SESS REPORT 2023

The State of Environmental Science in Svalbard – an annual report

SIOS
SVALBARD INTEGRATED ARCTIC EARTH OBSERVING SYSTEM

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Marjolaine Verret, Dariusz Ignatiuk, Renuka Badhe, Christiane Hübner, Heikki Lihavainen (Editors)

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Contents

Foreword

It is a privilege for me to provide the foreword for the 6th State of the Environment Science in Svalbard (SESS) report. This year it contains six updates to previous years' contributions. The synthesis report from the first four SESS reports' contributions has been published. The first four optimisation projects are based on these recommendations and are ongoing. The upcoming optimisation call will incorporate new recommendations, including those presented in this SESS report.

Year 2023 brought changes among SIOS' human assets. Shridhar Jawak, our remote sensing officer since 2018, embarked on new career challenges. His contributions to SIOS and remote sensing services have been both valuable and a pleasure to witness. May the force be with you! The Board of Directors (BoD) of SIOS also experienced what is probably the most significant change in its history, as Kim Holmén, Vito Vitale, and Piotr Glowacki concluded their terms. They were on the BoD right from the start of the operational phase of SIOS in 2018, and their work has built solid foundations for SIOS. Their legacy will be challenging to surpass. I am confident that the new BoD members will respond to this challenge.

The work we have done together in SIOS has been also noticed. SIOS has solidified its role as a prominent actor in Svalbard and the Arctic landscape of observing systems. But there is still work to be done. Improvements in our research infrastructure and continued harmonization of both the observation strategies used to obtain SIOS core data and the data themselves will be part of the prioritized core activities in coming years. Currently SIOS core data includes 51 variables from different spheres; however, they are very unevenly distributed between the themes. Proposals for new SIOS core data variables are welcomed, with the SESS report being one channel for their introduction.

The SESS chapters this year again reflect the comprehensive approach of SIOS. The updates deal with topics from high in the atmosphere through lower atmosphere to snow and plastic in seawater, sediment, algae, and walruses. To the editorial board, which has worked diligently to ensure the timely publication and high quality of this report: thank you for your efforts. The reviewers are the backbone of scientific work, too often left unnoticed. I thank them for the invaluable time they have dedicated to SESS contributions. Finally, to our team at SIOS Knowledge Centre, it is truly a privilege to be part of such a supportive team. It's great to work with you!

Longyearbyen, December 2023

Heikki Lihavainen

Director, SIOS

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Executive Summary

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The annual State of Environmental Science in Svalbard (SESS) report has established itself as a main driving force in the science-based development of the earth observing system in Svalbard. The SESS reports have collated more than 30 unique chapters with the first 5 reports since 2018. Chapters have ranged across all Earth system environments. An integral mission of the SESS reports is to highlight unanswered questions and provide future recommendations. As such, it reflects the iterative, ongoing nature of science, in a world where technology, particularly artificial intelligence (AI), and scientific infrastructure are fast evolving.

The SESS report is an overview tool that conveys scientific development to the scientific community, as well as stakeholders and the public. As such, the scientific chapters are preceded by the summaries for stakeholders, which provide an overview of each chapter.

The 6th State of Environmental Science in Svalbard Report reflects over past editions and offers six updates of chapters from previous editions. These update chapters are essential in showcasing the state-of-the-art research being conducted in Svalbard, especially at a time when the archipelago and the Arctic in general are being transformed by climate and environmental changes. Chapter 1 deepens our understanding of long-term air temperature forecasts for Svalbard, while chapters 2, 3 and 4 describe snow cover studies ranging from satellites to ground measurements. Lastly, chapters 5 and 6 discuss atmospheric and oceanic pollution respectively.

SATS23 is an update of chapter 1 in the SESS report 2022 "Seasonal asymmetries and long-term trends in atmospheric and ionospheric temperatures in polar regions and their dependence on solar activity" which investigates the intricate interplay between space, atmosphere, sea and land in long-term trends of atmospheric temperatures. Along with datasets of solar activity and ground temperatures, this year's chapter also includes sea temperatures and global atmospheric CO_2 content, enabling us to model ionosphere and mesosphere temperatures. Additionally, the chapter offers a preliminary outlook on how to use machine learning in processing large datasets with complex interactions.

Snow 23 is an update of chapter 11 in the SESS report 2020 "A multi-scale approach on snow cover observations and models". It summarises the state of art in snow science in Svalbard, namely the essential climate variables and SIOS Core Data: snow covered area, snow depth and snow water equivalent. The chapter describes how SIOS aims to create a supersite for snow parameter monitoring in Svalbard and discusses new and upcoming satellite sensors from NASA and Planet which will improve snow measurements in the near future. The chapter also proposes emerging AI-based coupling of models and observations as a tool to reduce model uncertainty.

PASSES 3 complements the previous chapters 10 in the SESS report 2020 "Terrestrial photography applications on snow cover in Svalbard" and 3 in the SESS report 2021 "Improving terrestrial photography applications on snow cover in Svalbard with satellite remote sensing imagery". PASSES has established the Svalbard network of time-lapse cameras to bridge the gap between automated snow stations, ground-based data collection and satellite remote sensing. This year, the chapter presents the design of the data processing chain based on open-source libraries and potential synergies offered by time-lapse cameras during the melt season.

