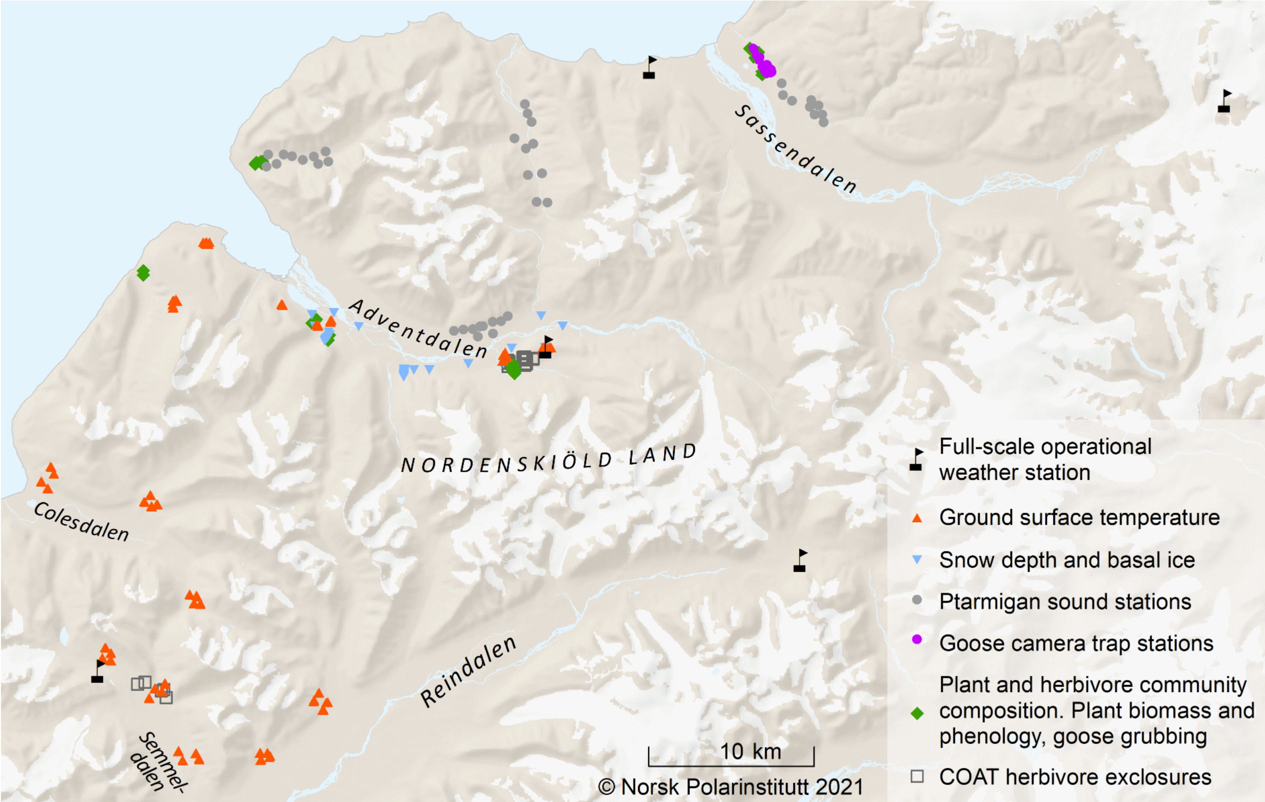
2. Current status and trends in the Svalbard terrestrial ecosystem

In 2021, the first operational assessment of the ecological condition of Norwegian Arctic tundra ecosystems was conducted by a scientific panel, using core long-term monitoring data from COAT Svalbard and MOSJ (www.mosj.no) and the methodology for *Panel-based Assessment of Ecosystem Condition* (PAEC; Jepsen et al. 2020). The assessment was based on analyses of 34 datasets, supporting 24 indicators unique to the terrestrial ecosystem in Svalbard (Appendix 3).

2.1. Climate characteristics and ecological implications

The Arctic tundra is one of Earth's largest terrestrial biomes, comprising all terrestrial ecosystems north of the continuous boreal forest. Here, temperatures are rising three times faster than the global average (IPCC, 2021). Since 1971, annual air temperature has increased 3–5°C in all seasons, with the largest increase in winter and the smallest in summer (Hanssen-Bauer et al. 2019). Current winters are characterised by fewer extreme cold days (Nordli et al. 2020) and more frequent mild days with precipitation falling as rain (Figure 2A). Climatic delineation of the Arctic bioclimatic subzones is based on July temperatures, as July temperature is a key characteristic of the plant growing season (Figure 2B). Changes in mean July temperature in Svalbard indicate that climatically, most of the Svalbard tundra has shifted by an entire bioclimatic sub-zone (Pedersen et al. 2021c). The bio-climatic zones are moving eastward in accordance with transport of atmospheric heat and moisture from the Icelandic low and the warm West Spitsbergen current (Hanssen-Bauer et al. 2019). Climatic change in these zones is expected to be accompanied by significant alteration of ecosystems and focal components with knock-on effects on function, structure and productivity (IPCC, 2021).

A)



B)

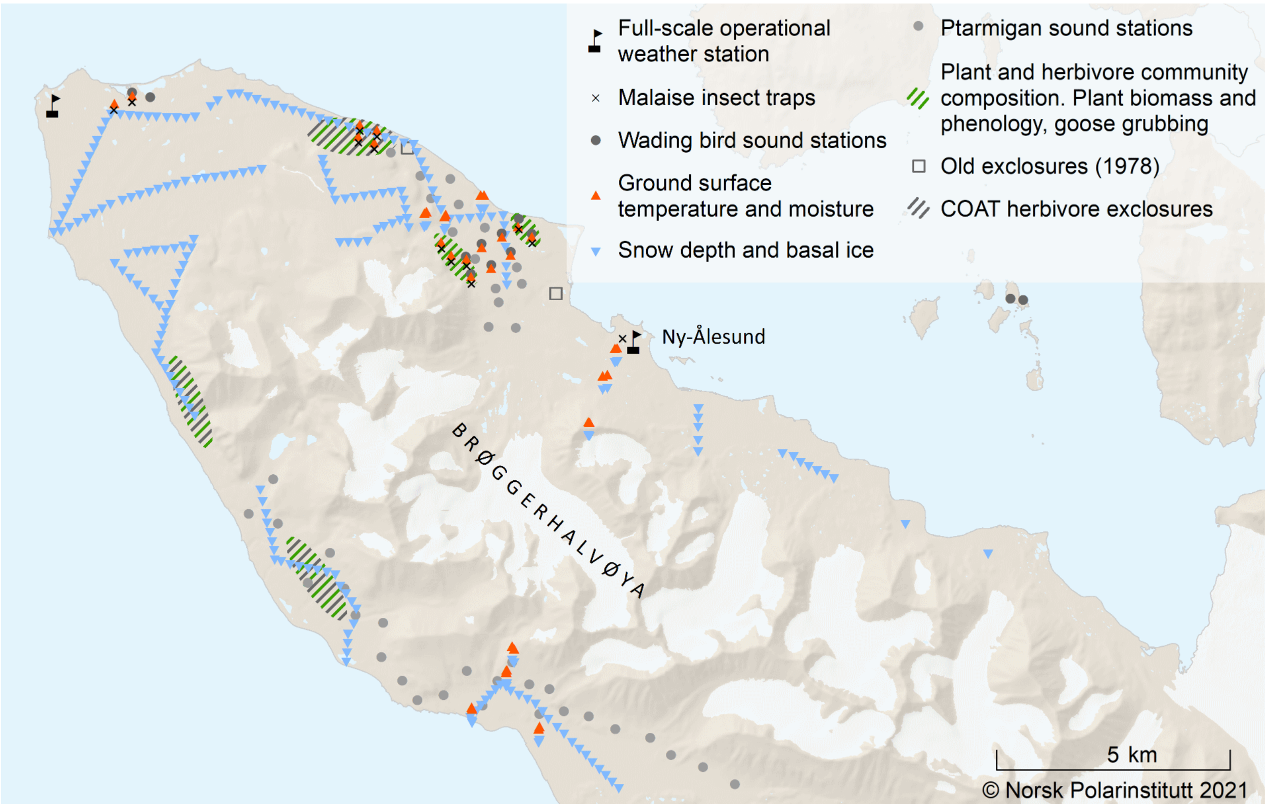


Figure 1: The Climate-ecological Observatory for Arctic Tundra (COAT) builds on and expands the existing monitoring in Svalbard to become fully ecosystem-based. COAT Svalbard is an essential component of the Svalbard Integrated Arctic Earth Observing System (SIOS) and serves to optimise and integrate the ecosystem-based terrestrial monitoring. Currently, COAT Svalbard has implemented research infrastructure in two focal study regions in A) Nordenskiöld Land and B) Brøggerhalvøya. In both these regions there are also existing long time-series on focal ecosystem components like the Arctic fox, geese, Svalbard reindeer and Svalbard rock ptarmigan. (Map: Anders Skoglund, NPI)

For the past 60 years, the measured annual precipitation at the four long-term Norwegian full-scale operational weather stations (Bjørnøya, Hopen, Svalbard Airport, and Ny-Ålesund) in the Svalbard region has increased by 30%–45% (Førland et al. 2020, Figure 2C). Higher winter temperatures cause more frequent episodes of winter rain (Figure 2D), resulting in a regime shift in winter climate (Peeters et al. 2019). The spatial extent and thickness of basal ice increased strongly with the amount of winter rain (Peeters et al. 2019). However, considerable spatial variation exists, particularly along the coast-inland gradient. Increased frequency of rain-on-snow, resulting in basal ground ice formation, has negative impacts on population growth rates of the resident herbivore species (Hansen et al. 2013). Basal ground ice damages vegetation (Milner et al. 2016) and prevents herbivores from accessing food. Increased winter mortality of reindeer, in turn, positively affects food availability for the Arctic fox (*Vulpes lagopus*) and subsequent reproduction (Nater et al. 2021). However, it is still unclear whether increasing temperatures will result in winters so mild that forage access is generally improved for herbivores (due to snow melting), rather than blocking access to foraging grounds (due to ground ice formation).

Hydrological characteristics are changing due to increased precipitation and snowmelt patterns (see Gallet et al. 2019 for a review). The annual average surface run-off has increased by more than a third, mainly due to increased glacier melt and increased winter precipitation. This may increase glacial lake outburst floods as well as affecting erosion intensity and sediment supply to rivers (Hanssen-Bauer et al. 2019). The snow season has decreased by approximately 20 days since the middle of the last century and this trend is expected to continue, resulting in shifts in spring and winter onset (Hanssen-Bauer et al. 2019; Figure 2E). Snow cover duration is decreasing everywhere in Svalbard, but most rapidly in the middle-Arctic tundra zone (Pedersen et al. 2021c).

Changes in season length have a range of implications for food web interactions. An extended growing and grazing season may have a positive effect on reproduction and habitat suitability for herbivores (Albon et al. 2017; Layton-Matthews et al. 2019). Furthermore, patterns of snow melt determine e.g. the extent and intensity of tundra disturbance caused by pink-footed goose (*Anser brachyrhynchus*) when grubbing for below-ground food items in early spring (Anderson et al. 2016) and the subsequent breeding success of migratory geese species (Jensen et al. 2014; Lameris et al. 2019).

The permafrost is thawing, altering landscape structure (Isaksen et al. 2016). Increased air temperatures and precipitation result in an increase in the thickness of the active soil layer above the permafrost in high-Arctic Svalbard (Etzelmüller et al. 2020; Hanssen-Bauer et al. 2019). This is also associated with an increase in the annual and seasonal temperature in the permafrost as well as the near-surface soils within the active layer (Etzelmüller et al. 2020) (Figure 2F). These changes can cause structural instabilities in slopes and in the ground as well as altering hydrology and vegetation, especially where permafrost layers are embedded in sediments (Hanssen-Bauer et al. 2019).

Sea ice decline is pronounced in Svalbard and the Barents Sea area (Onarheim et al. 2018). The loss and earlier retreat of sea ice in spring has implications for the terrestrial ecosystem. In spring, the sea ice has on average retreated two weeks earlier per decade since 1979 (Laidre et al. 2015). Whereas presence of abundant sea ice near the coast during the growing season favours local control of tundra productivity by sea ice, very likely through sea breeze (cold air advection from ice-covered ocean onto adjacent land during the growing season), the large-scale atmospheric and sea surface dynamics (captured by the NAO index) might reflect co-variability of sea ice and tundra productivity (Macias-Fauria et al. 2017). Sea ice loss reduces the possibilities for the Arctic fox to hunt and scavenge on this substrate (Fuglei and Tarroux 2019) and constrains reindeer dispersal (Pedersen et al. 2021b).

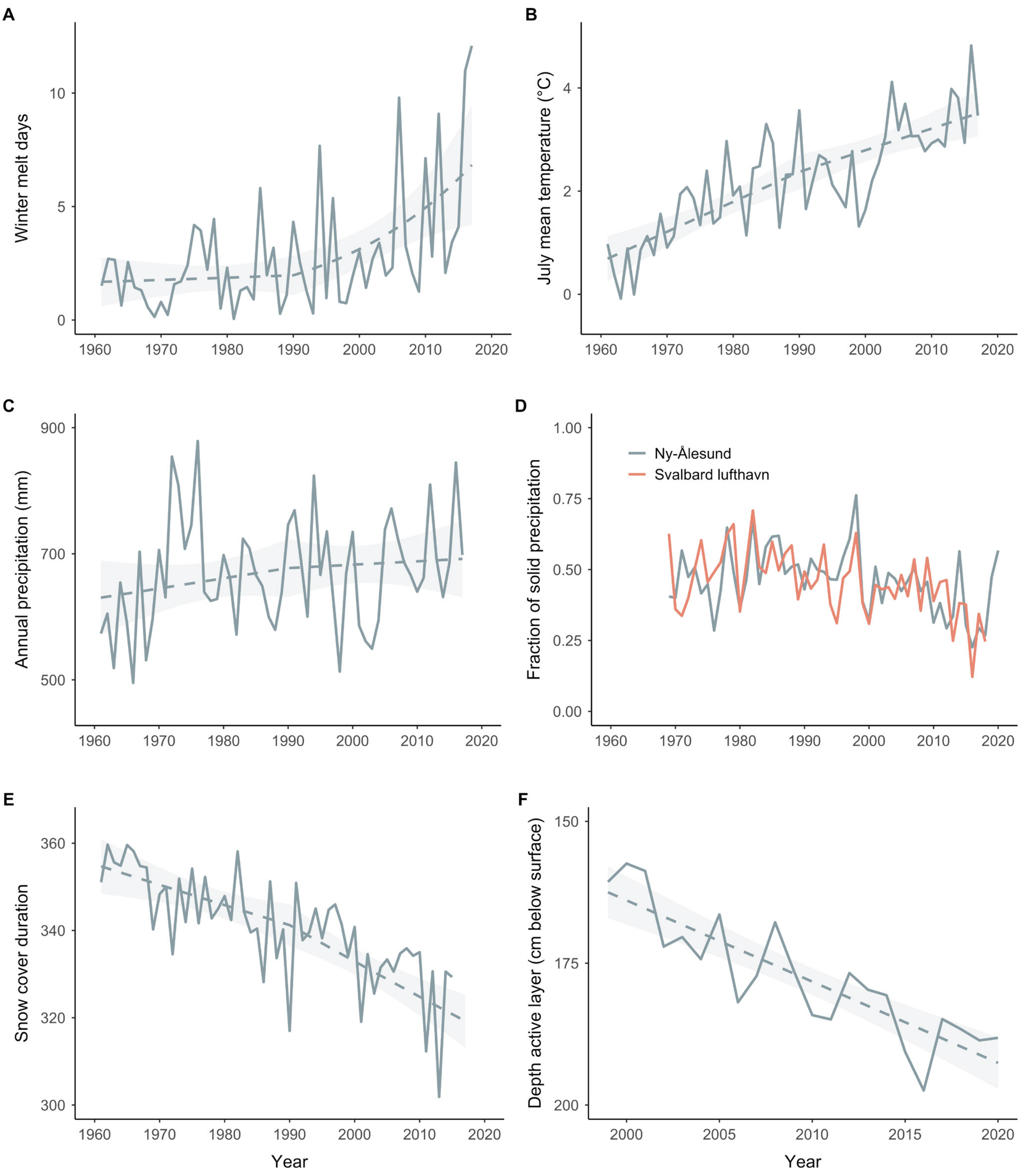


Figure 2: A) Number of winter melt days (daily mean temperature >0°C) per year for Svalbard archipelago, B) modelled annual mean July temperature (°C), C) modelled annual mean precipitation (mm), D) fraction of solid precipitation in Ny-Ålesund and Svalbard Lufthavn during 1969–2018 (modified from Førland et al. 2020), E) modelled number of days with snow cover per year and F) trends in depth (cm) of the active layer in Adventdalen in central Spitsbergen (www.mosj.no). Trend lines indicate the estimated linear rate of change and shading indicates ±2SE (modified from Pedersen et al. 2021b). Data for figure A-C and E are based on 1×1 km gridded datasets derived from downscaling of atmospheric reanalyses (Sval-Imp dataset 1961–2017; Østby et al. 2017). The trend line (A-C, E) displays the rate of change (±2SE) if the indicator value is assumed to be constant (solid grey and dashed) in the climatic reference period and NOT assumed to be constant (dotted; A-C and E) in the climatic reference period, but equal to the predicted regression line for the period 1961–1990.

2.2. Primary productivity

Primary productivity can be quantified as e.g. phenology or maximum productivity during the summer season. The recent assessment of ecosystem condition in the Norwegian Arctic tundra found a trend towards an earlier start of the growing season and increased maximum productivity, measured with satellite imagery between 2000-2019 (Pedersen et al. 2021c). There is, however, considerable spatial heterogeneity in the observed patterns. Accordingly, current changes in primary productivity still have limited impact on the ecological condition of the tundra ecosystem.

A recent pan-Arctic study found that reproductive phenology responds stronger to experimental warming than vegetative phenology (Collins et al. 2021). Flowering, end of flowering and seed dispersal all advanced with a moderate experimental warming, and the vegetation greened earlier and senesced later, resulting in a prolonged growing season. The average advances in leaf green-up and reproductive phenology were 0.7–2.9 days and delay in leaf senescence 0.8 days. These results highlight the importance of combining satellite-based data, typically only available at coarse temporal and spatial resolution, with detailed field studies to better understand drivers of the observed heterogeneity and to enhance the interpretation of changes in primary productivity in a food web context. This is critical, as herbivore populations are expected to be impacted by an altered timing of the phenological states (e.g. Lameris et al. 2019).

New satellite data, such as the Sentinel-2 mission, are expected to resolve the challenges of spatial and temporal resolution. Cloud coverage, however, remains an issue even with the frequent passages of the Sentinel satellites over Svalbard. Moreover, the linkage between ground observations and Sentinel-2 based estimates of growing season start are not uniform across the tundra habitats (Karlsen et al. 2021). There is a need to investigate several aspects of the different satellite time series to improve data quality and enhance comparison between the current MODIS time series and the emerging Sentinel-2 data. Field-based validation is required to understand what implications the satellite-observed changes have for nutrient content, compositional change and phenology of the tundra vegetation. To improve our understanding of changes in primary productivity and its implications for the food web, the COAT Svalbard vegetation work makes use of herbivore exclosures, monitoring at 57 field stations, imagery acquired with drones and satellites, and analysis of plant and soil nutrient contents (Ravolainen et al. 2020).

2.3. Changes in higher trophic levels and overall trends in monitoring targets

The Svalbard tundra ecosystem has undergone rapid and substantial changes in abiotic conditions, particularly increasing temperatures, longer and warmer growing seasons, shorter snow-cover seasons, and thawing of permafrost. The biotic implications of these changes are still mostly limited, and mainly evident in ecosystem characteristics (e.g., landscape-ecological patterns and biological diversity) and indicators (e.g., Arctic endemic species and plant communities) with strong causal links to climate (Appendix 4).

Currently, the abundance of monitored vertebrate populations appears to be stable or increasing (reindeer, ptarmigan, fox and geese; Fauteux et al. 2021; Hansen et al. 2019b; Johnson et al. 2020; Layton-Matthews et al. 2020; Marolla et al. 2021; Nater et al. 2021) (Figure 3). There could be several reasons for this. The monitored herbivores include resident and migratory species that are at the northern edge of their distribution range. They are adapted to harsh conditions, including food limitations and extreme cold, but show considerable plasticity. Thus, longer growing seasons would reduce food constraints and allow for better body condition, leading to increased reproduction (Albon et al. 2017; Loe et al. 2021). While stochastic perturbations in the form of large-scale rain-on-snow (ROS) events and resultant basal ice continue to affect annual variability in population growth rates of many species, their impacts may be at least partially alleviated by

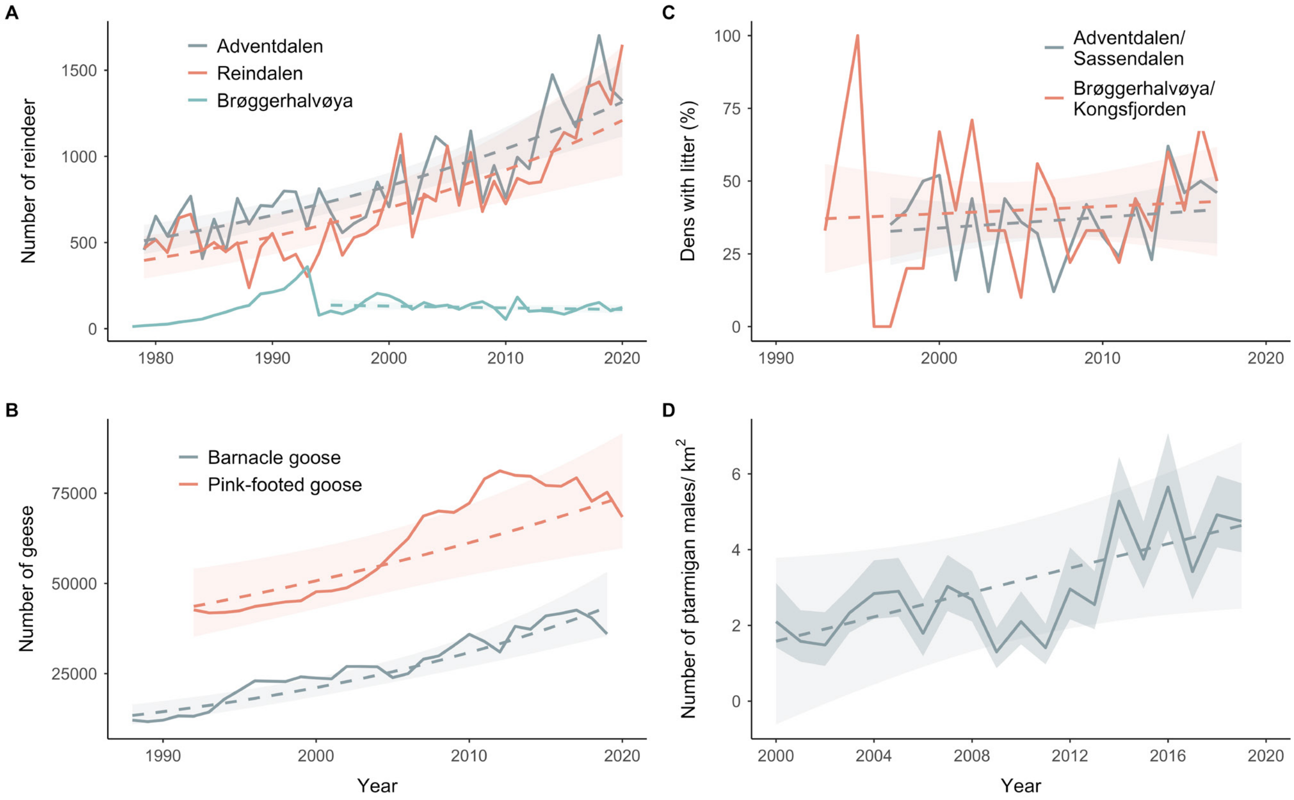


Figure 3: Time-series of the abundances of four key vertebrate species. A) Population size of Svalbard reindeer (modified from Pedersen et al. 2021c). B. Population size of Svalbard pink-footed goose and barnacle goose (modified from Pedersen et al. 2021c). C. Arctic fox dens with pups (modified from Layton-Matthews et al. 2020; Pedersen et al. 2021c). D) Number of ptarmigan males per square kilometer (modified from Marolla et al. 2021).

improved summer conditions. Indeed, while severe winter weather events can have drastic short-term consequences, Hansen et al. (2019a) documented that they may have a stabilising effect on reindeer population dynamics in the long run. Tundra plants respond immediately to warming summer temperatures by increasing growth (Van der Wal and Stien 2014), and both reindeer and geese can have local effects on plant biomass and modify the tundra vegetation communities (Ravolainen et al. 2020). Consequently, changes in their abundance, interacting with climate warming, are expected to have 'knock-on effects' on the composition, structure and productivity of the Svalbard vegetation communities.

The observed shift in bioclimatic zonation towards a low-Arctic zone provides suitable growing conditions for a higher diversity of plants and the potential for establishment of new functional groups (e.g., shrubs). Such changes in plant communities are not yet apparent. This may be due to long time-lags in vegetation community-level responses to climate. However, there is presently a lack of long-term monitoring data suitable for documenting slow community-level vegetation transitions (Ravolainen et al. 2020). This represents a major gap in our capacity to assess climate change impacts on tundra vegetation, including the cascading effects on food web dynamics and overall ecosystem functioning. COAT aims to fill this gap by establishing the required long-term monitoring and model-based analyses for disentangling changes in key food web processes (e.g., Ims and Yoccoz 2017; Ravolainen et al. 2020). This will provide a solid foundation for a better understanding of climate change impacts on the ecological condition of high-Arctic tundra ecosystems.

3. Unanswered questions, challenges and recommendations for the future

Long-term ecosystem-based monitoring is crucial to (1) establish how anthropogenic pressures affect the ecosystem, and to (2) assess the effectiveness of management actions (Christensen et al. 2020; Ims and Yoccoz 2017). Key success criteria are co-location of measurements at ecologically relevant spatial and temporal scales, harmonised and standardised methods, and procedures for data integration from observations and experiments to models of causal relations (Ims and Yoccoz 2017; Musche et al. 2019). For the long-term running of the ecosystem-based monitoring, we recommend the following:

Climatic drivers of ecosystem change: The ecosystem implications of a rapidly warming climate are central and a generally important arena for interdisciplinary research. COAT Svalbard scientists have quantified climate effects on central state variables in the monitoring modules (summarised in Pedersen et al. 2021a, Table 4). For example, ptarmigan population dynamics are mainly affected by increased winter temperature (Appendix 5; Marolla et al. 2021), while reindeer body mass and subsequent reproduction are driven by ROS events and the onset of snow in autumn (Loe et al. 2021). Further identification of such driver–response relationships ought to be given high priority.

COAT Svalbard has established observational time series of snow properties. However, the understanding of ecosystem impacts of changing snow conditions requires snow modelling products that provide accurate, spatially distributed and time-evolving datasets of snow properties. This can be acquired through the data-model fusion 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.

New methods and technologies: Ecosystem monitoring has entered an era where new technologies allow for automatic measurements that are spatially and temporally more extensive and have higher resolution than traditional manual measurements. Such ground (automatic sensors) and remotely (drones, satellites) based technologies should be optimised to improve the scope of field measurements (see examples in Kleiven et al. 2021; Mölle et al. 2021). There is a substantial effort involved in consolidating sensor-based data to ecosystem processes occurring on the ground. New developments should also include analytical tools (algorithms) to improve the assimilation and processing of large amounts of raw sensor data to operative ecological state variables, as well as refined statistical models that can be used for more robust causal inferences and short-term predictions based on such state variables.

Interface with end-users and cooperation: It is COAT's ambition to be highly relevant to policy makers and managers. Given the prospects of climate change, Arctic ecosystems are likely to be transformed beyond scientists' current abilities to make predictions and managers' capacity to implement mitigation and adaptation strategies. This grand challenge requires more sincere efforts to develop structured interfaces between monitoring-based ecosystem science and end-users than are presently implemented within COAT Svalbard (Ims and Yoccoz 2017; see Pedersen et al. 2021a, Table 4, for an overview and Henden et al. 2020 for an example).

4. Data availability

The COAT data management system is a crucial part of the research infrastructure. COAT's data portal (https://data.coat.no/) builds on international metadata standards (DCAT, schema.org-structured data and ISO 19115/CSW) compatible with SIOS's digital infrastructure. See Appendix 6 for a list of dataset sources in this chapter and Pedersen et al. (2021c; Table 3.2.b) for a complete list of all dataset sources for the indicators/state variables summarised in section 2.

5. Acknowledgements

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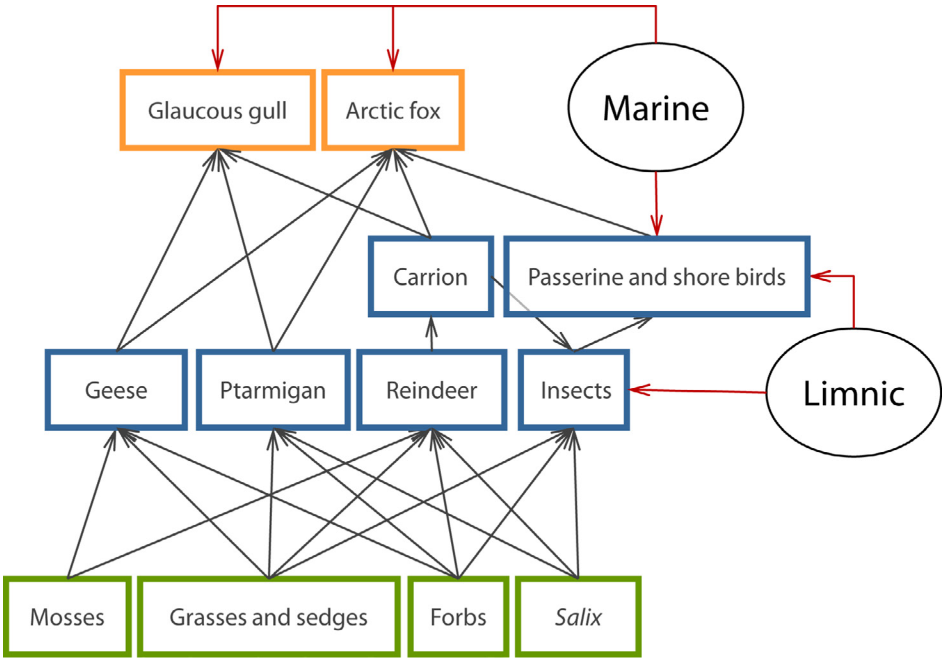
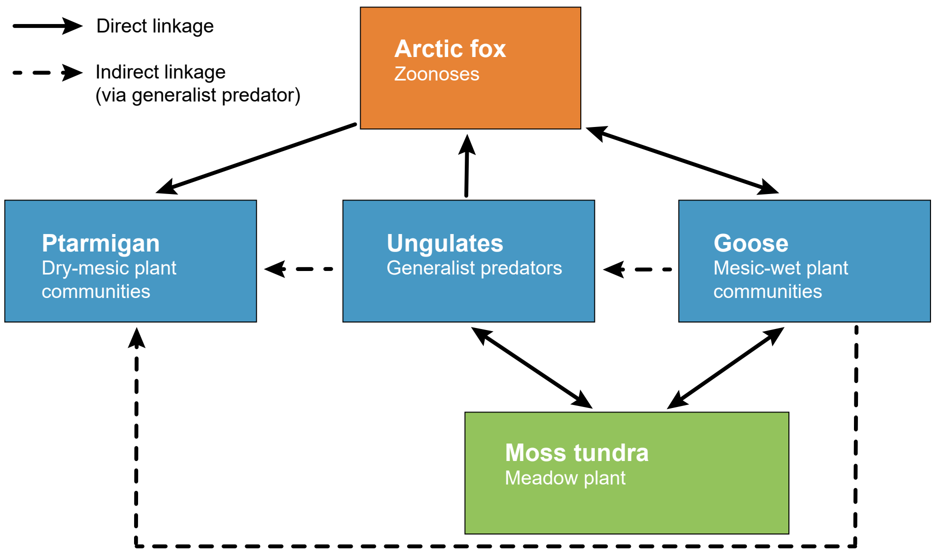
Appendix 1: The Svalbard terrestrial food web and the COAT monitoring modules





The terrestrial food web in Svalbard (upper panel) is represented with (lower panel) five biotic and one cross-cutting climate monitoring module (not shown here). For a detailed description of the Svalbard terrestrial tundra ecosystem, see Box 1 in Pedersen et al. (2020)[1] and Descamps et al. (2017)[2].

1 Pedersen ÅØ, Jepsen JU, Paulsen IMG et al (2021c) Norwegian Arctic tundra: a panel-based assessment of ecosystem condition. Report Series 153. Norwegian Polar Institute, Tromsø

2 Descamps S, Aars J, Fuglei E, et al (2017) Climate change impacts on wildlife in a High Arctic archipelago - Svalbard, Norway. Glob Change Biol 23:490-502. https://doi.org/10.1111/gcb.13381

Appendix 2: COAT Climate monitoring network

The climate module covers the main climatic variables that are expected to act as drivers on ecosystem components, i.e. air and soil temperature, precipitation, wind direction and speed, snow cover and depth, air humidity, radiation, basal ice cover, and timing of snowmelt.

Full-scale operational weather stations are a core infrastructure in COAT's climate monitoring network. They cover an important ecological gradient from the coast to inland valleys. Along with the weather stations, a network of ground temperature loggers was established to measure both temperature and soil moisture along elevational gradients, at module stations and in a network around selected weather stations.

The data from the COAT stations are also essential to calibrate spatial and temporal snow models (see Liston and Elder 2006[3] for an example), as the cryosphere has a key role in determining the dynamics of the Svalbard tundra ecosystem (e.g. Hansen et al. 2013[4]; Stien et al. 2012[5]).

The weather stations are 'hot-spots' for potential co-location and expansion of measurements to cover a wider range of variables related to both the biosphere and the cryosphere. Data from the weather stations can be downloaded from www.seklima.met.no/observations/.