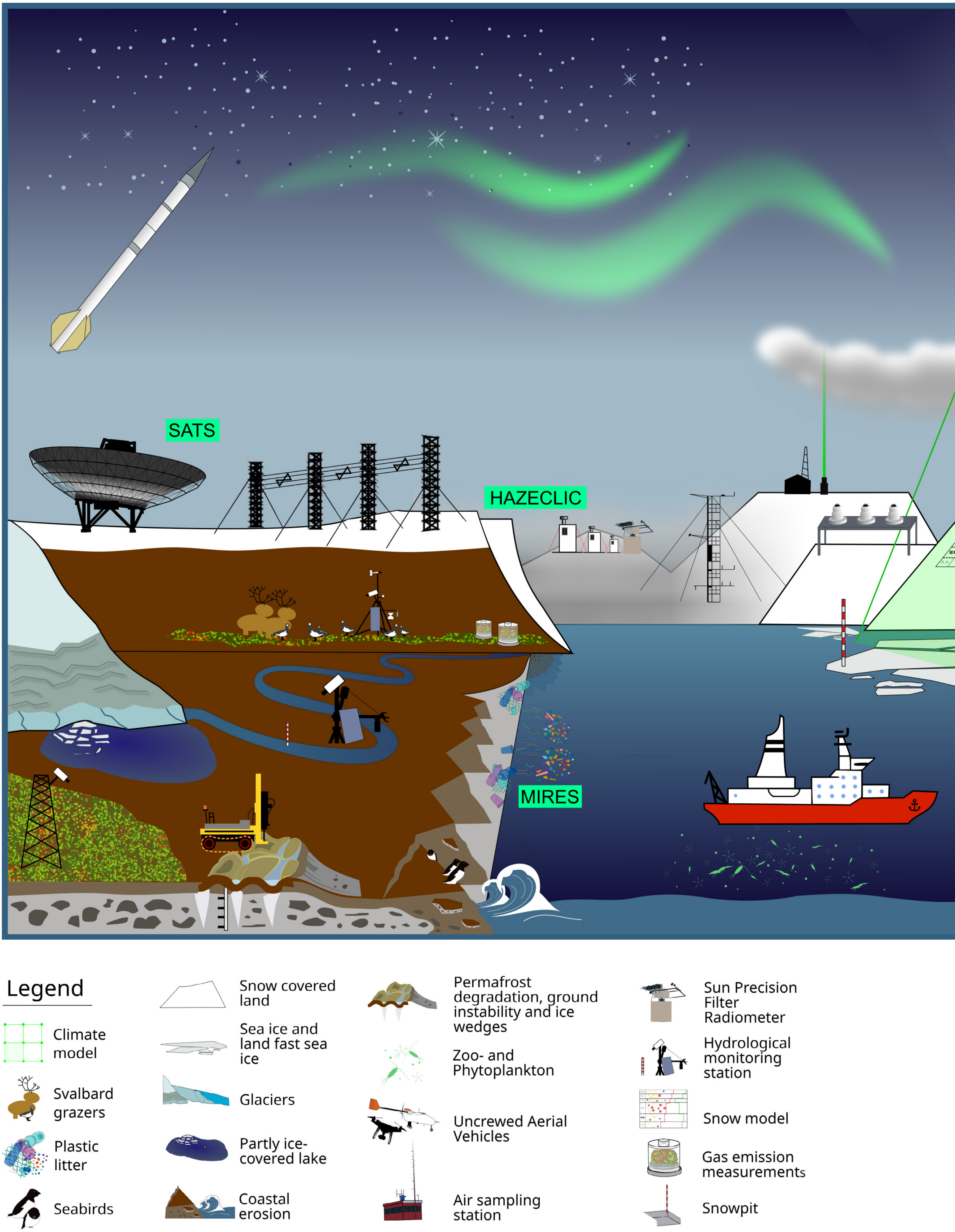
SATMODSNOW 2 is an update of chapter 8 in the SESS report 2020 "Satellite and modelling based snow season time series for Svalbard: Inter-comparisons and assessment of accuracy". The project aims to develop accurate, complete and consistent snow cover datasets in Svalbard using remote sensing observations and snow models. It builds on the previous chapter by utilising additional years of snow cover data from remote sensing and models to examine inter-sensor and inter-model differences.

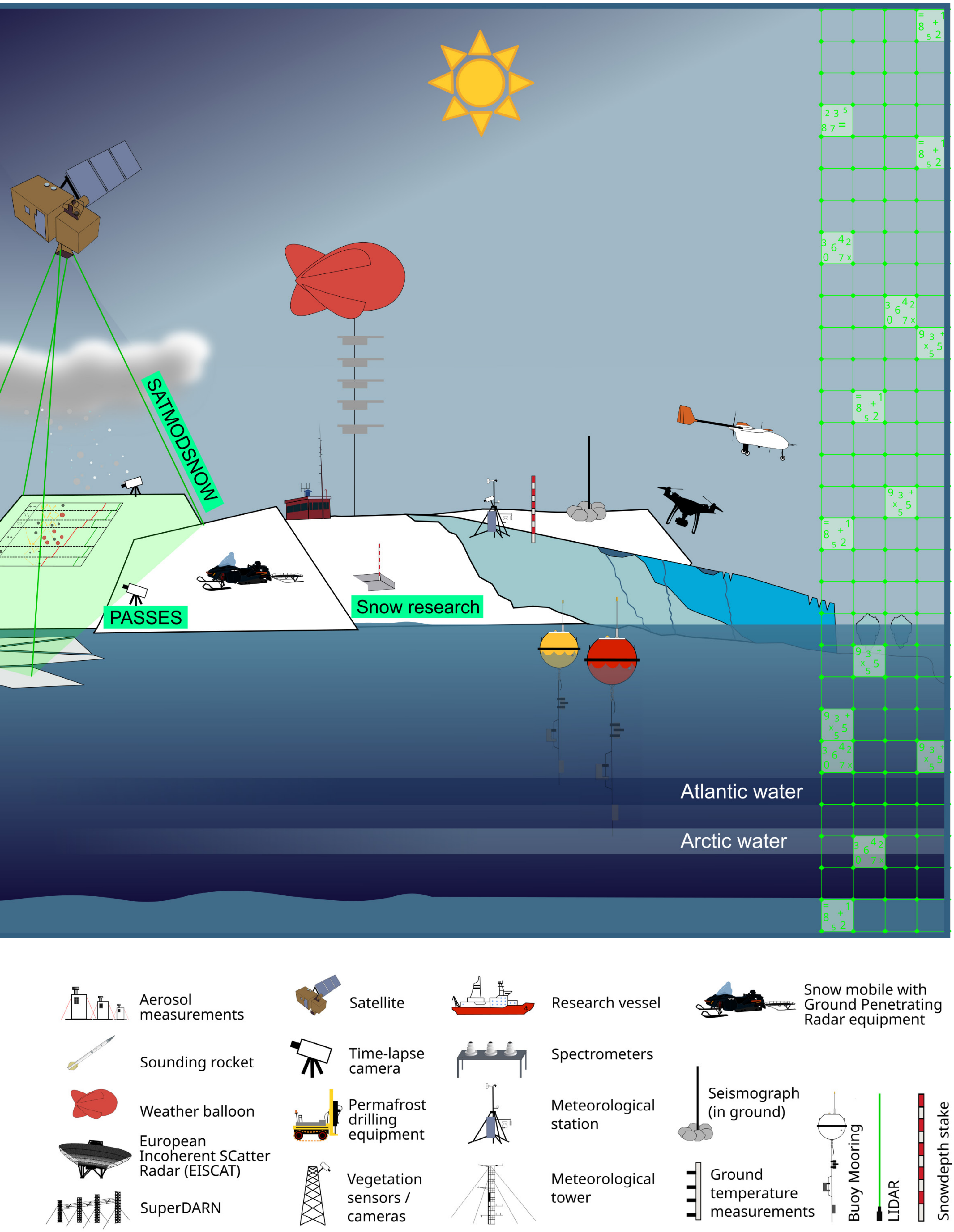
HAZECLIC 2 is an update of chapter 4 in the SESS report 2020 "Arctic haze in a climate changing world: the 2010-2020 trend". The chapter studies the temporal evolution of Arctic haze, in the form of anthropic sulphate, during the last decade in Ny-Ålesund. It presents promising results of decreasing sulphate concentrations in the atmosphere, which are likely due to air pollution mitigation strategies.

MIRES II is an update of chapter 5 in the SESS report 2020 "Microplastics in the realm of Svalbard: current knowledge and future perspective". The chapter aims to understand the sources, impacts, and interactions with the ecosystems. It highlights that microplastics are widespread in the Svalbard ecosystem and stresses the importance of mitigation strategies.

The authors of each chapter have identified knowledge gaps and unanswered questions. While the first four chapters address essential climate variables and SIOS Core Data that are crucial to understand future climate change in Svalbard, the two last chapters provide insights on the impacts of anthropogenic activity on the fragile Svalbard environment. The SESS reports are a bottom-up process where leading experts in Svalbard science are invited to make recommendations about future research infrastructures and societal needs in Svalbard. However, it is clear that research and observations conducted in Svalbard are essential players in pan-Arctic research. Each chapter has a strong focus on interdisciplinarity and also this year, all update chapters focus on topics that are relevant on a global scale.