Photos: Ketil Isaksen

3 Liston GE, Elder K (2006) A meterological distribution system for high resolution terrestrial modelling (MicroMet). J. Hydrometeor 7: 217-234. https://doi.org/10.1175/JHM486.1

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

5 Stien A, Ims RA, Albon SD et al (2012) Congruent responses to weather variability in high Arctic herbivores. Biol Lett 8:1002-1005. https://doi.org/10.1098/rsbl.2012.0764

Appendix 3: Biotic and abiotic indicators for each of the seven ecosystem characteristics addressed in the assessment of Arctic tundra in Svalbard

The reference condition, relative to which all assessments of current ecosystem condition should be made, is defined as 'an intact ecosystem state', which is characterised by the maintenance of the fundamental ecosystem structures, functions and productivity. The majority of indicators were derived from COAT, with support from SIOS, and the Environmental Monitoring of Jan Mayen and Svalbard (MOSJ) programme, dedicated specifically to the monitoring of Norwegian Arctic tundra ecosystems. See section 5 and Tables in Pedersen et al. (2021c)[6] for associated information.

Ecosystem characteristic	Indicator
Primary productivity	Maximum vegetation productivity
	Start of growing season
Biomass between trophic levels	Maximum vegetation productivity versus Svalbard reindeer
	Maximum vegetation productivity versus geese
	Herbivorous vertebrates versus Arctic fox
Functional groups within trophic levels	Herbivorous vertebrates
Functionally important species and biophysical structures	Pink-footed goose abundance
	Barnacle goose abundance
	Svalbard reindeer abundance
	Svalbard reindeer mortality rate
	Svalbard reindeer calf rate
	Arctic fox abundance
Landscape-ecological patterns	Bioclimatic subzones
	Wilderness areas
Biological diversity	Svalbard rock ptarmigan breeding abundance
Abiotic factors	Days with extreme cold
	Winter melt days
	Degree days
	Growing degree days
	Annual mean temperature
	July mean temperature
	Annual precipitation
	Permafrost
	Snow cover duration

6 Pedersen ÅØ, Jepsen JU, Paulsen IMG et al (2021c) Norwegian Arctic tundra: a panel-based assessment of ecosystem condition. Report Series 153. Norwegian Polar Institute, Tromsø

Appendix 4: Key conclusions from the assessment of ecological condition of Norwegian Arctic tundra

- Norwegian Arctic tundra ecosystems have since the climatic reference period (1961–1990) undergone rapid and substantial changes in the abiotic conditions manifested particularly as increasing surface temperatures, longer and warmer growing seasons, shortening of the snow-covered season, and increasing permafrost temperatures.

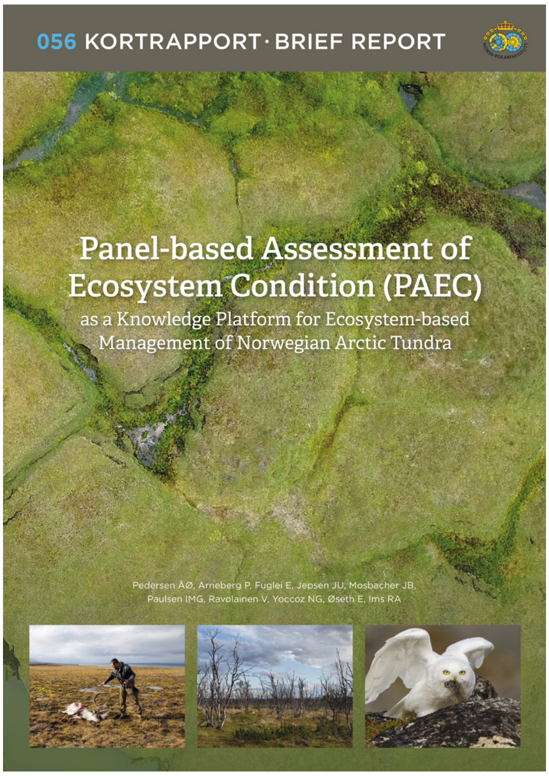
- The biotic implications of these changes are still mostly limited, and mainly evident in ecosystem characteristics (Landscape-ecological patterns and biological diversity) and indicators (e.g. Bioclimatic subzones, Arctic and endemic species, Plant communities) with strong causal links to climate.

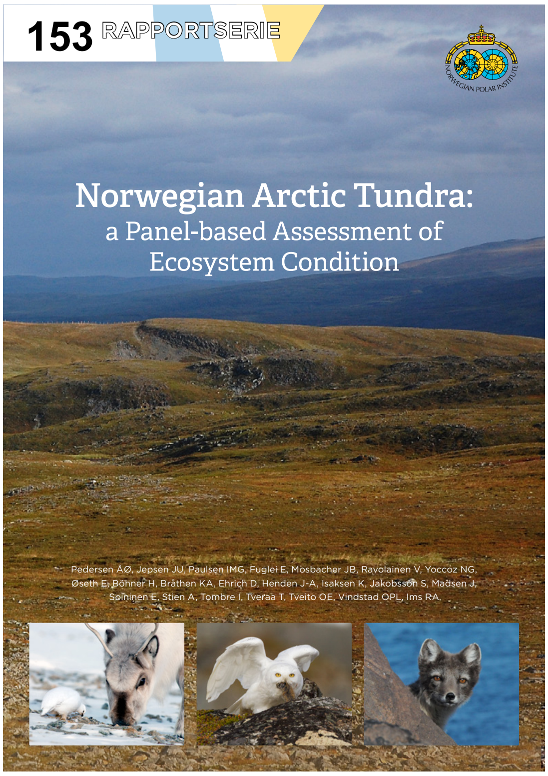
- The scientific panel concludes that Norwegian Arctic tundra ecosystems are overall in a good ecological condition, with fundamental structures and functions still maintained, despite substantial abiotic changes. However, some biotic ecosystem characteristics show deviations from the reference condition, while others are presently on significant change trajectories, which should be considered a warning of more extensive, incipient ecosystem changes. Of the two sub-ecosystems assessed, the low-Arctic tundra in Finnmark shows more pronounced and consistent deviations in biotic characteristics than the high-Arctic tundra in Svalbard. In Finnmark, the Arctic tundra ecosystems are on a trajectory of losing Arctic endemic species (Arctic fox and snowy owl) and are bioclimatically on a trajectory away from low-Arctic subzones towards boreal subzones.

Reports can be downloaded at:

https://brage.npolar.no/npolar-xmlui/handle/11250/2754696

https://brage.npolar.no/npolar-xmlui/handle/11250/2754717





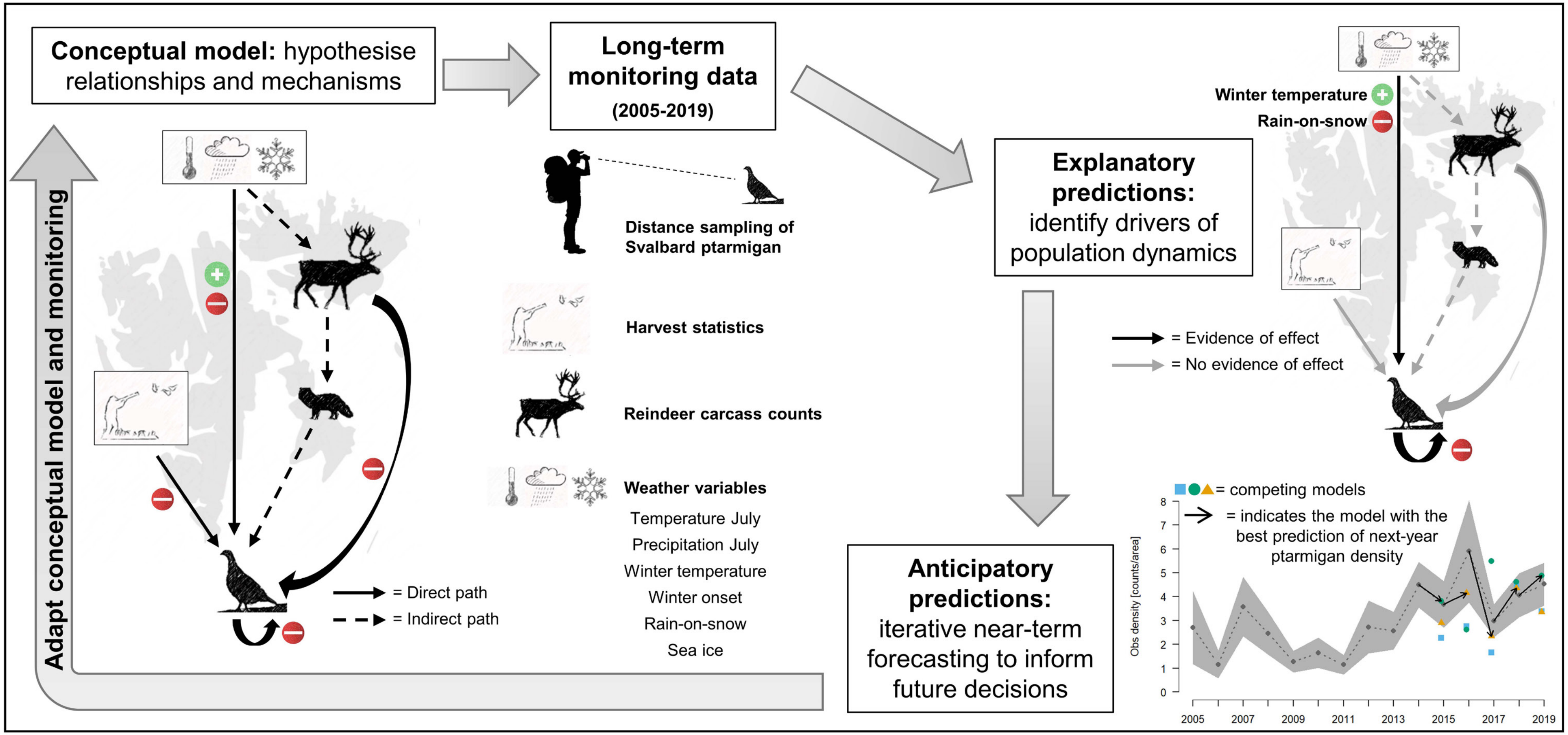
Appendix 5: Iterative model predictions for wildlife populations impacted by rapid climate change

Marolla et al. (2021)[7] used MOSJ and COAT long-term monitoring data of Svalbard rock ptarmigan and other biotic and abiotic ecosystem state variables to identify drivers of population dynamics and to evaluate the ability of state-space models to predict next-year ptarmigan density. Firstly, they laid out the hypothesised impacts of the biotic and abiotic drivers on ptarmigan dynamics and visualised them through the conceptual COAT model. They then fitted state-space models to Svalbard rock ptarmigan monitoring data to 1) quantify the effects of potential drivers of population dynamics (explanatory predictions) and 2) assess the ability of candidate models of increasing complexity to forecast next-year population density (anticipatory predictions).

Benefitting from the ecosystem-wide monitoring data, they were able to attribute a recent increasing trend in the ptarmigan population to major changes in winter climate, especially in terms of mean temperature. As winters become warmer, ptarmigan appear to benefit from these conditions, likely because their energy needs for thermoregulation are reduced. This probably improves their body condition throughout the winter and thus increases survival. The strong positive effect of increasing winter temperature on ptarmigan population growth currently outweighs the negative impacts of other manifestations of climate change, e.g., rain-on-snow events. The ptarmigan population also appears to compensate for the impact of the main manageable driver, i.e., current harvest levels.

This study highlights the value of the ecosystem-wide COAT monitoring in Svalbard and the application of multi-driver statistical modelling based on these monitoring data to assess and forecast the state of Svalbard rock ptarmigan populations.

7 Marolla F, Henden JA, Fuglei E, Pedersen ÅØ, Itkin M, Ims RA (2021) Iterative model predictions for wildlife populations impacted by rapid climate change. *Global Change Biology*, *27*(8), 1547-1559. https://doi.org/10.1111/gcb.15518



Graphical abstract, modified from Marolla et al. (2021) and Pedersen et al. (2021a)[8], describing the approach used to model the effects of manageable and non-manageable drivers on population dynamics of Svalbard rock ptarmigan.

8 Pedersen ÅØ, Arneberg P, Fuglei E et al (2021) Panel-based Assessment of Ecosystem Condition as a platform for ecosystem-based management of Norwegian Arctic tundra. Brief Report 056, Norwegian Polar Institute

Appendix 6: Summary of datasets and their availability

Overview of dataset name, owner institutions, temporal coverage and DOI/URL. The table is modified from Pedersen et al. (2021c; Table 3.2.b[9]).

Dataset	Parameter	Period	Location	Metadata access (URL)	Dataset provider
Arctic fox den monitoring (data are partly excluded from the public)	Number of active dens	1993/97–2019	Adventdalen and Sassendalen, Svalbard	http://www.mosj.no/en/fauna/terrestrial/arctic-fox-population.html	Eva Fuglei, NPI (eva.fuglei@npolar.no)
Svalbard Barnacle goose wintering population census	Population counts Demography	1988–2020	Svalbard archipelago (winter counts in Scotland and England)	https://monitoring.wwt.org.uk/our-work/goose-swan-monitoring-programme/species-accounts/svalbard-barnacle-goose/	Wildfowl & Wetlands Trust (WWT)
Svalbard Pink-footed goose spring population census	Population counts Demography	1991-2018	Svalbard archipelago (winter counts in Denmark, Belgium and the Netherlands)	https://www.sciencebase.gov/catalog/item/5cc8890ee4b09b8c0b77f1cd	Jesper Madsen, AU (jm@bios.au.dk)
MODIS EVI	Vegetation productivity	2000–2019	Svalbard archipelago	e4ftl01.cr.usgs.gov/MOLT/MOD13Q1.006/	NASA Goddard Space Flight Center, Ocean Ecology Laboratory, Ocean Biology Processing Group. Moderate-resolution Imaging Spectroradiometer (MODIS) Terra
Svalbard reindeer population abundance and calf rates	Population counts Demography	1978/79–2020	Adventdalen, Brøggerhalvøya, Reindalen	http://www.mosj.no/en/fauna/terrestrial/svalbard-reindeer-population.html https://data.coat.no/dataset/s_ungulates_abundance_kongsfjorden_summer_v1 https://data.coat.no/dataset/s_ungulates_summary_adventdalen_summer_v1	Åshild Ø. Pedersen, NPI (ashild.pedersen@npolar.no) Audun Stien, NINA (audun.stien@uit.no)
Svalbard reindeer carcass abundance	Number of carcasses	1979/1991–2020	Adventdalen	https://data.coat.no/dataset/s_ungulates_carcasses_adventdalen_summer_v3	Åshild Ø. Pedersen, NPI

9 Pedersen ÅØ, Jepsen JU, Paulsen IMG et al (2021) Norwegian Arctic Tundra: a Panel-based Assessment of Ecosystem Condition. Report Series 153. Norwegian Polar Institute, Tromsø

Svalbard rock ptarmigan breeding abundance	Population counts	2000–2019	Nordenskiöld Land	https://data.coat.no/dataset/s_ptarmigan_counts_v3	Eva Fuglei, Åshild Ø. Pedersen, NPI
Sval-Imp gridded temperature	Temperature (degrees)	1958–2017	Svalbard archipelago	https://doi.org/10.11582/2018.00006	Ole Einar Tveito, MET Norway (oleet@met.no)
Sval-Imp gridded precipitation	Precipitation (in mm)	1958–2017	Svalbard archipelago	https://doi.org/10.11582/2018.00006	Ole Einar Tveito, MET Norway
Sval-Imp gridded snow cover	Fractional snow cover	1958–2017	Svalbard archipelago	https://doi.org/10.11582/2018.00006	Ole Einar Tveito, MET Norway
Solid precipitation	Fraction of solid precipitation	1969-2020	Longyearbyen, Ny-Ålesund	https://doi.org/10.1175/JHM-D-19-0252.1	Eirik Førland, MET Norway (eirikf@met.no)
Permafrost monitoring	Permafrost temperature Depth of active layer	1999–2020	Adventdalen	www.mosj.no/en/climate/land/permafrost.html	Ketil Isaksen, MET Norway (ketili@met.no)
COAT weather stations	Precipitation, temperature, wind speed	2020-	Nordenskiöld Land, Brøggerhalvøya, Kaffiøyra	https://seklima.met.no/observations/	Ketil Isaksen, MET Norway

Improving terrestrial photography applications on snow cover in Svalbard with satellite remote sensing imagery (PASSES 2)

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1. Introduction

The dynamics of seasonal snow is a key element of changing ecosystems in Arctic regions, and the ability to monitor it requires filling the gap that exists between in situ and satellite observations (Salzano et al. 2021b). The outcomes of PASSES (Salzano et al. 2021a) gave an overview of terrestrial photography applications on the snow cover, but future actions focused on enhancing and maintaining snow observations must include data integration and assimilation while considering different platforms and spatio-temporal resolutions. The wide availability of time-lapse cameras highlighted their significant potential as a bridging point, enabling comparison of detailed descriptions of the snow cover with large-scale assessments of the snow variability obtained by satellite platforms (Aalstad et al. 2020; Gascoin et al. 2020). Time-lapse camera networks are important data sources for calibrating and validating satellite products, but guidelines about the required resolutions are needed to support creation of a regional infrastructure in the framework of the Svalbard Integrated Arctic Earth Observing System. This contribution provides: an updated and more detailed survey about terrestrial and satellite-based applications for snow cover monitoring; a comparison between different image processing algorithms; guidelines for the selection of the most appropriate spatial and temporal resolutions for terrestrial photography; and examples of the integration of data obtained by terrestrial photography with satellite remote sensing data.