Photo: Christiane Hübner


SATS
HAZECLIC
MIRES
Legend
Climate model
Svalbard grazers
Plastic litter
Seabirds
Snow covered land
Sea ice and land fast sea ice
Glaciers
Partly ice-covered lake
Coastal erosion
Permafrost degradation, ground instability and ice wedges
Zoo- and Phytoplankton
Uncrewed Aerial Vehicles
Air sampling station
Sun Precision Filter Radiometer
Hydrological monitoring station
Snow model
Gas emission measurements
Snowpit



Earth system science in Svalbard as described in the SESS report series. Acronyms of chapters that are updated in the current report are shown. (Figure: Floor van den Heuvel)

CHAPTER 1

Aurora over Longyearbyen seen from the Kjell Henriksen observatory near Longyearbyen. Aurora is one of the most spectacular manifestations of coupling between space and Earth's upper atmosphere. (Photo: UNIS media)

Seasonal asymmetries and long-term trends in atmospheric and ionospheric temperatures in polar regions: an update (SATS 23)

Click here for full chapter

HIGHLIGHTS

- Arctic annual average temperatures are increasing at ground level and in the lower atmosphere. Temperature differences between winter and summer are decreasing.
- Ground temperatures now follow the seasons less closely. Notably, the warmest day comes later in the year. At the top of the atmosphere, incoming solar energy and temperature correlate well.
- Machine learning modelling helped clarify interactions between processes in the upper atmosphere and ground temperatures.

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During the last decades, temperatures in the Arctic have risen faster than in other parts of the globe. The cause of this rapid temperature increase remains elusive, but likely several factors are in play. Global warming due to the greenhouse effect, in which certain gases in the atmosphere trap heat, is one important factor. Cyclic changes in sea currents and ice coverage also probably play an important role. Moreover, high-latitude Svalbard faces more direct exposure to electromagnetic energy from the Sun; the converging geomagnetic field in this region concentrates electromagnetic energy into the atmosphere – sometimes manifested as spectacular aurora.

Comprehending the relative contributions of these factors, and the intricate interplay between space, atmosphere, sea, and land, remains a challenge. Therefore, an interdisciplinary team of scientists initiated a project to collect as much data from the Svalbard region as possible, to investigate and better understand these interactions. Their findings were presented in the SESS-2022 report.

This chapter updates the original SATS chapter in 2023 with additional data and new methodology. In addition to incremental updates to the existing data set, we include new measurements of sea surface temperatures from several regions around Svalbard, as well as global atmospheric carbon dioxide measurements.

Our recent measurements continue to show rising ground temperatures and reduced temperature differences between summer and winter. We also observe increasing seasonal asymmetry, with peak temperatures shifting towards later parts of the year.

To effectively process and make sense of the growing volume of data, we also explored the use of machine learning. As a proof of concept, we created a simple machine learning model that used upper atmospheric measurements, solar activity indices, and global CO_2 levels as input variables to predict ground temperatures.

This modelling exercise showed that ground temperatures could be predicted quite accurately, suggesting that machine learning could be used for filling data gaps or forecasting temperatures in places where measurements are not feasible. Second, and in contrast to our SESS-2022 results, the machine learning model unveiled discernible, albeit small, correlations between ground temperatures and those in the middle layers of the atmosphere. The causal relationship remains unknown, but it is possible that ground (and sea surface) temperatures influence the upper atmosphere, rather than the other way around.

RECOMMENDATIONS

- Decisions to address challenges arising from the observed warming trend should be based on scientific data.
- Interdisciplinary studies and cooperation across many fields of science should be encouraged.
- Machine learning combined with use of cross-disciplinary data sets should be explored to address the complex interaction between processes in the sea, the atmosphere and space.

The European Space Agency Sentinel-3 mission provides a comprehensive set of environmental parameters, including measurements of sea surface temperatures. (Image: ESA Medialab)

CHAPTER 2

Drone measurements of snow in Adventdalen April 2021. (Photo: Eirik Malnes)

A holistic approach to snow observations and models in Svalbard (Snow 23)

Click here for full chapter

HIGHLIGHTS

- SIOS is in the process of developing a super site for snow parameter monitoring in Svalbard that will improve our ability to assess the snow cover significantly.
- New and upcoming satellite sensors will allow measuring snow depth and snow water equivalent in the coming decade. These sensors need support from ground observations and aerial sensors to obtain desired quality.
- Snow models need development and capacity to assimilate all types of observations.
- A digital twin for the snow cover in Svalbard – AI based coupling of models and observations could potentially solve some of the assimilation issues related to snow models.

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The chapter gives joint recommendations from the two updated SESS chapters SATMODSNOW and PASSES in this SESS report and set them into a wider context on snow research in Svalbard where SIOS now develops supersites for snow parameter monitoring in several projects such as Crios, SIOS Snow Pilot and SnowInOpt. The chapter also gives a brief overview over upcoming satellite sensors allowing for measurements of snow depth and snow water equivalents, which previously have been unavailable from satellites. The chapter also reviews the snow observations provided in the SIOS Data Management System, and advises improvements. We also highlight the importance of snow models and their ability to assimilate different in situ and earth observations to accurately represent the snow cover. At the end of the chapter, we look forward to new possibilities for a holistic approach where models (from past data and future climate scenarios) and observations are merged in a digital twin based on AI techniques for pattern recognition, allowing for detailed prediction of the future snow cover.

Preparations for field campaigns in Longyearbyen. The use of avalanche transceivers is mandatory during field work. (Photo: Markus Eckerstorfer)

RECOMMENDATIONS

- Intercomparisons (and intercalibrations) of snow products from coarse scale (4 km, AVHRR), via medium scale (500 m, MODIS) and detailed (10–20 m, S2-MSI) to sub-meter scale (time-lapse cameras) should continue and be used to improve products.
- The SIOS supersite for remote sensing of snow must be continued as a reference for upcoming satellite products and snow parameter retrieval methods. Funding of snow water equivalent transects using GPR and web-camera operations should be sought from available sources.
- Attempts should be made to map, harvest and maintain (if possible) all kinds of Earth Observation products of snow over the archipelago and validate/quantify errors in each of the datasets.
- The assimilation of Earth Observation data in snow hydrology and snow process models needs to be further investigated.
- A digital twin framework for the snow cover in Svalbard should be implemented to assimilate data in models using AI-concepts, and possibly make future predictions about the snow cover.

Aerial photo of snow cover in Longyearbyen April 2021. (Photo: Eirik Malnes)

CHAPTER 3

The IG PAS time-lapse camera view at Hornsund. (Photo: Bartłomiej Luks)

Terrestrial photography applications on the snow cover: developing a data service for monitoring extreme events in Svalbard (PASSES 3)

Click here for full chapter

HIGHLIGHTS

- The Svalbard time-lapse camera network focused on snow cover monitoring has been established.
- Three focal sites have integrated previously established and novel camera systems, and conceptualizing a shared data service.
- Earth observations provided by the infrastructure assist in describing emerging phenomena occurring in Svalbard.