2. The state of terrestrial photography applications on the snow cover

2.1. The updated survey

There are a myriad of time-lapse cameras in Svalbard that can potentially be used for assessing the evolution of the snow cover. Knowledge about available datasets, metadata descriptions, processing chains, and product specifications are all important factors for obtaining a complete overview of terrestrial photography applications in such a remote area. This overview of cameras operating in the Svalbard archipelago has been approached by searching specifically for applications on the snow cover and by collecting information about images that can be found on the web that are not solely focused on research purposes in the cryospheric domain. Compared to the previous survey (Salzano et al. 2021b) the number of cameras identified by the survey is nearly doubled. However, this updated survey considered an additional parameter related to the research topic each camera is intended to address. Most of the new cameras (88%) are in previously identified locations where the presence of research infrastructure facilitates camera installation and maintenance, whereas 12% of the newly identified cameras are outside already surveyed locations (mainly in the eastern part of the archipelago). Regarding the survey of scientific publications, an analysis was performed in Scopus using the query string (time-lapse OR camera OR photography OR webcam) AND Svalbard to search in paper titles, abstracts, and keywords. A total of 163 articles were found from which 29 used terrestrial photography, with institutes from Norway, United Kingdom, France, Italy, Sweden, United States and Poland being the most represented (Salzano et al. 2021c).

The updated survey considers a total of 106 cameras of which 84 were installed for research purposes (79%), 12 were private cameras (11%), and 10 (10%) were multi-purpose for both private (e.g., security) and research purposes. Among the cameras installed for research purposes, the main topics were snow and/or glaciers that together represent 53% of the category; the remaining cameras were dedicated to flora and fauna monitoring, weather, permafrost, and ecology in general (Figure 1). The survey shows that 46% of the cameras are still active; the rest belong to finished projects or do not report their state of activity. Most of the cameras are active for a period that spans from a month to a season (51%), followed by cameras that operate year-round (29%) and by cameras used for a limited time (less than a month, 18%).

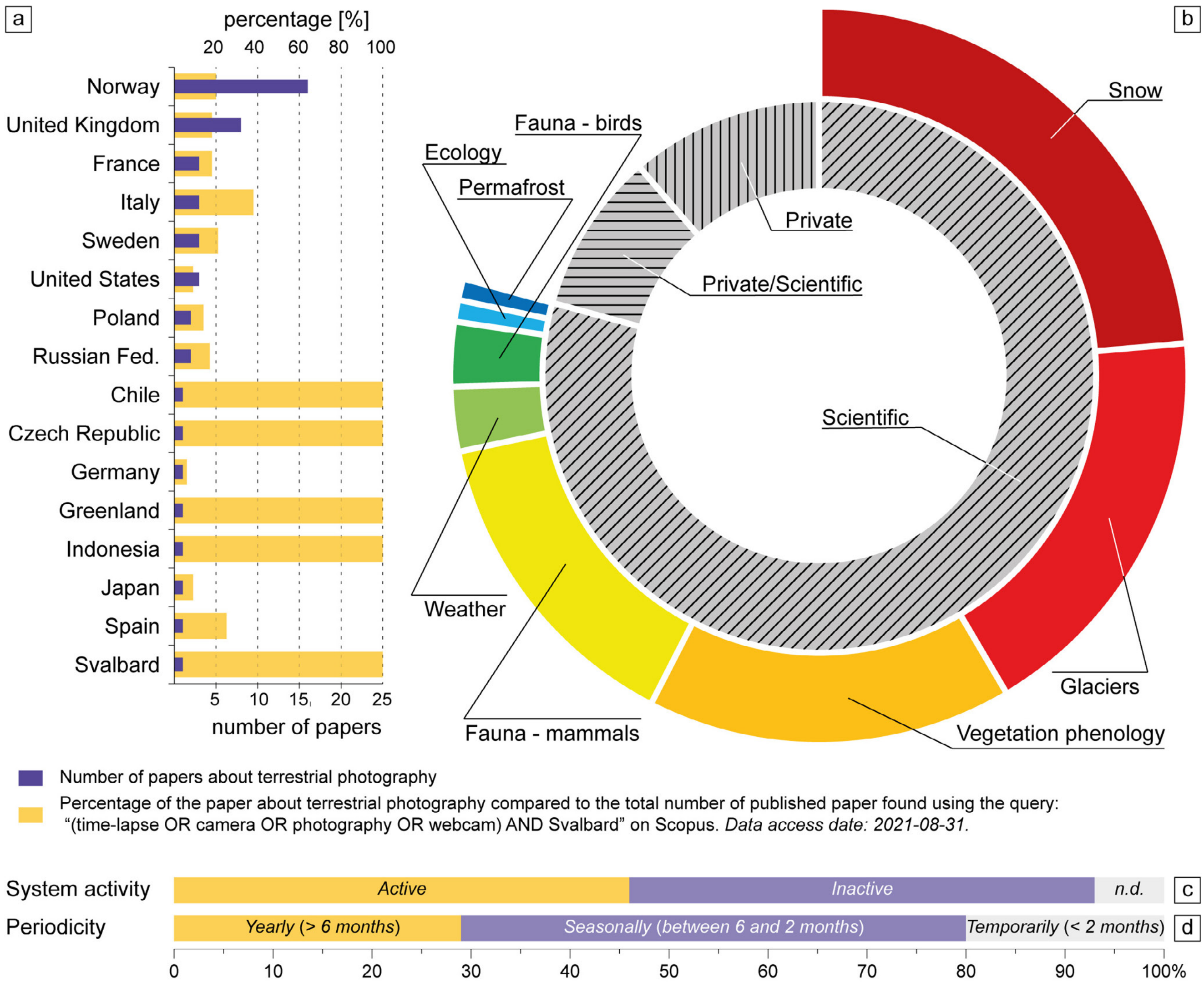

Figure 1: *(a) Number of published papers about terrestrial photography (dark bars) and percentage of these paper relative to the total number of papers published by nations on terrestrial photography applications in Svalbard (pale bars). (b) Distribution of terrestrial cameras by purpose (inner ring) and percentage of scientific topics for which a camera was installed (outer ring). State of activity of the terrestrial camera (c) and the period of the activity (d).*

2.2. Guidelines for the selection of the most appropriate spatial and temporal resolutions for terrestrial photography applications

One key recommendation of our previous SESS report (Salzano et al., 2021a) was to establish a shared protocol for terrestrial applications. Such applications support the definition of different metrics about the snow cover: the Snow-Covered Area (SCA) and the Fractional Snow-Covered Area (FSCA), also known as the Fractional Snow Cover (FSC) or Snow Cover Fraction (SCF). While SCA is a binary classification of the state of the snow cover (snow or no snow), FSCA is the areal fraction of a pixel that is covered with snow. It is challenging to estimate FSCA at the pixel level with terrestrial photography, so FSCA is usually obtained by aggregating SCA to a coarser resolution through spatial averaging. The SCA image classification algorithm considers each pixel: the SCA is strictly related to the heterogeneity within each projected surface, bearing in mind that the larger the distance from the sensor position, the larger the projected surface and, consequently, the larger the potential for mixed composition (both snow and not snow) (Figure 2). The same holds for the FSCA estimation but, in this case, the necessary aggregation of pixels motivates statistical analysis. The uncertainty in retrieving FSCA is related to the number of pixel elements included in the projected cell unit under consideration. Since the associated uncertainty could be defined as a Poisson distribution of the number of correctly classified binary pixels, it is possible to estimate the uncertainty as the square value of the number of pixels included in each cell unit. This implies that the smaller the number of projected pixels in the aggregated cell unit, the larger the related uncertainty (Figure 2). Starting from the output definition and the related uncertainty while taking into account past experience, it is possible to summarise that the major elements involved in selecting the most appropriate application are: the spatial resolution (observation geometry, sensor specifications, cell size); the time resolution; and the classification algorithm selection.

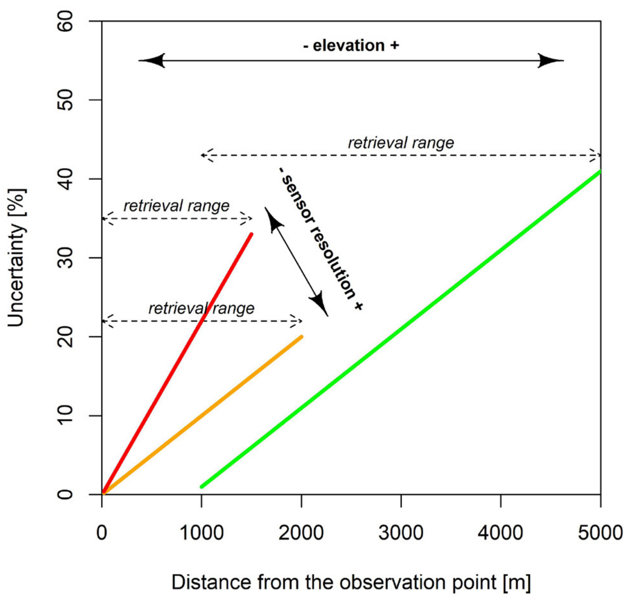

Figure 2: *Relation between distance from the observation point, the range (minimum and maximum distance) and the uncertainty of* Fractional Snow-Covered Area *(FSCA) retrievals. Coloured lines represent real experimental setup estimated considering cameras with different sensor resolutions installed at the CCTower (orange and red) and the camera located at the Zeppelin Observatory (green). Each double ended black solid arrow refers to a specific setting where the elevation of the camera location and the sensor resolution are relevant information for finding the right retrieval range.*

2.2.1. The spatial resolution of time-lapse cameras

The observation geometry is strongly controlled by: the camera location (altitude), the viewing setup (orientation), the camera sensor (image resolution), and the final output representation (cell size). The optimal design is driven by the application type, and it is possible to provide some examples aimed at helping the community select the best solution for their application. The first case study is based on different setups operating in the Ny-Ålesund area, where the coastal plain has been observed for 10 years from different locations and using different perspectives for various applications (Salzano et al 2021b). This first example combines observation of the Kolhaugen site from the Zeppelin Observatory, from the Amundsen-Nobile Climate Change Tower, and from a vertical setup associated with a field spectroscopy experiment. The combination of those oblique setups gives us indications about the relation between sensor resolution, installation elevation, and uncertainties. Vertical geometries, for example, limit the field of view and provide a detailed description of the surface, but the spatial representativeness of the observed snow dynamics is poor. Oblique geometries are significantly impacted by the perspective and resolution of the sensor: installing the time-lapse camera at 20 m above ground rather than at ground level expands the observation area from tens of square metres to about 1 km^2. The aggregation of the projected pixel in the final output grid, generally based on satellite grid formats, will of course affect the final uncertainty levels, which can rise if a 10 m grid resolution is selected (Sentinel-2 for example). Conversely, the MODIS grid resolution (500 m), supports smaller uncertainty levels, although this comes at the cost of a limited number of cell units. Increasing the sensor resolution can improve the retrieval of FSCA and thus increase the quality of the terrestrial photography application. This information supports the definition of an altitude-resolution-distance relationship that can help the community find the best compromise for designing new systems.

2.2.2. The temporal resolution of terrestrial photography applications

The temporal resolution of a time-lapse camera is a user setting that should match the application requirements and consider different data processing issues. Designing a camera system to monitor snow dynamics requires several choices, and the major limitation is related to image storage: higher sensor resolutions imply larger image file size. The temporal resolution affects the required storage volume: daily acquisitions require lower storage capacity than hourly acquisitions. Cloud cover is an additional element that must be considered since the observing location could be above or below the cloud base depending on local meteorological conditions. Considering the daily revisit time of different satellites (MODIS, and Sentinel-2 MSI), the installation altitude, which may occasionally be above the cloud base, is a key parameter since cloud cover can be highly variable even on hourly timescales in Svalbard.

2.2.3. Considerations on classification algorithms

The processing of images obtained by terrestrial photography consists of two main steps: image ortho-rectification and image classification. The first task is based on the so-called monoplotting procedure, a well-established mathematical problem focused on associating pixels to ground control points. The image classification can be approached using many different methods. In Svalbard, we have identified the use of two methods: the blue thresholding (BLT) and the spectral similarity (SS). To test these methods, we considered imagery acquired in Ny-Ålesund from the Scheteligfjellet site and in Hornsund from the Fugleberget location. This analysis was aimed at comparing the BLT and the SS algorithms on the same datasets even if images were filtered to limit difficult illumination conditions and topographic effects. Both approaches were performed on 12.2-megapixel imagery acquired by sensors located at about 700 m a.s.l. on Scheteligfjellet and at 550 m a.s.l. on Fugleberget. Both datasets were sampled daily during the melting season from April to August, and contained images selected near solar noon when the solar elevation angle is highest. This comparison highlighted a good agreement between the automated approaches under consideration, and the final description of snow dynamics at daily resolution is not affected by the algorithm selection. The considered images were, in fact, screened before being classified selecting the optimal illuminating conditions. Considering the dataset obtained by a camera located at the Zeppelin Observatory (485 m a.s.l.) and operating since 2015 with a 4.9-megapixel camera, the same analysis was carried out including heterogeneous illumination conditions. This analysis showed a better performance for the SS than for the BLT method, as the latter was impacted by misclassified projected pixel associated with the projection distance. The limitations of BLT retrievals can be associated with poor illumination conditions (low sun or heavy cloud coverage) and surface roughness. While low sun can occur regularly in the early morning or in the late afternoon, surface roughness and cloud coverage are not time-dependent. While BLT can generally provide good results between 11:00 a.m. and 3:00 p.m. local time, SS can increase this time span, since it is more robust to both solar elevation and cloud cover. While hourly acquisitions required a more careful choice of classification algorithm, with SS being superior, both algorithms performed well for daily imagery.

2.3. Integration with satellite remote sensing

Terrestrial photography is a promising tool for cal/val of snow-related retrievals from satellite remote sensing. This is largely due to the very high spatial and temporal resolution that is obtainable using strategically placed time-lapse cameras. These cameras also allow for long temporal and large spatial coverage. As such, the sheer volume of data captured by such systems is virtually unparalleled by other terrestrial and even airborne observations targeted towards satellite cal/val. Terrestrial photography is primarily used to generate very high-resolution maps of binary snow cover which can be spatially aggregated to estimate FSCA at the resolution of the satellite products that are to be validated.

Space-borne sensors can get close to matching the combined spatiotemporal coverage and resolution of automated terrestrial photography. As a result, satellite retrievals are usually validated with higher resolution satellite retrievals. This exercise can be problematic. For example, it has been shown that high resolution retrievals on the order of tens of metres (e.g., from Landsat or Sentinel-2) may contain considerable biases if mixed pixels (subpixel variability) are not accounted for in the retrieval algorithm (Aalstad et al. 2020). These biases do not average out after spatial aggregation. This is where the resolution of terrestrial photography shines by providing a source of independent validation data for satellite retrievals, helping to support (or challenge) conclusions that are drawn higher up the validation chain.

Given this potential, there has been a growth in snow research using terrestrial photography together with satellite remote sensing. Gascoin et al. (2020) used time-lapse photography as a validation tool to retrieve FSCA, instead of binary snow cover, through a nonlinear sigmoid-based regression on the Normalised Difference Snow Index (NDSI). This approach is now used operationally to generate the FSCA product from Sentinel-2 imagery in the pan-European high-resolution snow and ice monitoring of the Copernicus Land Monitoring Service (CLMS). In Svalbard, Aalstad et al. (2018) used an automatic camera system on Scheteligfjellet near Ny-Ålesund to validate Sentinel-2 and MODIS FSCA retrievals that were then used for snow data assimilation. Subsequently, Aalstad et al. (2020) used the same camera to evaluate various FSCA retrieval techniques applied to MODIS, Sentinel-2, and Landsat 8 imagery.

The contribution of terrestrial photography to the gap reduction between in situ observations and satellite data is evidenced by Figure 3, where an area close to the Kolhaugen site (approximately 100x100 m^2) supports the description of the 2020 snowmelt season with different observation data. The impact of mixed pixels is highlighted in terms of snow depletion curve, and it suggests focusing the attention on this issue for assessing the spatial distribution of the snow cover on the ground.