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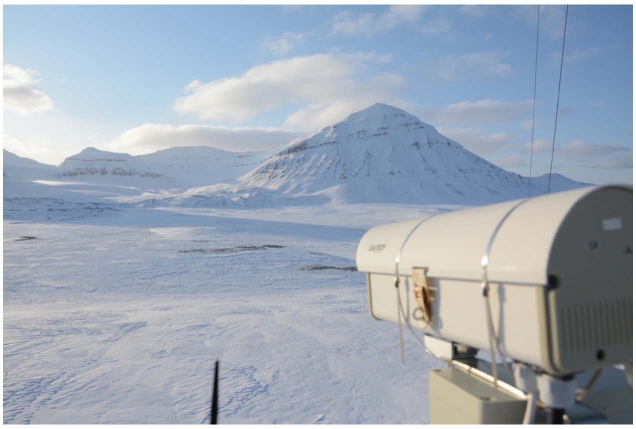
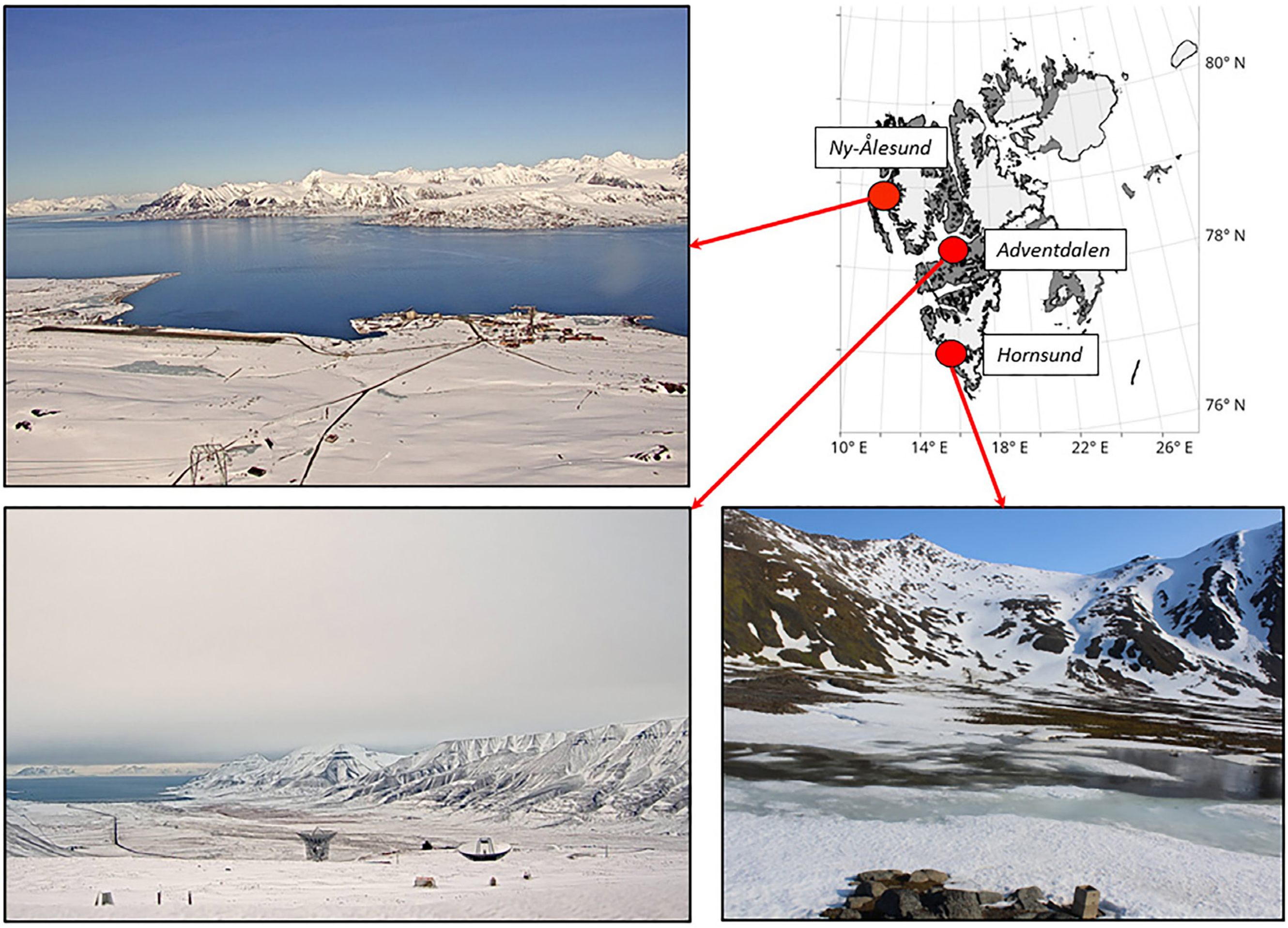
The PASSES initiative has matured within the framework of SIOS activities, resulting in the establishment of the Svalbard network of time-lapse cameras. The primary objective of this network is to monitor the evolution of the snow cover during the melting season. A survey of available applications served as a valuable tool for identifying scientific priorities and potential opportunities. By optimizing the operation of these applications through a collaborative approach, we supported the design of the network architecture and the development of a data service, including a product prototype. The continuity of Earth Observation (EO) data obtained through terrestrial photography is invaluable for describing emerging phenomena in the changing Arctic. These observations primarily serve to bridge the gap between automated stations, ground-based data collection, and satellite remote sensing. Moreover, they enable continuous observation, facilitating the integration of data from various sources.



The CNR time-lapse camera at the Amundsen-Nobile Climate Change Tower. (Photo: Riccardo Cerrato)

RECOMMENDATIONS

1. Promote projects involving use of the time-lapse cameras, particularly in the more remote areas of Svalbard. Utilise distributed computing systems to facilitate the use of systems built into the "internet of things", aiming to overcome data transfer limitations.
2. Support the maintenance of the Svalbard camera system network and advocate for the establishment of a dedicated data service for processing images captured by various devices for snow cover applications.
3. Enhance the understanding of snow dynamics and processes by combining high-resolution terrestrial images and large-scale satellite data with advanced machine learning and artificial intelligence methods.
4. Encourage the use of time-lapse cameras across disciplines where high-resolution temporal information can be harnessed for various purposes, including glaciology, hydrology, plant and animal ecology, coastal processes, sea ice tracking, and satellite imagery calibration and validation (Cal/Val).



The three selected sites of the Svalbard camera network. (Photos: Roberto Salzano)

CHAPTER 4

Snow cover has significant impacts on terrestrial and marine ecosystems. (Photo: Hannah Vickers)

Satellite and modelling based snow season time series for Svalbard: Intercomparisons and assessment of accuracy (SATMODSNOW 2)

Click here for full chapter

HIGHLIGHTS

- Snow models produce patterns of later snow melt and snow onset compared to remote sensing (RS) observations.
- Snow cover derived from remote sensing datasets is very dependent on the retrieval algorithm used.
- Methods exploiting artificial intelligence (AI) are needed to extract finer detail from low-resolution remote sensing observations and for combining remote sensing observations with snow models to obtain accurate snow cover time series.

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Climate change is taking place at a much faster pace in the Arctic and polar regions compared to the global average. Across the Norwegian archipelago of Svalbard, a warming climate is impacting where and when there is snow cover, which in turn has consequences for the physical environment, terrestrial and marine ecosystems. Remote sensing observations and snow models represent valuable tools for large scale monitoring of snow cover and provide historical data spanning several decades. These approaches provide complementary data that can contribute to filling important gaps in both datasets. However, we must first understand the how and how much the datasets differ.