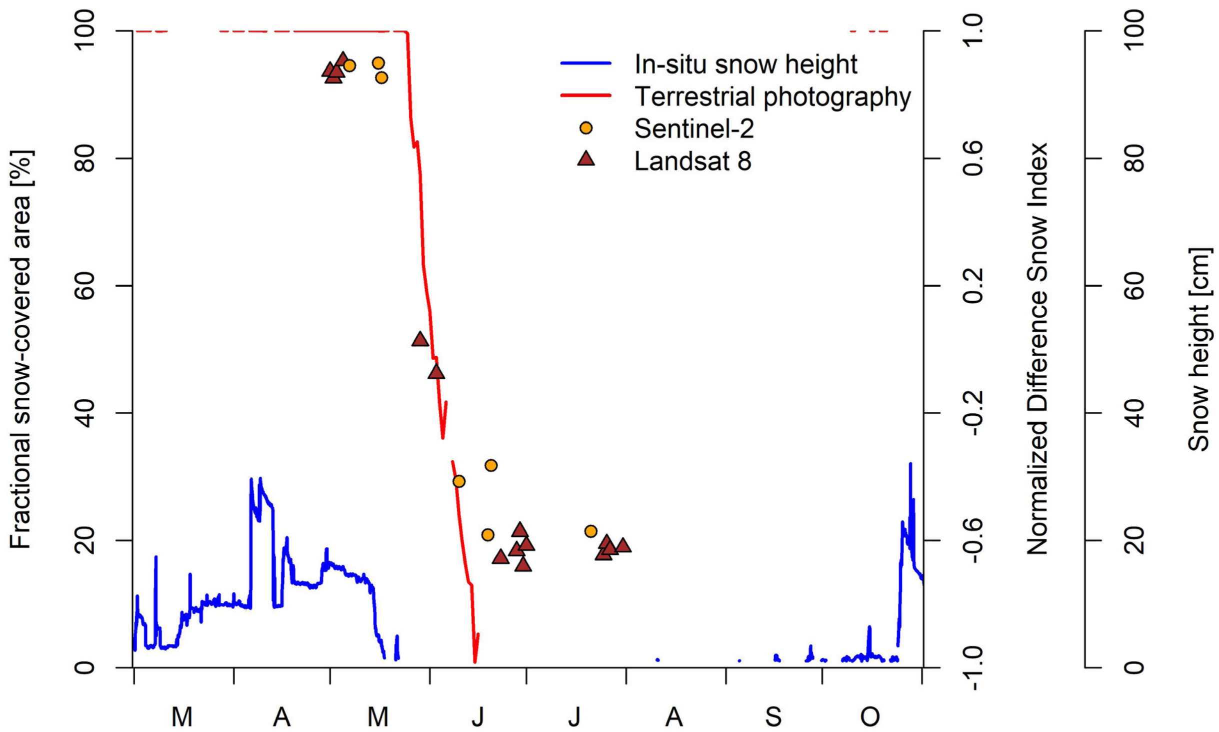

Figure 3: *Evolution of the snow cover at the Kolhaugen site (Ny-Ålesund) in 2020 combining the fractional snow-covered area (FSCA) retrieved by terrestrial photography, in situ measurements of the snow height (Mazzola et al. 2021) at the Climate Change Tower and the Normalised Difference Snow Index (NDSI) obtained by Landsat 8 and Sentinel-2 platforms.*

This was supported by the evaluation of Aalstad et al. (2020) where spectral unmixing, which explicitly accounts for mixed pixels, performed best overall. Moreover, NDSI regression, which implicitly accounts for mixed pixels, could provide nearly the same performance at a considerably lower computational cost. These results helped support the new Let-it-Snow (LIS) algorithm in Gascoin et al. (2020) and provided observation error estimates for snow data assimilation (Alonso-González et al. 2021; Fiddes et al. 2019), exemplifying the benefits that terrestrial photography can bring to snow science. LIS has yet to be tested in Svalbard, which is currently outside the pan-European operational domain of CLMS. As such, we performed an initial validation of LIS in the high-Arctic and compared it to other retrieval algorithms. For the validation, we used the Zeppelin dataset described in Salzano et al. (2021a), where images were ortho-rectified and classified using SS to yield FSCA at 10 m resolution. To avoid artefacts, we cropped the area of interest to exclude the village and airport of Ny-Ålesund. We selected camera-based FSCA maps for five days during June 2019 where cloud-free atmospherically corrected (L2A) multispectral satellite imagery from Sentinel-2A/2B was also

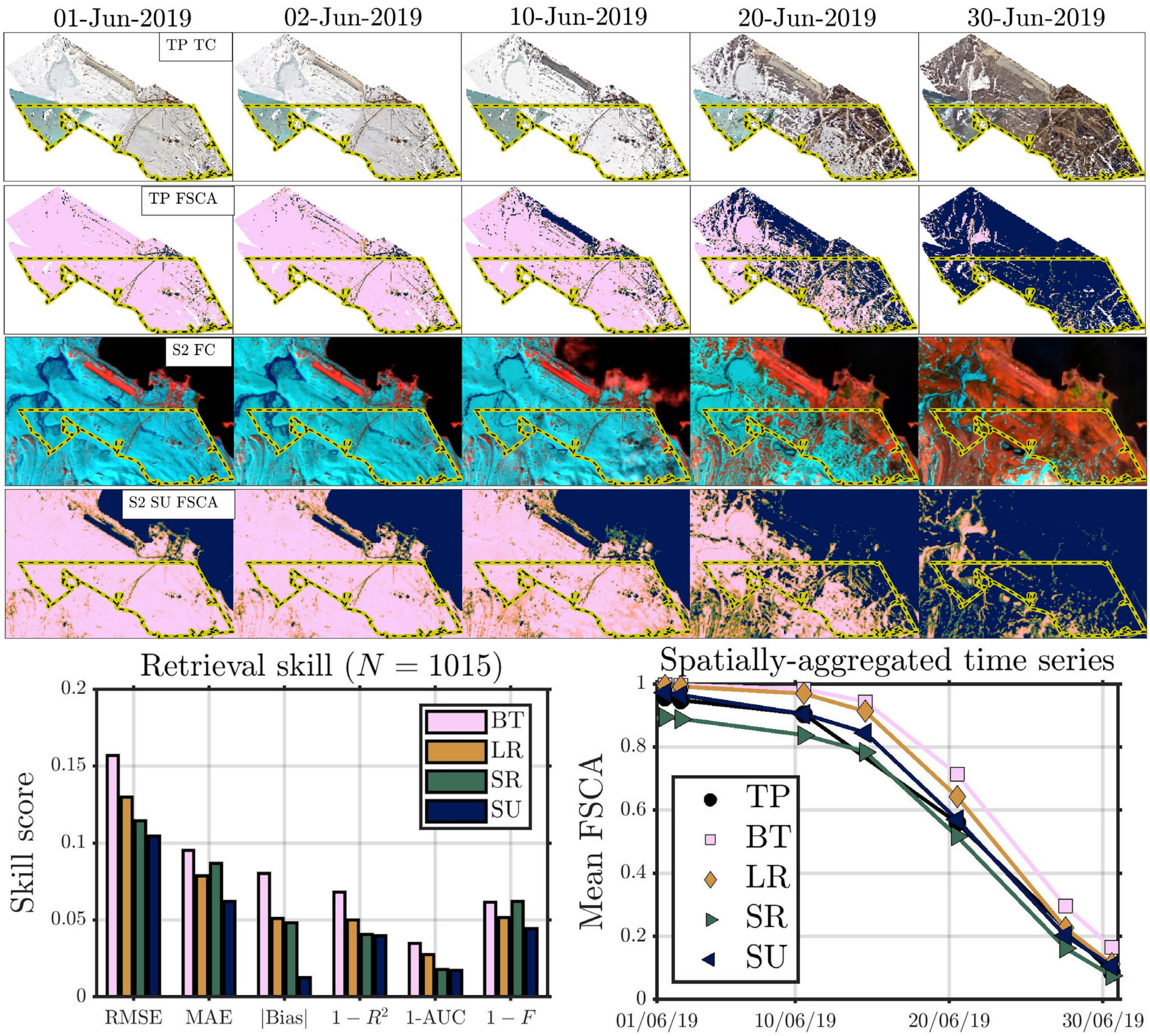

Figure 4: True colour orthophotos from Zeppelin (first row), Fractional Snow-Covered Area (FSCA) retrievals from these orthophotos (second row), false colour imagery from Sentinel-2 (third row), and FSCA retrieved from this imagery using Spectral Unmixing (fourth row). The yellow polygon is the Area of Interest. The bar chart (bottom left) shows the skill scores of the Sentinel-2 FSCA retrievals using 1015 coincident satellite-camera samples. The time series (bottom right) shows the evolution of the spatial mean FSCA during June 2019 from the retrievals: Terrestrial Photography (TP); Binary Thresholding (BT); Linear Regression (LR); Sigmoid Regression (SR); Spectral Unmixing (SU).

available. We estimated FSCA at 10 m resolution from the Sentinel-2 imagery using: (i) binary thresholding (BT) on the NDSI as used in the old LIS approach (Gascoin et al. 2019) and in several studies in Svalbard (Vickers et al. 2021); (ii) linear regression (LR) on the NDSI originally proposed for MODIS; (iii) sigmoid regression (SR) now used in LIS (Gascoin et al. 2020), and (iv) spectral unmixing (SU; Aalstad et al. 2020). To target scales that are relevant for most snow modelling in the validation, we aggregated the retrievals from 10 to 100 m resolution.

Based on this validation exercise (see Figure 4) we found that the SR-based retrieval approach used in the new LIS algorithm performed very well, outperforming both LR and BT for most of the skill scores considered (see Aalstad et al. 2020 for definitions). It was only outperformed by SU, which is considerably more computationally intensive and requires knowledge of local non-snow end-members (i.e., land cover). Through further tuning of SR, we were able to match the performance of SU, showing that this is a promising and computationally feasible approach for Svalbard-wide FSCA mapping with higher resolution optical satellites such as Sentinel-2 or Landsat. Our preliminary validation could be extended to other sites, sensors, and emerging algorithms such as generalised approaches to SU.

3. Unanswered questions

This terrestrial photography survey in the Svalbard archipelago is a key action for the identification of relevant data sources for different disciplines. The optimisation of active and future observing systems will be designed considering the PASSES legacy where different setups were included ranging from heterogeneous camera devices (different sensor resolutions, fore optics, sensor types), to installation features (site elevation, perspective coverage, acquisition seasoning), image data processing (ortho-rectification and classification), and uncertainty quantification. There is a need for a shared strategy for the different components of these data processing chains, and the final solution will be a compromise between maintenance issues, logistic requirements, resource allocation and data/privacy constraints. This update also highlighted the need for integrating terrestrial photography as a cal/val tool for satellite remote sensing, which is arguably the application of terrestrial photography with the largest potential scientific impact.

4. Recommendations for the future

Several problems and knowledge gaps hinder the full use of the opportunities presented by terrestrial photography. To enhance its usefulness for snow cover and related topics, we propose the following actions that can be taken by the SIOS community to support research in this field:

1. Promote actions and projects that use time-lapse cameras, especially in the more remote areas of Svalbard. Cameras that cover the field of view of higher-elevation terrain should be particularly welcomed.
2. Stimulate the creation of a Svalbard camera system network. There is a need to create a common and easy-to-apply algorithm for processing large quantities of images from different devices for snow cover applications.
3. Promote the integration between terrestrial photography and satellite remote sensing since this approach is a promising strategy for extending in situ observations to improve regional monitoring.

4. Stimulate the use of time-lapse cameras by different disciplines where high time-resolved information can be retrieved for different purposes (glaciology, hydrology, plant and animal ecology, coastal processes, sea ice tracking, satellite cal/val).

5. Data availability

Dataset	Parameter	Period	Location	Metadata access (URL)	Dataset provider
Time-lapse cameras in Svalbard ver 2	Camera locations and ancillary information	2000-2021	Svalbard archipelago	http://iadc.cnr.it/cnr/metadata_view.php?id=113	CNR
FSCA at Ny-Ålesund	FSCA	2020	Bayelva	http://iadc.cnr.it/cnr/metadata_view.php?id=128	CNR
Satellite NDSI at Ny-Ålesund	NDSI	2014-2020	Bayelva	http://iadc.cnr.it/cnr/metadata_view.php?id=129	CNR + UiO
Satellite NDSI at Hornsund	NDSI	2014-2020	Fuglebekken	http://iadc.cnr.it/cnr/metadata_view.php?id=130	CNR + UiO

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The extreme Arctic ozone depletion in 2020 as was observed from Svalbard (EXAODEP-2020)

4

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1. Introduction

Observations of ozone column density and solar ultraviolet (UV) irradiance (~295 – 400 nm) reaching the ground at Svalbard were presented in the 2018 SESS report (Petkov et al. 2019). Instruments operating at four stations (Table 1) provide data about ozone amount, erythemally weighted UV (UVE) irradiance and intensity of the UV-B (~295 – 315 nm) and UV-A (315 – 400 nm) spectral bands. The devices were compared in the frame of the intercomparison campaign performed in late April 2018 with the aim to unite them in a local network (Petkov et al. 2019).

As was shown in the 2018 SESS report (Petkov et al. 2019), ozone density oscillates during the year, reaching its annual maximum in spring: this is the typical behaviour over the Northern Hemisphere (Brasseur and Solomon 2005). In Antarctica, however, spring is the period when strong stratospheric ozone depletions usually occur (Farman et al. 1985; Solomon et al. 1986, Solomon et al. 2007). This difference is attributed to the polar vortices, which are much less marked in the Arctic. Nevertheless, some unusual ozone reduction events took place in the region around the North Pole during the past three decades. The most pronounced were the ozone depletion episodes observed in 1996, 1997, 2011 and 2020. The magnitude of the 2020 depletion was comparable with the Antarctic ozone hole (Lawrence et al. 2020; Manney et al. 2011 and 2020; Svendby et al. 2021; Weber et al. 2021). It was found that such events are able to impact the ozone column at lower latitudes in both late spring (Petkov et al. 2014 and 2021) and summer (Karpechko et al. 2013), underlining the significance of the polar regions for the environment in the densely populated mid-latitude areas. In this regard, the present chapter update aims to describe the most recent significant ozone reduction registered by the instruments operating in Svalbard.

Table 1: Instruments operating in Svalbard that perform observations of the ozone column and solar UV radiation.

Station (coordinates)	Instruments	Measured parameters	Measurement frequency
Ny-Ålesund (78°56'N, 11°55'E)	Brewer MKIV #050	Ozone column, UVE	~ 20 min
	GUV radiometer	Ozone column, UVE, UV-A, UV-B	1 min
	UV-RAD radiometer	Ozone column, UVE, UV-A, UV-B	5 min
Barentsburg (78°24'N, 14°9'E)	Ozonometer M 124	Ozone column	~ 1 h
Longyearbyen (78°13'N, 15°39'E)	Kipp & Zonen UVS-E-T	UV-E	1 min
Hornsund (77°00'N, 15°33'E)	Kipp & Zonen UVS-AE-T	UV-E	1 min

2. A strong Arctic ozone depletion event occurred in 2020

While satellite-borne instruments can provide a general and large-scale look at the event (see next subsection), the instruments in Svalbard are able to present precisely the development of the event. Moreover, these ground-based measurements allow a quantitative assessment of the effect that ozone variations produce on the solar UV irradiance reaching Earth's surface (discussed in subsection 2.2).

2.1. A general picture of the 2020 Arctic ozone depletion

The appearance of the ozone-reduced areas in the polar regions in spring is considered a result of combined action of dynamical and chemical processes (Brasseur and Solomon 2005; Feng et al. 2021). The polar vortex that forms in early winter and may persist through spring is the main dynamical factor for the ozone depletion episodes in the Antarctic and the Arctic. Isolating huge areas over the poles from the mid-latitude air masses, the vortex contributes to a sharp cooling of the stratosphere. This cooling creates conditions for the formation of the polar stratospheric clouds, which in turn favour heterogeneous reactions leading to the appearance of the active halogen species (chlorine and bromine) that destroy the ozone (Molina and Rowland 1974; Solomon et al. 1986). In Antarctica, the vortex is usually very stable and has given rise to significant ozone depletion almost every year in the past decades. In contrast, the Arctic vortex is frequently disturbed by dynamic processes that make it quite unstable. This impedes the appearance of appreciable stratospheric cooling and, hence, of severe ozone depletion like in the Antarctic. The effects of vortex formation/non-formation are illustrated in figure 1, which presents the potential vorticity (PV) in the Arctic, extracted from the ECMWF database (ECMWF 2021) for three winter–spring months of 2019 and 2020. It is considered that PV is able to

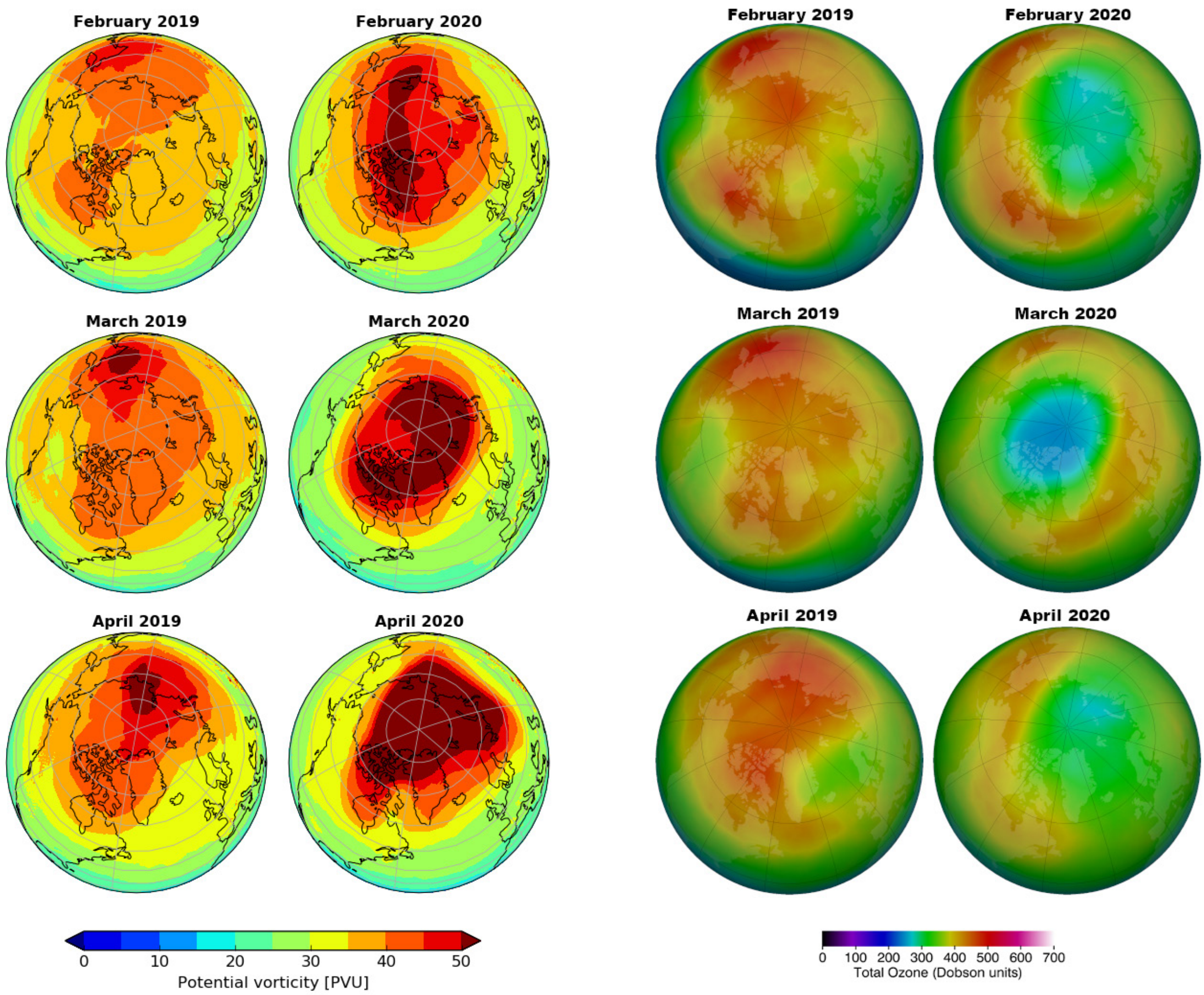

Figure 1: The left two columns represent the monthly mean potential vorticity over the Northern Hemisphere as extracted from ECMWF (2021) database for February-April 2019 and 2020 in the Arctic, while the right two columns give the corresponding ozone amount distributions (NASA 2021).

outline the polar vortex (Hoskins et al. 1985). Actually, figure 1 (left columns) shows the monthly mean PV assuming that such an averaging filters the short-term oscillations and better represents the status of the polar vortex within a month. The two columns on the right side of figure 1 show the distribution of the monthly mean of the ozone column during the corresponding months.

The difference between the PV patterns in 2019 and 2020 is obvious. While the PV contours outline a large area with rather high PV values for each of the months in 2020, no similar picture can be identified in 2019. As mentioned, this is due to the frequent perturbations of the Arctic vortex; the monthly mean PV in 2019 depicts a quite weak vortex. It should be noted that the development of the 2019 vortex represents typical Arctic behaviour, whereas in 2020 the vortex was exceptionally strong (and long-lasting). Figure 1 demonstrates also the response of the ozone column to the vortex features. In 2019 the ozone content was close to the normal values whereas in 2020, areas characterised by significantly reduced total ozone can be recognised in each of the monthly patterns. Svalbard was inside or in the periphery of these areas, and the next subsection presents a picture of the ozone depletion using results from the instruments operating in Svalbard.

2.2. The development of the 2020 ozone depletion over Svalbard and its consequences

The behaviour of the ozone column over Svalbard in the spring of 2020 is presented in figure 2. All the instruments registered a deep minimum that lasted about a month, from late March to late April. This minimum was found to be nearly 150 DU below the climatological value; this represents an almost 40% decrease. At the same time, this minimum is about 70 DU lower than the 2.5-percentile of the climatological mean value. In the second half of April, the ozone column sharply returned to average values with episodical drops under the 2.5-percentile level.

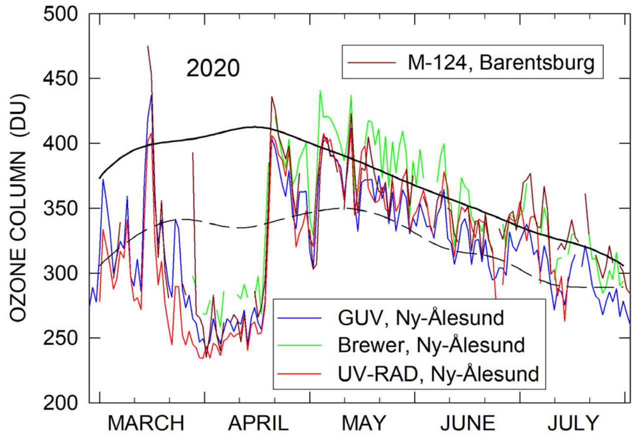

Figure 2: Time patterns of the daily ozone column, observed over Svalbard by the instruments located in Ny-Ålesund and Barentsburg during the first half of 2020. The solid black curve shows the mean annual ozone course during the period and the dashed curve represents the 2.5-percentile. Both parameters were estimated from historical measurements performed at Ny-Ålesund during the past 20 years (Petkov et al. 2019; Svendby et al. 2021).

Such a profound ozone column decrease was expected to cause a considerable increase in the solar UV-B irradiance reaching the ground, as UV-B penetrance is quite sensitive to ozone changes. This is confirmed by the upper panel of figure 3, where the daily integrated values (daily doses) of radiation in the UV-B range are presented for 2018 – 2020. It is seen that the annual course of UV-B doses is quite similar for the years 2018 and 2019, which were characterised by normal ozone amounts, while the development seen in 2020 shows a doubling of the values in March – April, when the ozone column reached the extreme minimum shown in figure 1. At the same time, the evolution of UV-A irradiance (lower panel of Fig. 3), which only weakly depends on the ozone column, shows almost the same behaviour in 2020 as in the previous two years. These findings confirm the strong relationship between the ozone column and surface UV-B irradiance.

Figure 4 exhibits the daily doses of the erythemal UV irradiance (UVE) calculated through the weighting of the solar radiation by the erythemal action spectrum (Mckinlay and Diffey 1987). It shows that UVE irradiance was also subject to significant enhancement, similarly to the UV-B band. These results are consistent with those obtained by Bernhard et al. (2020), who observed a 75% increase in ultraviolet index in Canada in March 2020.

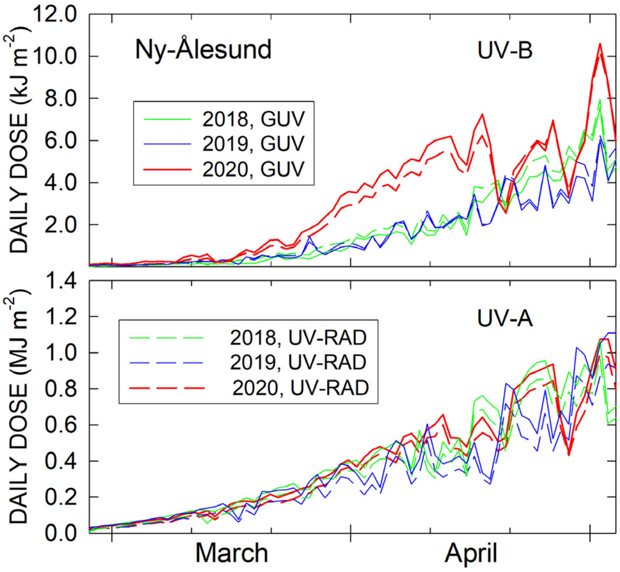

Figure 3: Daily UV-B and UV-A doses registered by GUV (solid curves) and UV-RAD (dashed curves) at Ny-Ålesund during the early spring periods of 2018 – 2020. The discrepancy between GUV and UV-RAD data that is particularly marked in the period of the ozone reduction, can be attributed to the different approaches applied to extract the doses from the output voltages of both instruments, which approaches depend on the ozone behaviour and other geometrical factors (see WMO (2010) and Petkov et al. (2006) for GUV and UV-RAD, respectively).

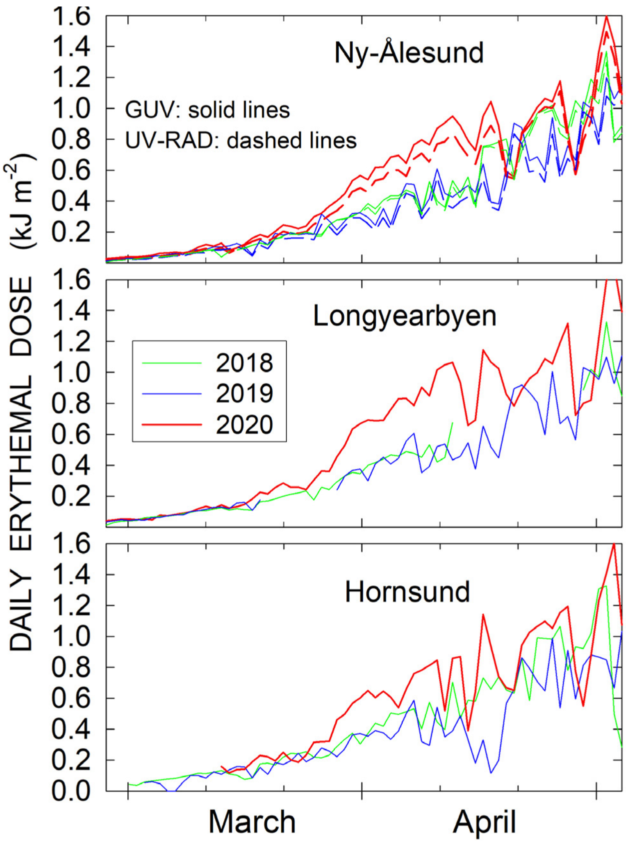

Figure 4: Evolution of the daily UVE doses observed at three of the Svalbard stations in March – April of 2018, 2019 and 2020. As in the case of the patterns in figure 3, the discrepancy between GUV and UV-RAD is attributed to the different techniques applied to extract the erythemal irradiance from the corresponding output voltages.

Studies performed to analyse the dependence of UV radiation on the ozone column led to the introduction of the so-called radiation amplification factor (RAF, Madronich et al. 1998) determined by the equation:

$$\frac{I}{I_0} = \left(\frac{Q}{Q_0}\right)^{-\mathrm{RAF}}, \qquad (1)$$

where UV irradiances I and I_0 correspond to the ozone columns Q and Q_0, respectively. The RAF is usually determined empirically under cloud-free sky and at a certain solar elevation, to underline the effect of the ozone on UV radiation and reduce the impact of clouds and aerosols. However, we could formally assess RAF through Eq. (1) by taking into account the daily mean ozone column given in figure 2 and daily UV-B and UVE irradiance doses presented in figures 3 and 4, respectively. In this case the effect of clouds, aerosols and solar elevation turns out to be smoothed but it persists in the RAF assessments. The estimate shows that the RAF varied between 2 and 3 for UV-B and from 1.1 to 1.4 for UVE doses. These values are consistent with assessments reported in other studies (Antón et al. 2011; Bais and Zerefos 1993; Blumthaler et al. 1995; Lakkala et al. 2018; Petkov et al. 2012; Seckmeyer et al. 2005). Hence, the 2020 ozone depletion in the Arctic led to an increase in the UV-B and UVE irradiance levels. This increase in both UV-B and UVE agrees with the established relationship between ozone and UV radiation. The consistency between the RAFs calculated here using data obtained under a range of conditions involving factors that impact UV-B and UVE (e.g., clouds, aerosols, low solar elevation), and RAFs calculated conventionally (i.e. using data obtained in the absence of such factors) suggests that the effect of ozone depletion was dominant in spring 2020. In other words, even though cloud cover can significantly reduce the UV radiation reaching the ground during the day, the depleted ozone column over Svalbard turned out to be a decisive factor for the UV-B irradiance level over relatively long periods.

The appreciable increase in the short-wave part of the solar UV irradiance observed in Svalbard in the period of the strong ozone reduction was an unusual deviation from the common spring environmental conditions in the Arctic. Such an occurrence can be assumed to be able to cause stress on the plants and animals (e.g. Kvíderová et al. 2019) living in Svalbard. The expected effects of UV radiation on the polar ecosystems will be a subject of future studies.

3. Unanswered questions

The recurrence of the atypically strong winter polar vortices in the Arctic can be considered a consequence of the effects of climate change on Arctic stratosphere dynamics. These occurrences caused at least three appreciable ozone depletion episodes in the past 30 years that led to corresponding increase in solar UV irradiance on the ground. Such an increase is likely to impact the Svalbard ecosystems on both short and long time scales, but these effects have not been studied yet. Another important issue that needs to be addressed concerns the interconnection between climate change and ozone evolution in both Arctic and densely populated mid-latitude areas.

4. Recommendations for the future

- In view of the unanswered questions, studies on the surface UV irradiance increase should be performed jointly with experts on experimental physiology and polar ecosystems.
- All instruments operating at Svalbard should be coordinated in a regional network to ensure reliable and coherent data over a large area of Svalbard in a long-term perspective.
- In particular, the coverage of UV spectral observations should be improved.
- The solar UV observation network should be extended across the Fram Strait to Eastern Greenland.
- The effects of climate change on the frequency of profound ozone reductions in the Arctic need to be taken into account in future studies.

5. Data availability

Dataset	Parameter	Period	Location	Metadata access (URL)	Dataset provider[1]
Ozone_EXAODEP-2020	Ozone column (DU)	March – July, 2020	Svalbard (Ny-Ålesund, Barentsburg)	https://metadata.iadc.cnr.it/geonetwork/srv/eng/catalog.search#/metadata/77556de7-c3ec-48f7-883e-6d9e6ad3c03c	Tove M. Svendby (NILU), Boyan H. Petkov (ISP-CNR), Anna Solomatnikova (GGO)
UV_EXAODEP-2020	Daily erythemal, UV-B and UV-A irradiance doses (W m-2)	March – July, 2020	Svalbard (Ny-Ålesund, Longyearbyen, Hornsund)		Bjørn Johnsen (NILU), Boyan H. Petkov (ISP-CNR), Kamil Láska (MU), Piotr S. Sobolewski (PAS)

1 Abbreviations can be found in the list of institutions in the beginning of the report

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Update to Scientific Applications of Unmanned Vehicles in Svalbard (UAV Svalbard Update)

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Keywords: Svalbard, unmanned, drone, UAV, UAS, AUV, ROV, RPAS, review

Update of chapter 3 in SESS report 2020

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1. Introduction

This report is an update to a previous chapter focussing on the scientific application of unmanned vehicles in Svalbard, published in the 3rd SESS report for 2020 (Hann et al. 2021). This chapter serves two main purposes. The first is to give an updated overview of the scientific literature that utilises unmanned vehicles in Svalbard. Even though only one year has passed since our previous report, a substantial number of relevant articles have been published. A total of 15 new articles published between August 2020 and 2021 are added in this update to the original literature database, which contained 49 entries. The high number of recent publications in this field highlights the great importance and large potential of unmanned systems for scientific applications in Svalbard.

The second objective of this chapter is to examine the new drone regulations and their application in Svalbard. The new EU-wide drone regulations have been gradually introduced throughout 2021 and will completely replace the existing Norwegian drone laws from 2022 onwards. This chapter describes the main rules applying to scientific unmanned aerial vehicle (UAV)[1] missions in Svalbard and givs practical information on how to operate drones in Svalbard according to the new rules. The information is intended for Norwegian and non-Norwegian operators.

2. Method

The literature review follows the same method used for the original chapter (Hann et al. 2021). Relevant publications were identified in Google Scholar by using a combination of the following keywords: Svalbard, Spitsbergen, UAV, UAS, RPAS, drone, unmanned, vessel, ASV, ROV, AUV. This literature review identified 15 new articles which were published after the cut-off date for the previous literature review in August 2020. In addition, two older articles were discovered that had been missed in the original literature view. All publications were categorised according same identifiers as in the 3rd SESS report (Hann et al. 2021).

3. Database update

Appendix 1 shows all publications that have been included in the database, along with a few selected characteristics. The updated full database with additional characteristics is available as literature list (SESS UAV Database, 2021) and as searchable database[2]. Of the 15 publications, only three used unmanned marine vehicles. For this reason, the emphasis in the following section will be on aerial systems.

3.1. Publication dates

The original literature review identified 49 publications in the period from 2007-2020. During one year, from August 2020 till August 2021, a total of 13 publications using UAVs in Svalbard have been published. Two additional publications from 2015 and 2017, that were missed in the original report, were also added. Figure 1 shows the number of publications over the total review period. The large number of publications in 2021 has to be seen in the context of the COVID-19

1 *Note: Following the terminology of the original chapter, the terms "UAV" and "drone" are used synonymously. Other common terms are remotely piloted aircraft system (RPAS), unmanned aerial system (UAS), unoccupied aerial vehicle, or uncrewed aerial vehicle.*
2 https://sios-svalbard.org/UAV_Svalbard

pandemic which prevented many field activities in that year (Jawak et al. 2021). Indeed, the work published in 2021 typically uses data that has been collected in the last 2-3 years. A sensible hypothesis could be that many scientists used the pandemic effectively to publish older datasets. The full effects of the pandemic on fieldwork in Svalbard, especially with respect to long-term monitoring, are not fully captured yet.

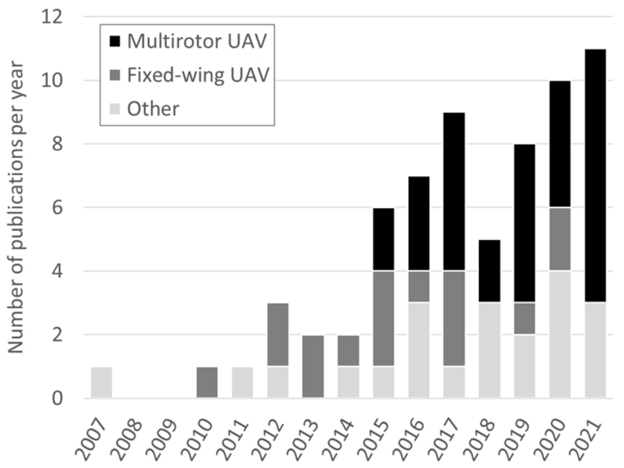

Figure 1: Overview of the number of publications using UAVs in the updated dataset. Other systems referring to unmanned marine systems.