Only then can we use these complementary datasets to develop accurate, complete and consistent snow cover time series for Svalbard. The research in this update chapter builds on the SESS report 2020 chapter SATMODSNOW by utilising additional new years of snow cover data from remote sensing and models to examine inter-sensor and inter-model differences. Our results highlight some systematic differences in the temporal characteristics of snow cover onset and disappearance between models and remote sensing, as well as the significance of cloud cover masks and retrieval algorithms on the snow cover fraction derived from identical remote sensing datasets.

RECOMMENDATIONS

- Develop methods using remote sensing data to improve hydrological models for better representation of snow cover distribution.
- Increase measurements of snow temperature and liquid water content for use in validation/ground truthing for models and remote sensing datasets.
- Utilise wet snow cover datasets obtained with Synthetic Aperture Radar (SAR) in combination with optical snow cover fraction maps to improve snow cover detection during the melting period, especially on overcast days when optical sensors cannot provide snow cover data.

The current availability of ground truthing data in Svalbard is sparse. (Photo: Hannah Vickers)

The spatial distribution of snow cover in Svalbard can be highly inhomogeneous and vary over small scales. (Photo: Hannah Vickers)

CHAPTER 5

Close-up of Zeppelin observatory (Zeppelin Mountain), continuously operated by NILU since 1989. The village of Ny-Ålesund can be seen at the left. (Photo: Ove Hermansen)

Arctic haze in a climate changing world: the 2010–2022 trend (HAZECLIC 2)

Click here for full chapter

HIGHLIGHTS

- Source apportionment method applied to atmospheric sulphate from two sites in Ny-Ålesund to quantify anthropic contribution.
- Anthropic sulphate used to study the evolution of Arctic haze from 2010 to 2022.
- Air pollution mitigation strategies appear to be improving air quality.

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For this update of the HAZECLIC chapter in SESS report 2020, we studied the temporal evolution of the Arctic haze over the past decade in Ny Ålesund (at Gruvebadet and Zeppelin observatories) through data on atmospheric sulphate, which is the most reliable marker of Arctic haze. By using other source chemical markers, we managed to quantify the solely anthropic sulphate and study its behaviour between 2010 and 2022. Although detecting a trend was not straightforward, we observed decreasing levels of anthropic sulphate when the haze is present (April) while no trend could be observed when the haze is not present (September). These results have various implications: first, they suggest that atmospheric sulphate arising from anthropic activities and present during non-haze months has reached a bottom threshold, a sort of "background level" which is probably difficult to reduce further. Second, it appears that atmospheric sulphate is still slowly decreasing during haze months, likely due to a persistent long-term effect of stricter air quality policies.

Aerosol sampling devices operated at Gruvebadet observatory since 2010 by University of Florence in close cooperation with CNR-ISP.
(Photo: Mauro Mazzola)

RECOMMENDATIONS

1. Continue with the experimental observations at the Gruvebadet and Zeppelin observatories. two highly strategic sites. The continuous long-term aerosol measurements at both observatories will allow constraining the impact of the haze at ground level and above the atmospheric boundary layer.
2. Define the "natural Arctic baseline". The natural aerosol emissions are progressively changing due to the environmental impact of anthropic activities. Since natural aerosol plays a key role in the radiative balance of Arctic regions, a more accurate assessment of the "moving natural baseline" would represent an asset in understanding and forecasting the impact of human activities in the Arctic.
3. Upgrade the Gruvebadet facility with measurement of trace gases. Gruvebadet observatory has been acknowledged in the last years as a relevant facility to accomplish several atmospheric studies. The instrumental set-up has been successfully used to measure the chemical composition of aerosols, but so far the gas phase has only been investigated during spot campaigns. A systematic measurement array for key gas species acting as aerosol precursors (such as dimethylsulphide), possibly via on-line instruments, would yield an expanded overview of the gas–aerosol–cloud interaction.

Overview of the two observation facilities mentioned in the report: Gruvebadet - GVB (at left in the foreground) and Zeppelin - ZEP observatories (right, near the top of the mountain), Ny-Ålesund. (Photo: Mirko Severi)

CHAPTER 6

Plastic litter in Svalbard. (Photo: Norwegian Polar Institute)

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

Click here for full chapter

HIGHLIGHTS

Plastic pollution in Svalbard is an increasing environmental issue. Despite Svalbard's remote location, microplastics are infiltrating this pristine environment. Understanding their sources, impacts, and interactions with the ecosystem is crucial for mitigation strategies.

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Microplastics, tiny plastic fragments (<5mm), have emerged as a global concern, infiltrating even the most remote regions such as Svalbard. The surge in plastic production has led to widespread contamination. Svalbard, like the broader Arctic region, is already contending with issues related to climate change, pollution, and invasive species, and it now faces an additional risk in the form of microplastics. Recent studies conducted in Svalbard have advanced our understanding of microplastics in seawater, sediment, algae, fulmars and walruses. Ongoing monitoring indicates that microplastics could potentially be harmful to the Svalbard environment over extended periods. It is imperative to maintain a comprehensive grasp of the status of microplastics and adopt a proactive approach. This is crucial for assessing and conveying the significance of prevention and reduction efforts targeting plastic pollution in the Arctic. It serves as a rallying call for all of us to reduce our plastic consumption and seek sustainable alternatives whenever feasible. Each small effort we make can contribute significantly to a reduction in microplastic pollution.

RECOMMENDATIONS

- **Harmonization:** Organize a workshop with experts on microplastic, to reach agreements on microplastics monitoring on Svalbard.
- **Collaboration:** Establish a Svalbard plastic task force. Its members should meet regularly to develop methods and monitoring recommendations to ensure a concerted effort to fulfil knowledge gaps.
- **Mapping:** Microplastic has not been mapped properly in Svalbard. This knowledge gap includes biota both from the terrestrial and marine ecosystems. In depth mapping studies should be done to enable reliable risk assessment for both the environment and human consumers.
- **Long-term monitoring:** A monitoring programme should be designed to include societal needs. Scientists working on microplastics can provide advice regarding plastic use in Svalbard, wastewater treatment, effects of recreational (cruises/tourists) and fishing activities.
- **Experiments:** Experimental studies on microplastics effects in Arctic key species should be promoted and the possible trophic accumulation of microplastics under Arctic conditions should be investigated.

Plastic litter in Svalbard. (Photo: Geir Wing Gabrielsen)

Seasonal asymmetries and long-term trends in atmospheric and ionospheric temperatures in polar regions: an update (SATS 23)

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Update of chapter 1 of SESS report 2022.

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1. Introduction

During the last decades, temperatures in Arctic regions have increased much faster than the rest of the world (e.g. Rantanen et al. 2022). Svalbard, with its comprehensive infrastructure and availability of long-time measurement series is an ideal place to observe and investigate potential processes responsible for these changes. With this in mind, a cross-disciplinary group of researchers initiated a project, "Seasonal asymmetries and long-term trends in atmospheric and ionospheric temperatures in polar regions and their dependence on solar activity (SATS)", to study these processes. Initial results from this study were presented in the SIOS 2022 report (Haaland et al. 2023, hereafter referred to as SATS).