3.2. Type of operation

The data in Figure 1 also show that the use of multirotor UAVs has been high since 2015, while fixed-wing UAVs are used substantially less. Indeed, all publications in 2021 involved use of multirotor UAVs. Of these, all were commercially available drones, most belonging to the Phantom or Mavic series from DJI. This underlines one of the main conclusions of the chapter in the previous SESS report about basic drone operations being an increasingly important research method in Svalbard (Hann et al. 2021). These basic operations use off-the-shelf multirotor systems that can be purchased at a relatively low cost. Drones provide a birds-eye perspective to capture visual images that are mostly processed using photogrammetric methods (structure from motion) to generate digital elevation models (DEMs) and orthomosaic maps. Such products are useful for a wide range of scientific applications, such as geomorphology, ecology, atmospheric sciences, oceanography, glaciology, and more.

Another observation in the updated dataset was that several publications included contained inadequate descriptions of the methods used, and that key information was often omitted. This ranged from missing information about the exact UAV system, to lack of detail about post-processing software. As outlined in the previous SESS report, it is important to include sufficient information about the method in order to ensure scientific quality (transparent and reproducible method). This situation highlights the importance of having an active discussion in the scientific community and developing a standardised way to report drone-based results.

3.3. Map

Figure 2 shows the updated map of the sites in Svalbard where unmanned systems have been used to gather data that were subsequently subjected to peer reviewed publications. Most of the studies published within the last year focus on the existing clusters around Longyearbyen/Adventdalen, Pyramiden/Billefjorden, and Ny-Ålesund/Kongsfjorden. This confirms the trends already seen in the last report. The large number of studies that are co-located and possibly cover overlapping study areas opens up a substantial potential for establishing long-term monitoring. This potential was identified in the previous report, where recommendations were formulated intending to increase collaboration within the community. The recent publications reaffirm this opportunity and emphasise the need for more discussions and cooperation.

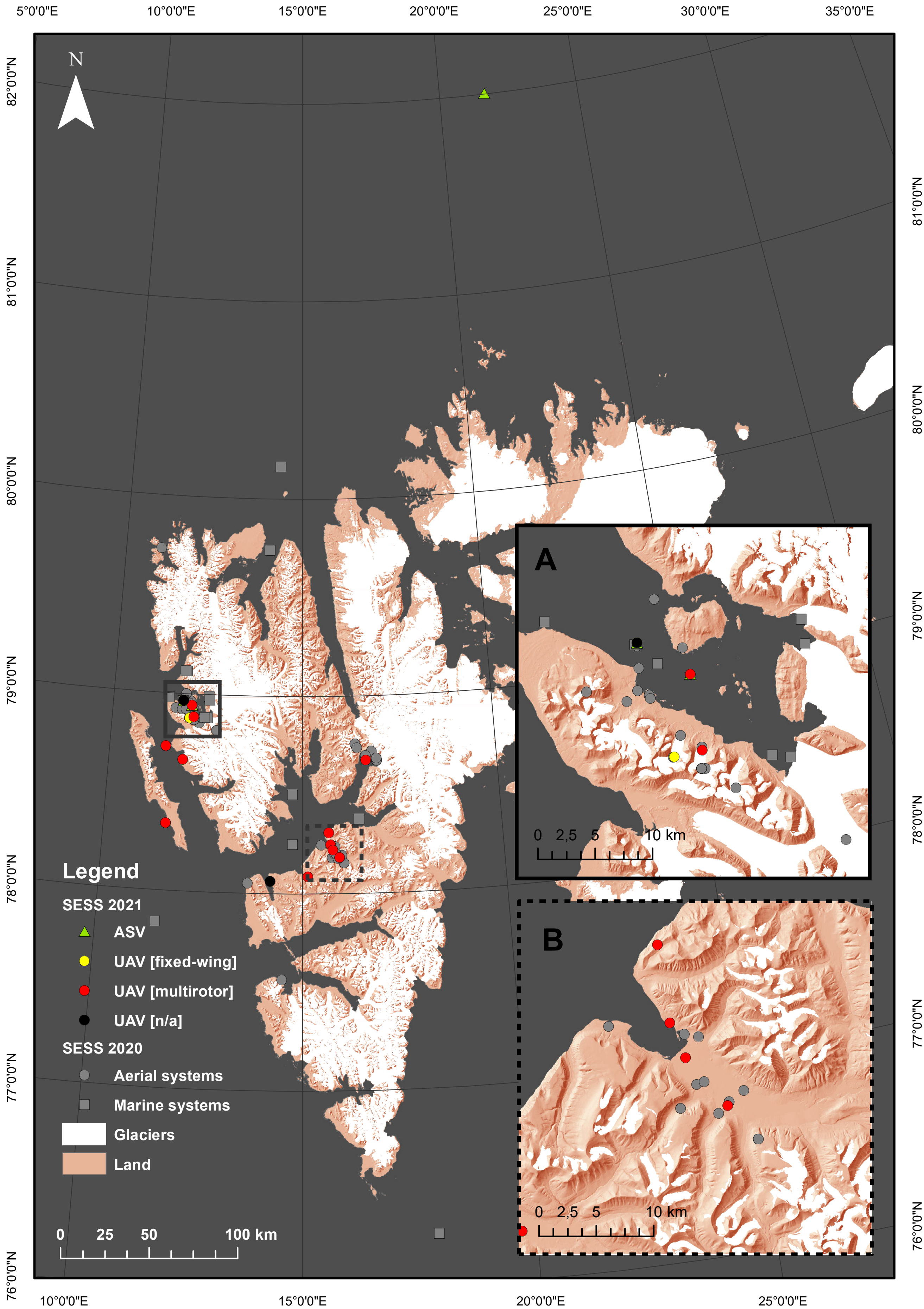

Figure 2: Location of study sites: A: Kongsfjorden region; B: Adventdalen region; ASV - Autonomous Surface Vehicle, UAV - Unmanned Aerial Vehicle.

4. New EU regulations

Until 2020, drone operations in Svalbard were regulated by the Norwegian Civil Aviation Authority (CAA, Norwegian: Luftfartstilsynet). Starting in 2021, new regulations from the European Union Aviation Safety Agency (EASA) were implemented EU-wide. These also apply in Norway and Svalbard. The old Norwegian rules are gradually being replaced with the new EU regulations during a transition period from 1 January 2021 to 31 December 2021. From 2022 onwards, the new EU drone regulations apply in full force in Svalbard.

There are several significant differences between the old rules and the new EU regulations that affect drone operations in Svalbard. The following section is intended to give an outline of how the new regulations affect basic drone operations in Svalbard. Note that it is each drone operator's responsibility to follow the correct regulations and this text is intended as guidance only. For further reading, we recommend the following online resources: www.luftfartstilsynet.no/en/drones, www.flydrone.no, and www.easa.europa.eu/domains/civil-drones-rpas.

4.1. EU regulation framework

The new rules are specified in EU Regulation 2019/947 and EU Regulation 2019/945. Drone operations are classified into 'open', 'specific', and 'certified' categories, see Appendix 2. Differences are mainly related to drone type, maximum altitude, and proximity to uninvolved persons. For scientific operations in Svalbard, the most important categories are 'open' and 'specific'. The old operations types (RO1, RO2, and RO3) are transitioning into these categories. A new rule is that drones will be required to have a CE marking ('Conformité Européenne'). Drones will be assigned a CE-marking with a number between 0 and 6 (C1, C2, ..., C6), depending on their weight and technical equipment. For certain missions or operation categories, drones may require a specific CE-marking. The exact regulations around the CE-markings are still under development but are expected to be implemented by 1 January 2023.

4.2. Rules for basic drone operations

Basic drone operations are mostly covered within the open category; there are several subcategories in open, which are shown in Appendix 3. In simple terms, the categories can be translated into:

- A1: Small drones under 250 g
- A2: Fly drones close to people
- A3: Fly drones far from people

The majority of drone operations in Svalbard are basic flights with commercial off-the-shelf rotary drones and within visual line of sight (VLOS) conditions in remote areas far from people (Hann et al. 2021). Under the new EU regulations, these types of operations will be covered within the A3 category. The following limitations are important for this type of operation:

- Pilots need to be registered and have a valid EASA certificate of competency and have read the user manual.
- The maximum drone weight is 25 kg.
- The operator must have valid liability insurance for the drone in accordance with Regulation (EC) No 758/2004, covering at least 9.2 million NOK.
- The drone must be marked with the operator registration number.
- No uninvolved persons[3] are allowed in the area of flight operations.
- Generally, the 1:1 rule should be followed, i.e. the horisontal distance between the drone and uninvolved persons should be at least the same as its altitude (e.g. if the drone flies at 50 m altitude, it should keep a horisontal distance of 50 m to uninvolved persons).
- A distance of 150 m to residential, commercial, industrial, or recreational areas must be maintained.
- Operations must be conducted only with continuous and unaided visual contact, i.e.

3 *An uninvolved person is a person who is not participating in the drone operation or who is not aware of the instructions and safety precautions given by the drone operator.*

VLOS. The drone and surrounding airspace must be visible at all times and may not be obstructed by fog, clouds, terrain, smoke, buildings, etc. A remote observer situated alongside the pilot may assist in this task.
- The maximum altitude is 120 m from the closest point of the earth.
- No-fly zones must be respected. In Svalbard, the most important no-fly zones are within a 5 km-distance from the airports in Longyearbyen and Svea and within a 20 km distance around the settlement of Ny-Ålesund (radio silence). Operations in these areas are forbidden but may be authorized upon request.
- Drones must not carry dangerous payloads or drop items.
- It is forbidden to disturb wildlife.
- Operations must be discontinued if a risk to other aircraft, people, wildlife, environment or property arises.
- Operations at night are possible if the drone is visible (VLOS). This requires lights on the drone. From 1 July 2022 drones will be required to have a green flashing light when flying at night.
- Drones do not need to be labelled with a CE-marking.
- Drone operations involving several pilots are required to have an operation manual that includes operation procedures and a list of all personnel and their responsibilities. Persons acting as operators and pilots do not require an operation manual.
- Automatic operations, where the drone follows pre-determined flight paths, are allowed. For these missions, the remote pilot needs to be able to take control of the drone at any moment in case of unforeseen events.
- Note that a proposed amendment to the Svalbard Environmental Protection Act may introducee strict drone access rules in protected areas in Svalbard (Miljødirektorat 2021).

For drone operations that require closer distance to uninvolved persons, the subcategory A2 is required. Within this subcategory, drones can approach uninvolved persons to a minimum horizontal distance of 30 m. Drones with a low-speed function (max. speed 3 m/s) can fly as close as 5 m. The A2 subcategory allows a maximum drone weight of 2 kg. Drones need to be marked with a CE-marking, issued by the producer. After 31 December 2022, all drones without CE-marking will be considered as 'legacy'-class. Unmarked legacy-class drones can only be operated in subcategory A3 from 2023 onward.

The largest difference between the old rules and the new EU regulations is the dropped distinction between private and commercial operations and the added requirement of EASA-competency certification. Furthermore, the definition of altitude has changed and now encompasses the distance measured from the closest point of the earth (e.g. this can be a vertical cliff). In addition, there are changes in the minimum distances to uninvolved persons.

4.3. Norwegian drone operators

The following rules apply to all drone operators from Norway. Pilots who have previously been certified under RO1/RO2/RO3 must fulfill the same requirements as new operators. In other words, after 1 January 2022, all previous certification is obsolete and all drone operators must fulfill the following:
- All operators and pilots must register online (www.flydrone.no), even if they have previously been certified RO operators. Annual fee 180 NOK for private persons and 2 000 NOK for companies.
- Online training courses for A1/A3 must be completed. These are free of charge.
- A basic online exam must be taken for A1/A3. A passing grade is valid for five years. Free of charge.
- Operators must have liability insurance and drones must be marked with operator registration numbers.
- A2 operations require first passing a theoretical exam for A2. In Norway, the exam can be taken at and costs 1,400 Driver and Vehicle Licensing Offices for 1 400 NOK (2021). The old 'drone exam' for RO2/RO3 is no longer sufficient. In addition, practical self-training must be completed. The operator needs to declare that they can perform basic flight manoeuvers (take-off, landing, etc.).

4.4. Non-Norwegian drone operators

For operators that are not registered as such in Norway and want to fly drones in Svalbard the following regulations apply. Citizens of EASA member states[4], must be registered as drone operators in their home country with a valid EASA A1/A3 or A2 certificate of competency. The process of obtaining this certificate of competency is typically the same as in Norway (see above). For operators that are registered in an EASA member country, it is not necessary to register in Norway in order to fly in the open category. In short, all pilots that are allowed to fly open category in an EASA member state can fly open category in Svalbard.

Citizens of non-EASA-member states and people who are not registered as drone operators in an EASA member state, must register in Norway (flydrone.no) and follow the same rules as Norwegian drone operators (see above). Online courses, practical self-training, and exams are all available in English.

Note that insurance requirements may vary within EASA member countries. In Norway, all drones (except CE-marked toys) must have third-party liability insurance according to Regulation (EC) No 758/2004. Other countries may not require insurance for lighter drones.

4.5. Rules for advanced drone operations

Advanced drone operations in Svalbard, typically involving flight above 120 m altitude and beyond visual line of sight (BVLOS), are covered under the 'specific' category. Operations in this category entail higher risk and operators require approval from the Norwegian CAA. Approval can be granted via four different processes:

- Standard Scenario (STS): EASA has defined (currently only two) standard scenarios of operations. Operators who use STS can declare this to the Norwegian CAA for approval. STS-01 covers VLOS flights below 120 m in populated areas. STS-02 covers BVLOS flights over sparsely populated areas with special class C6 UAVs (e.g. C6 class UAVs may require an emergency landing system such as a parachute).
- Specific Operation Risk Assessment (SORA): Operators have to conduct a risk assessment that identifies all possible operational risks and proposes measures for risk mitigation and submit this to the Norwegian CAA for approval.
- Predefined Risk Assessment (PDRA): This is a simplified risk assessment for the typical operations that have been identified by EASA. Instead of conducting a full risk assessment, the operator fills out a form and submits it to the Norwegian CAA for approval.
- Light Unmanned Aerial System Operator (LUC): Operators can become certified as LUC by the Norwegian CAA which grants them the privilege of self-assessing the risks of the operation and authorising it themselves.

5. Recommendations for the future

Our previous SESS chapter developed four recommendations, which are still valid. In addition, four more recommendations were developed in the scope of this update.

The results from the literature review clearly show that basic drone operations are a very valuable tool for many scientific applications in Svalbard. The new EU drone regulations are expected to have a

4 *EASA member countries: AUT, BEL BGR CHE CYP CZE DEU DNK ESP EST FIN FRA GRC HRV HUN IRL ISL ITA LIE LTU LUX LVA MLT NLD NOR POL PRT ROU SVK SVN SWE*

double-edged impact on drone operators. On the one hand, it makes it easier for non-Norwegian pilots and scientists to operate in Svalbard. Flying in the open category A3 is easy and lowers the barrier for scientists to implement UAVs into their research. On the other hand, the new regulations introduce higher barriers to more advanced operations, such as extended VLOS or flight at altitudes higher than 120 m.

Recommendation 1: Develop national standard operational scenarios (NSTS) for Svalbard.

Most areas in Svalbard are remote and uninhabited. This means that drone missions have lower risks compared to operations on the mainland. This offers the potential for extending the operational envelope, especially for basic type operations. Similar NSTS have already been developed in other countries, for example in Poland, and SIOS should discuss this with the Norwegian CAA. In Svalbard two main scenarios are desirable for scientific applications:

- Extended VLOS operations (with observer) with drones below 2.5 kg and altitude below 120 m. Such operations are relevant for mapping activities.
- VLOS operations near take-off point with drones below 2.5 kg and altitudes below 400 m. Such operations are relevant for meteorological or geomorphological measurements.

Recommendation 2: Disseminate information about the new EU drone regulations.

The information about the new EU drone regulations in this chapter should be distributed to potential scientific drone users in Svalbard beyond the scope of this report, for example online as dedicated blog posts, posters, brochures, and similar.

Recommendation 3: Establish an interdisciplinary communication platform.

Expanding on our findings and recommendations presented in the 2020 SESS report, our literature review reveals that a wide range of science fields use unmanned systems. This diversity means that there is a need for an interdisciplinary platform where researchers with different backgrounds can come together to discuss, share experiences, develop best practices, etc. This would benefit experience transfer, development of standards, and help to build a knowledge base. Such a platform could also be combined with education and training activities. Especially for basic applications of UAVs, there is a large number of very diverse users who could learn from each other and develop common standards for data reporting or establishing long-term monitoring datasets. We suggest that the Svalbard Science Forum or the SIOS Polar Night Week could be used for this purpose.

6. Acknowledgements

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Drone fieldwork at Tunabreen (Photo: Cristophe Castagne).