This brief report updates the original SATS report, and we address some of the open issues and recommendations from the initial report. In addition to incremental updates of the existing data sets, we have added data sets describing the sea surface temperatures around Svalbard as well as a proxy for the global atmospheric CO_2 content. We also present some initial results, and provide an outlook for the use of machine learning to investigate large data sets.

2. The state of temperature trends in Svalbard

As in SATS, the aim of this study is to characterize long term trends in temperatures at and around Svalbard, and their response to external inputs such as atmospheric and ionospheric conditions and solar activity. The latter is of relevance since Svalbard possesses strong seasonal variations, is located in the geomagnetic cusp region (see e.g. Fritz and Fung 2005), and thus is more exposed to effects of the solar wind than lower latitudes. To perform such a characterization, we employ observations from a number of ground temperature stations, combine them with measurements and proxies for potential input parameters including atmospheric and ionospheric temperatures, sea temperatures, and solar activity, and use this data set as input to a model. Correlations between observations, as well as potential cause–effect links are discussed.

2.1. Overview of observations

Figure 1 shows the location of observatories used in the present study. In this update, we have extended data sets with another year of data, and investigated sea surface temperatures near Svalbard and their potential impact on ground temperatures. To get the global context, time series of atmospheric CO_2 content have also been added to the data set. Below, we briefly introduce the new data sets and data handling. Due to limited space, we refer to the original SATS report and the cited references for more details about individual data sets.

2.1.1. Ground temperatures

In contrast to SATS, published last year, temperatures from the 6 ground stations are now combined into a single time series – *median ground temperature* (MGT). It contains the median of the different stations' temperature measurements for any time with at least four operative stations. We use this parameter to represent an average Svalbard temperature.

2.1.2. Sea surface temperatures

The Operational Sea Surface Temperature and Ice Analysis (OSTIA) cooperation generates high resolution sea surface temperature maps of the global ocean from satellite and in situ data (Donlon et al. 2012). OSTIA's satellite data come from infrared and microwave instruments on satellites, while in situ data (primarily used for calibration) are

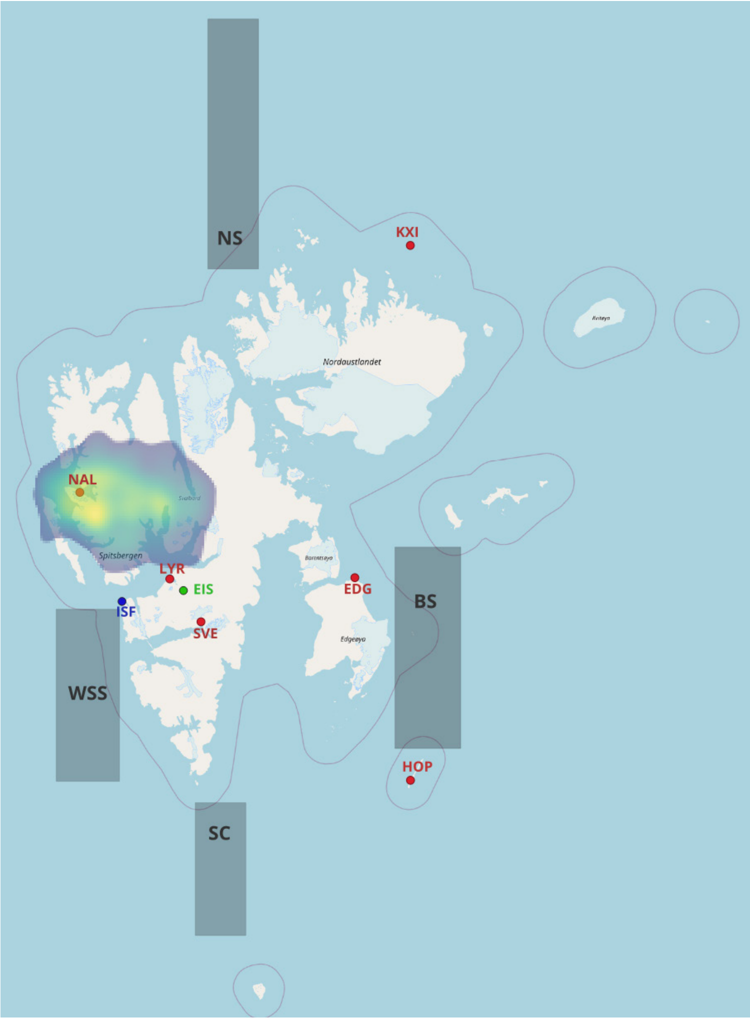


Figure 1: Observatories used in this study. Red dots show ground temperature observatories, the blue dot indicates a mooring and the green dot indicates the position of the EISCAT radar system. The Mesospheric radar station is located near EISCAT. Sea surface temperatures used for the model are spatial averages from four different areas: North Svalbard (NS), Barents Sea (BS), South Cape (SC) and the West Spitsbergen Shelf (WSS). The colour-coded cloud around Ny-Ålesund indicates density of balloon observations as they drift in the wind after release, with yellow indicating dense observation frequency, blue indicating fewer observations. See Table 1 for observation periods and observatory coordinates.

from ships and buoys (Good et al. 2020). We have used spatially averaged data from 4 representative regions (Fig. 1) around Svalbard as proxies for the sea surface temperature.

2.1.3. Global atmospheric CO_2 content

Carbon dioxide (CO_2) is a greenhouse gas, i.e., it absorbs significantly more heat than the atmosphere's main natural constituents (nitrogen and oxygen), and releases parts of the stored heat back to the atmosphere. An increase in atmospheric CO_2 is therefore linked to global warming. Local CO_2 measurements series are available from Ny-Ålesund (Platt et al. 2022), but as our aim is to set the observations into a global context, we source global CO_2 data from the Mauna Loa Volcanic Observatory in Hawaii (NOAA, 2023).

2.2. Methodology: Detrending seasonally varying data

Our focus is on *long term trends* in Svalbard temperatures. However, many of the observed parameters have strong seasonal variations governed by changing solar illumination as Earth rotates and orbits the Sun (effects of diurnal variations are filtered out by using the daily averages of the parameters). To filter out seasonal variations, we *detrend* the data as described in SATS. Basically, we fit the time series to a sinusoidal model representing season as shown in Equation (1), and extract three different key parameters from each measurement time series. The fit in this updated study is done over the years 2011-2018.

$$T(t, \alpha, C, \phi) = \alpha \sin\left(\frac{t+\phi}{365.242}\right) + C \qquad (1)$$

Amplitude (α) can be interpreted as the difference between minimum and maximum temperatures. A decrease in amplitude over years would indicate less pronounced seasons. **Offset (C)** can be interpreted as a yearly average. An increase in offset over the years can be interpreted as a warming trend. **Phase shift (ϕ)** can be interpreted as the seasonal asymmetry. Due to heat storage capacity in the sea, ice and land, the highest temperatures do not occur at maximum solar illumination at midsummer, but are typically shifted towards autumn.

3. Results

3.1. Temperature characteristics

The results on trends and average profiles of amplitude, offset and phase shift of the temperature curves are not substantially altered by the inclusion of one additional year of data. The top part of Figure 2 is an update of Figure 5 included in last year's report (Haaland et al., 2023), but now augmented by 4 sea surface temperatures as described in section 2.1.

For the sea surface temperatures, indicated by coloured triangles in Figure 2, several features should be pointed out. The Barents Sea (BS) temperature has a lower average amplitude and a considerably larger average phase shift than the other regions investigated. This region has the lowest average sea surface temperature (see Table 1). A larger phase shift is also seen for the North Svalbard (NS) region. These two regions are typically covered by ice parts of the year. The behaviour can thus at least partly be explained by the higher heat capacity in the surrounding ice, associated feedback loops, and consequently longer response times to seasonal changes (Onarheim et al. 2018). Furthermore, the West Spitzbergen Shelf (WSS) and South Cape (SC) regions are strongly correlated with each other. This correlation is primarily a result of heat transport by sea currents (e.g. Nilsen et al. 2016).

Figure 2d shows linear correlations between the different time series in the form of a colour coded correlation matrix. The brief update precludes a comprehensive discussion of all features, but we have labelled a few regions of particular interest in the correlation matrix. Label 1 highlights the strong correlation between sea surface temperatures in the WSS and SC regions, which can be attributed to sea currents. Label 2 highlights the difference in behaviour between the sea surface temperatures in the sometimes ice-covered BS region and the SC region, which is ice-free year-round. The difference in behaviour of these regions is most pronounced in the phase shift.

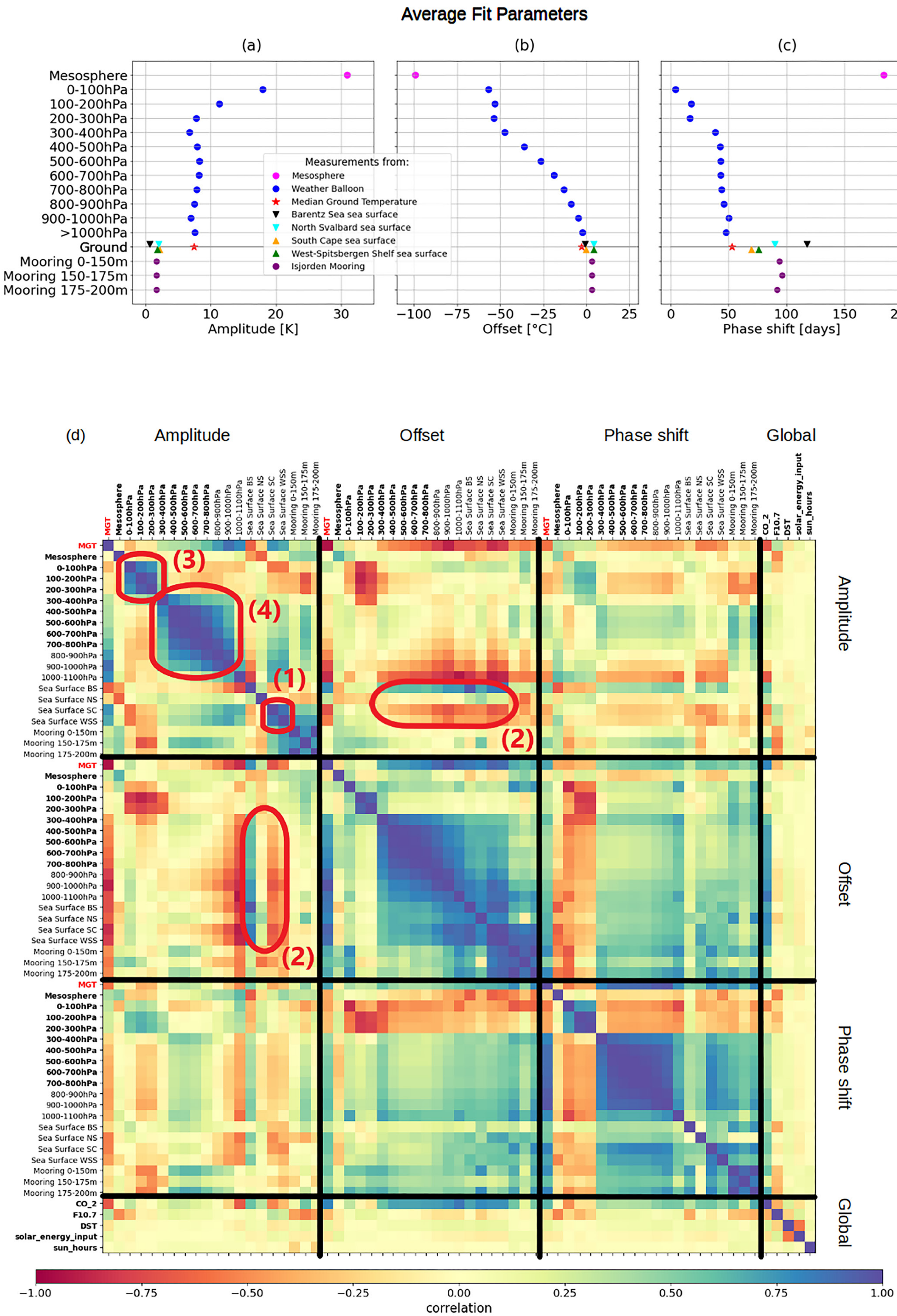
This correlation matrix also highlights some interesting features in the atmosphere. The 300 hPa size bin serves as a boundary (i.e., the tropopause) between the high-altitude, stratospheric region (pressure levels 0 to 200 hPa - label 3), and the tropospheric pressure levels at lower altitudes (label 4). This clear distinction between these regions is apparent in both amplitude, offset and phase shift.

4. New possibilities with machine learning

The large amount of data and the complex interactions between the regions studied led us to investigate alternative data processing methods. Machine learning methods lend themselves well to large datasets. For studying long-term trends in the temperature, the use of regression supervised learning is of particular relevance (e.g. Rolnick et al. 2022). Supervised learning has the ability to learn mappings between inputs and outputs in a continuous numerical form due to its regression (in data science, inputs to a model are often referred to as *features*, and outputs are referred to as *targets*).

4.1. Choice of model: Multi-Variate Linear Regression

This brief update of SATS does not allow an elaborate explanation of the various machine learning methods, or exploration of all aspects of our large data set. However, as a proof of concept, the simplest supervised learning regressor model, the Multi-Variate Linear Regression (MVLR) model, was tested for this update. The aim was to predict ground temperatures (targets) based on input parameters such as solar energy influx and temperatures in the upper atmosphere (features).



Average Fit Parameters
(a)
(b)
(c)
Measurements from:
Mesosphere
Weather Balloon
Median Ground Temperature
Barentz Sea sea surface
North Svalbard sea surface
South Cape sea surface
West-Spitsbergen Shelf sea surface
Isjorden Mooring
Amplitude [K]
Offset [°C]
Phase shift [days]
(d)
Amplitude
Offset
Phase shift
Global
correlation