Appendix 1

An overview of all the new literature that has been added to the database in the scope of this update

Title	Discipline	Fieldwork location(s)	Unmanned system	Publication type	Reference
High resolution mapping of supra-glacial drainage pathways reveals link between micro-channel drainage density, surface roughness and surface reflectance	Glaciology	Midtre Lovénbreen	UAV/fixed wing	Article	Rippin et al 2015
Spatial variability of CO2 uptake in polygonal tundra: Assessing low-frequency disturbances in eddy covariance flux estimates	Atmosphere	Adventdalen	UAV/rotary wing	Article	Pirk et al 2017
Monitoring of Sea-Ice-Atmosphere Interface in the Proximity of Arctic Tidewater Glaciers: The Contribution of Marine Robotics	Glaciology	Kronebreen, Blomstrandbreen glacier front, Ny-Alesund Harbour, Kongsbreen, Conwaybreen	ASV, UAV/ rotary wing	Article	Bruzzone et al 2020
Using ship-deployed high-endurance unmanned aerial vehicles for the study of ocean surface and atmospheric boundary layer processes	Meteorology, Oceanography	Kongsfjorden	UAV/fixed wing	Article	Zappa et al 2020
Analysis of the paraglacial landscape in the Ny-Ålesund area and Blomstrandøya (Kongsfjorden, Svalbard, Norway)	Geomorphology	Kongsfjorden	not specified	Article	Berthling et al 2020
New Cost-Effective Technologies Applied to the Study of the Glacier Melting Influence on Physical and Biological Processes in Kongsfjorden Area (Svalbard)	Glaciology, Oceanography	Kongsfjorden	ASV	Article	Pasculli et al 2020
Applications of unmanned aerial vehicle (UAV) surveys and Structure from Motion photogrammetry in glacial and periglacial geomorphology	Geomorphology	n/a	n/a	Review article	Śledź et al 2021
Drones and marine mammals in Svalbard, Norway	Biology	Midtøya, Sarstangen, Nordenskiöldbreen, Deltaneset, Tempelfjorden, Grønfjorden	UAV/rotary wing	Article	Palomino-González et al 2021
Moving out of town? The status of alien plants in high-Arctic Svalbard, and a method for monitoring of alien flora in high-risk, polar environments	Biology	Barentsburg	not specified	Article	Bartlett et al 2021

Coastal Erosion of Arctic Cultural Heritage in Danger: A Case Study from Svalbard, Norway	Cultural Preservation	Hiorthhamn	UAV/rotary wing	Article	Nicu et al 2021
Seeing beyond the outcrop: Integration of ground-penetrating radar with digital outcrop models of a paleokarst system	Geomorphology	Rudmosepynten	UAV/rotary wing	Article	Janocha et al 2021
Where will widening occur in an outwash braidplain? A new approach to detecting controls on fluvial lateral erosion in a glacierized catchment (north-western Spitsbergen, Svalbard)	Geomorphology	Kaffiøyra	UAV/rotary wing	Article	Weckwerth et al 2021
3D modelling and interpretation of depositional elements in the Aspelintoppen Formation, Spitsbergen, Svalbard, a facies analysis	Geology	Colesdalen	UAV/rotary wing	Thesis	Bøgh 2021
Back analysis of a coastal cliff failure along the Forkastningsfjellet coastline, Svalbard: Implications for controlling and triggering factors	Geomorphology	Forkastningsfjellet	UAV/rotary wing	Article	Kuhn et al 2021
Multiscale mapping of plant functional groups and plant traits in the High Arctic using field spectroscopy, UAV imagery and Sentinel-2A data	Biology	Adventdalen	UAV/rotary wing	Article	Thomson et al 2021
Snowcover Survey over an Arctic Glacier Forefield: Contribution of Photogrammetry to Identify "Icing" Variability and Processes	Glaciology	Austre Lovénbreen	UAV/rotary wing	Article	Bernard et al 2021
Adaptive Sampling of Surface Fronts in the Arctic Using an Autonomous Underwater Vehicle	Oceanography	North of Svalbard	ASV	Article	Fossum et al 2021

Appendix 2

An overview of the open, specific, and certified categories in the new EU drone regulations

OPEN	SPECIFIC	CERTIFIED
Pilots must register on flydrone.no and pass an online exam.	Operators need approval based on specific risk assessments, standard scenarios or pre-defined risk assessments.	Same risks as manned aviation. Requires EASA-certification of aircraft, operator, pilot.
Under 25 kg	Above 25 kg	Flight with passengers
VLOS	BVLOS	Flight over inhabited areas
Under 120 m altitude	Over 120 m	Urban operations
Basic drone operations	Advanced drone operations	Highest risk operations

Appendix 3

An overview of the requirements of the open category in the new EU drone regulations

Category	Limitations / Requirements	CE-Marking / Weight	Competence
all	• Max altitude 120 m • VLOS • No dropping of objects • No dangerous payloads		• Register at flydrone.no
A1	• Avoid flying over uninvolved persons • No flying over assemblies of persons	• C0 marked or • Unmarked* • Under 250 g & max speed 19 m/s	• Read user manual • Register only if camera onboard
	• No flying over uninvolved persons • No flying over assemblies of persons	• C1 marked or • Unmarked* • Under 500 g	• Read user manual • A1/A3 course and exam
A2	• Min 30 m from uninvolved persons • Min 5 m from uninvolved persons in low-speed mode	• C2 marked	• Read user manual • A1/A3 course and exam • A2 course and exam • Practical self-training
	• Minimum 50 m from uninvolved persons	• Unmarked* • Under 2 kg	
A3	• Min 150 m from residential, commercial, industrial, or recreational areas • No uninvolved persons in the area of operation	• C3 or C4 marked or • Unmarked drones after 1. Jan 2023 • Under 20 kg	• Read user manual • A1/A3 course and exam

*Unmarked drones only valid until 01 January 2023. Thereafter considered legacy drone in A3.

SIOS Core Data (SCD)

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1. Introduction

Svalbard Integrated Arctic Earth Observing System (SIOS) is a regional observing system for long-term measurements in and around Svalbard addressing Earth System Science (ESS) questions. SIOS integrates the existing distributed observational infrastructure to generate added value for all partner organisations beyond what their individual capacities can provide. SIOS brings together observations in a coherent and integrated observational programme that will be sustained over a long period. Only in this way can the inherent coupling processes in this regional-scale Arctic system and its connections with the Earth System at large be addressed adequately. In brief, SIOS facilitates addressing key scientific questions in ESS with a sustained measurement programme.

The SIOS Data Management Service (SDMS)[1] is one of the key services provided by SIOS. SDMS enables data submission, discovery, access, use and preservation of SIOS-relevant datasets and metadata across contributing data centres (operated by partners) and relies on the principles of distributed data management. The distributed data management approach means that the contributing data centres host all the datasets, and SDMS provides access to them through regularly harvested access metadata. In addition, information is harvested from third party data centres that have information of relevance for the SIOS community. Among the main products and services of SIOS are data useful for addressing identified key research questions in Earth System Science. A subset of the data, the SIOS Core Data (SCD), comprises the data needed to scientifically assess the state of the environment in Svalbard.

The core observational programme carried out by SIOS partners provides the research community with systematic long-term observations and allows for integration of upcoming new methodologies and techniques, as well as research questions. The SIOS observational programme – and hence also the core data – are continuously monitored and if necessary updated based on the recommendations from annual SESS reports, the SIOS infrastructure optimisation report and interaction with the calibration/validation and modelling communities.

2. SIOS data

The scientific themes that guide the observations and the optimisation of the observing system of SIOS are:

- Energy and mass exchange;
- Combined effects of human perturbations;
- Effects of Global Environmental Change on organisms, populations, and ecosystems.

To address these themes, a comprehensive dataset of state variables allowing the diagnostics for Global Environmental Change is mandatory. Data products addressing the identified key research questions in ESS are a core product and making them accessible is a central service of SIOS. The geographical extent of the SIOS region is limited, and thus ESS monitoring and observation activities need to be limited to regionally accessible and relevant variables which can be expected to change over timescales of years to decades. There is another aspect of data from the SIOS perspective: SIOS members must follow the SIOS data policy[2], which adheres closely to the FAIR guiding principles. A central element of this data policy is that all data are open and accessible for everyone. SIOS data also include higher-order products (level 3+, as described by NASA[3]).

1 https://sios-svalbard.org/Data
2 https://sios-svalbard.org/sites/sios-svalbard.org/files/common/SIOS_Data_Policy.pdf
3 https://earthdata.nasa.gov/collaborate/open-data-services-and-software/data-information-policy/data-levels

SIOS data are defined as all the ESS data available in the SIOS Data Access Portal[4], including, e.g., solitary measurements and third-party data, see Table 1. SIOS data must be accompanied by discovery metadata, making them findable and accessible. Where possible, predefined observation protocols (e.g. from ACTRIS[5], GAW[6], WMO[7] etc.) should be included.

Table 1. Data definition in SIOS

Type of SIOS data	Policy	Category	Comment
Single field experiments	Transparency (data have been collected)		SIOS data if available in the SIOS Data Access Portal
Historic data records, including long-term measurements, but discontinued	Transparency (data exist). Submitted at owner's discretion		SIOS data if available in the SIOS Data Access Portal
SIOS Access call, SESS report, and other higher-level data	Available after the project		SIOS data if available in the SIOS Data Access Portal
Long-term observations	Transparency (data exist). Submitted at owner's discretion		SIOS data if available in the SIOS Data Access Portal
SIOS Core Data (SCD)	Transparency (data exist and available online)	Core	Fulfils SIOS criteria of scientific requirements, data availability and >5 years collecting commitment (see section 2.1.1-3 in this chapter). Available in the SIOS Data Access Portal
SIOS Core Data – Candidate (SCD-C)	Will become available online within one year	Core data candidate	Fulfils the same criteria as core data but data is not yet available online

2.1. SIOS core data

The SIOS core data[8] comprises the data needed to scientifically assess the state of the environment in Svalbard. The first set of SCD variables is based on the Essential Climate Variables (ECV) as defined by the Global Climate Observing System (GCOS)[9]. The Svalbard-relevant variables were selected according to recommendations from SIOS' Scientific Optimisation Advisory Group (SOAG). In addition, SIOS-KC conducted a series of interviews with scientists in modelling and remote sensing calibration and validation (cal/val) communities to identify the most relevant variables for the first set of SCD.

SIOS core data are a dynamic set of key variables. Researchers can suggest new variables through SESS reports or even by directly addressing SOAG, which would evaluate whether the variables would qualify as SCD candidates. The core data are provided by SIOS members, who commit to provide them on a regular and long-term (more than five years) basis. All SCD follow predefined file formats and are properly associated with appropriate metadata.

The three criteria described in the following subsections must be met for data to qualify as SCD, as defined by a task force organised by SOAG. The criteria are based on standards of scientific excellence in the Earth Science System, in SIOS' 'legal' framework and SIOS data policy. In 2020, the first set of SCD were defined to optimise the resources contributed by the SIOS research community. An updated list of variables for SCD

4 https://sios-svalbard.org/metsis/search
5 The Aerosol, Clouds and Trace Gases Research Infrastructure, https://www.actris.eu/about
6 Global Atmosphere Watch Programme, https://community.wmo.int/activity-areas/gaw
7 World Meteorological Organization, https://public.wmo.int/en
8 https://sios-svalbard.org/sites/sios-svalbard.org/files/common/CoreData_Documentation.pdf
9 https://gcos.wmo.int/en/home

has been prepared in 2021 and is waiting for approval and new mapping by SIOS partners. The SCD definition process promotes compliance with FAIR guiding principles[10] (see figure in summary) for scientific data management and stewardship for key datasets.

SIOS Core Data Candidates (SCD-C) are data that fulfil the criteria outlined above but are not yet available online. Contributing members have committed to making the SCD-C available through the SDMS within a year of their qualification as SCD-C. SIOS provides support for its member institutions in transforming SCD-C to SCD.

2.1.1. Scientific requirements

To qualify as SCD, the variable must be critical to answer the key research questions as defined in the SIOS infrastructure optimisation report, and further updates in SESS reports. The requirement for temporal and spatial coverage varies between variables, and potentially depending on the scientific question. This should be considered in the scientific requirement (optimisation). Connection with GCOS ECVs and other Essential variable schemes, as for example Essential Ocean Variables, and marine Essential Biodiversity Variables, can provide guidelines and criteria for selection and prioritisation.

2.1.2. Data availability

SCD must be available through SDMS and accessible in the SIOS Data Access Portal. SCD candidates should be made available as soon as possible and at latest one year after data collection. Data must be described with sufficient discovery and use metadata, which include the necessary information for finding the datasets of interest and the formatting of the data, respectively. Where possible, existing measurement and calibration protocols (e.g. WMO, GAW, BSRN[11], ACTRIS and ICOS[12]) should be used to collect SCD to secure comparability. Instrument inter-comparisons are highly recommended. SIOS will work on promoting data exchange and observation protocol harmonisation, and sustain and facilitate intercomparison campaigns.

2.1.3. Members' commitment

For SCD, there must be a commitment from the data-providing institute to maintain the measurement infrastructure setup and data production for at least 5 years, as well as making the data available through SDMS. Even though SIOS membership is based on a non-binding agreement, there are strong incentives for members to sustain their credibility in the system. There are cases in which the data delivery fails regardless of the members' commitment to delivery, for example in case of failures of key instruments that are mounted on weather stations or satellites. In these cases, it is expected that the data providers do their best within their means to ensure continuation of the measurements.

An example of a commitment in the SIOS 'legal' framework could be a letter indicating intentions of the member about data offered to SIOS, a period of validity of the offer, and at least a tentative plan for frequency of delivery (following rules fixed in criterion 2).

10 https://doi.org/10.1038/sdata.2016.18
11 Baseline Surface Radiation Network, https://bsrn.awi.de/
12 Integrated Carbon Observation System, https://www.icos-cp.eu/

3. The state of SIOS core data

The state of the SCD is mapped regularly through reviewing the SCD variable coverage and number of datasets available through the Data Access Portal. As part of this, the mapping effort also provides a review into the development of SIOS in general. The most recent full mapping was completed in November 2020 and has since been updated twice, in December 2020 and May 2021, with the mapping results available online[13]. Out of the 26 member institutions, 21 have indicated that they can deliver SCD and SCD-C datasets. Eighteen of these 21 have committed to delivery of SCD (up from 16 member institutions committed to delivery of SCD over last year). Note that not all SIOS members conduct ongoing monitoring in or around Svalbard, which obviously affects the number of institutions that can provide SCD.

SCD have been divided into 4 categories, between which there is no balance in the number of variables: ATMOSPHERE (30 variables), CRYOSPHERE (11 variables), TERRESTRIAL (1 variable), OCEANS (9 variables). The most obvious gap is in the TERRESTIAL category and is due to the collaboration with COAT under the SIOS INFRANOR project[14]. When the COAT database is integrated into the SDMS and SIOS receives information about key monitoring activities, this gap will be filled.

Currently 51 SCD variables[15] have been identified in collaboration by SOAG, the Research Infrastructure Coordination Committee and additional scientific experts. Another 21 variables pending approval by SOAG were identified in the SESS reports and SCD workshops. Of the 51 SCD variables, 29 currently have datasets available through SDMS. The currently available SCD datasets are based on what has been made available and continuous delivery of datasets has been committed to. The list of variables is dynamic, and regularly reviewed and added to as part of SIOS development. It should however be noted that data being available for a SCD variable does not necessarily mean that the variable can be considered thoroughly covered in time and space, but rather that at least one dataset of this type exists; the temporal and spatial resolution varies between datasets. Both the coverage and number of SCD variables having data available are expected to increase over the next year, as there are currently 37 SCD-C datasets. These 37 SCD-candidates include data on 11 SCD variables that are currently not available through SDMS.

4. Core Data development efforts

Several recurring and ongoing efforts in SIOS facilitate and support the development and refinement of SCD availability. The most relevant actions are briefly described in this section.

An SCD seminar was organised in 2020 during the Polar Night Week in Longyearbyen. The workshop aimed to familiarise the community with the idea of SCD and present the results of work from SOAG and the task force on the definition of SCD and measurement protocols. In addition, a list of variables proposed as SCD was presented.

Discussion and work on SCD with groups interested in sharing and harmonising data as SCD continued at subsequent SCD workshops in November 2020 and January 2021. During the first workshop, the SCD identification and mapping process and the results were presented. The discussion and work covered issues related to harmonisation and standardisation of measurement protocols. The subsequent workshops continued on the topics already undertaken and discussed the list of new variables that should be added to the SCD list.

13 https://sios-svalbard.org/CoreData
14 https://sios-svalbard.org/InfraNor
15 https://sios-svalbard.org/sites/sios-svalbard.org/files/common/CoreData_Appendix_v1.pdf

SIOS facilitated two one-off efforts called 'SCD curation calls' in 2020 and 2021. These calls allowed for member institutions to apply for SIOS support for transformation of SCD-C to FAIR data. Eight such projects were carried out by member institutions. The project deliverables are undergoing final review during the writing of this report and based on initial assessment the outcomes of the projects were mostly successful in transforming SCD-C into SCD.

The SDMS Working Group has recently initiated a task force with the aim of supporting harmonisation of SCD. Together with SIOS-KC, the task force will create a plan for harmonisation of the metadata and measurement standards for core data.

5. Recommendations for the future

- Facilitate transformation of SCD-candidates to SCD and verification of previously reported SCD-candidate variables
- Prioritise defining and harmonising measurement protocols and data protocols for SCDs
- Do an annual evaluation of variables on the SCD list to ensure their significance and reusability
- Activate hidden data from multi-year monitoring efforts that are currently not available in any database that meets the FAIR data principles
- Share knowledge, expertise, and experience of the SCD definition process in international projects

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