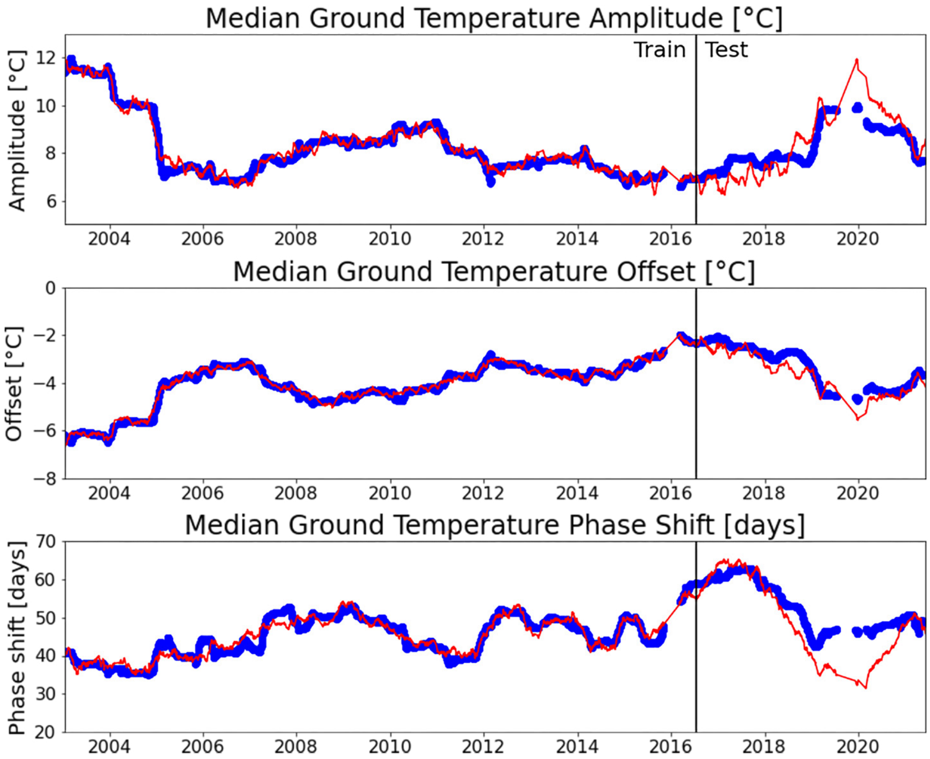


Figure 3: Fit parameters (amplitude, offset and phase shift) based on measurements in blue, and the same parameters predicted from the MVLR model outputs in red.

Due to its linear structure it is easy to determine feature importance, and its simplicity makes MVLR a versatile model that can be applied to many different problems. MVLR also has downsides that are not easily overcome, such as its tendency to over-fit when a large number of (partially correlated) input features are used. Moreover, outliers in the data set can significantly influence model output, and a good fit on the data does not necessarily imply causality. Still, the model gives further insight in the data set, and allows for predictions of the output targets.

4.2. Predictions from the MVLR model

Although multi-label regression models and classifiers capable of predicting several targets exist, we chose the simplest possible approach: 3 separate MVLR models are set up, each predicting one of the 3 targets: median ground-station temperature (MGT) amplitude [°C], offset [°C], and phase shift [days], respectively. For this proof of concept, 27 input parameters based on data collected at high altitudes (>700 hPa isobar, corresponding to ~3 km or more above sea level) and 5 global parameters (global atmospheric CO_2 concentration, the $F_{10.7}$ solar activity index, the *DST* magnetic disturbances index, the solar energy influx P_{in}, and the average Svalbard sun hours) are used as input features to the 3 models. Input features are indicated in bold black text, and targets in red bold text in Figure 2.

We used a 3:1 train/test ratio for the model. That is, the MVLR model is trained on the first 75% of the data set (years 2003-2016; days with data gaps have been removed). The last 25% (from late 2016 to 2021) are predicted. Figure 3 shows the result of this fit, in the form of detrended fit parameters (amplitude, offset and phase shift) in blue, and MVLR model outputs of the same parameters in red. The figure demonstrates that the MVLR model can reasonably predict the detrended fit parameters of the MGT by using features that are normally not considered to have a strong linear correlation on

Figure 2: Profiles of the sine wave parameters fitted to the temperature measurements (top) and correlations between modelling parameters (bottom). a): Amplitude (i.e., essentially difference between min and max temperatures). b): Offset (can be interpreted as yearly average temperature). c): Seasonal offset (i.e., phase shift between seasonal solar illumination and temperature). d): Colour-coded matrix showing correlations between parameters. Parameters printed in bold text at the edges are used in the machine learning model discussed in section 4. Red ellipses labelled (1) to (4) indicate key features discussed in the text on page 27.

their own as shown in Figure 2.

Although the model suffers from over-fitting the data, the introduction of global variables such as CO_2 reduces this over-fitting. This can largely be attributed to the introduction of significant long-term trends in the feature pool allowing the model to reproduce and predict the observed trends in ground temperatures. Note that we did not try to optimize the model or choice of input features (e.g. Van Der Maaten et al. 2009) in this proof of concept. We expect to achieve even better prediction accuracy with other models and further optimizations.

5. Contributions to interdisciplinarity

In SATS, we studied long-term trends in temperatures around Svalbard from to the sea to space. Here we have updated our existing dataset through summer 2023. We now also included ocean/sea surface measurements based on remote sensing by satellites. As in SATS, this update involves science disciplines from sea to space: oceanography, meteorology, atmospheric physics, ionospheric physics and space physics. Our data set is comprehensive and diverse (also see Table 1).

5.1. Main findings

The addition of a year of observations did not significantly alter the overall conclusions reported in SATS. Based on our new, updated data set, the following main findings still hold:

- Ground temperatures in Svalbard increase over time, and the difference between summer and winter temperatures decreases.
- The seasonal asymmetry increases; the day of the year with maximum ground temperature shifts toward autumn.
- Ground temperatures seem largely unaffected by solar activity; the last solar cycle is weaker in terms of electromagnetic energy transfer than previous solar cycles, but ground temperature trends still show an increase.
- Temperature trends in the lower atmosphere (below the tropopause) are similar to those for ground temperatures.

Sea surface temperatures around Svalbard show distinct differences between regions. In particular the BS and NS regions, which are partly covered by ice for periods, show less summer–winter variation, and a larger seasonal shift (longer response times). The other regions are connected by sea currents and show more similar behaviour.

Results from MVLR machine learning model reveal correlations between ground temperatures and the upper atmosphere, mesosphere as well as global proxies such as CO_2 content, geomagnetic activity and solar activity. Classical methods do not show any significant correlations between these parameters. The cause-effect link is not clear, though. It may be that ground (and sea surface) temperatures affect the upper atmosphere rather than vice versa. Still, machine learning can provide new insight and reveal new correlations, and will probably become more important for processing of large data sets in the future.

As demonstrated, machine learning can also be used to predict temperatures based on input parameters from other regions. Potential uses for machine learning could be to predict temperatures in places where no observations are available or possible, predict future trends and fill data gaps in observations.

6. Open questions and recommendations for the future

Several open questions remain. We still do not know what underlies the observed trends and changes. Are the changes primarily the result of global effects (cf. the greenhouse effect as discussed in IPCC (2023)), or can the observed trends primarily be attributed to local conditions? The impact of sea ice coverage and heat transport by sea currents is also still not fully understood. Another question is how and whether the observed trends will continue in the future. How do long-term cyclic effects, e.g., ice extent and ice cap motion, affect ground temperatures? Finally, what consequences will the observed trends have for society in Svalbard?

In this study, we barely touched upon possibilities with machine learning and data-driven models. One clear recommendation from this update is to further utilize such methods, and make use of cross disciplinary data sets as inputs to the models. New data-driven models and use of machine learning also allow larger data sets to be processed, and greater spatial and temporal variations to be assessed. So far we have not utilized local wind measurements or local solar radiance measurements (and these do not exist for all stations), but these should be included where available.

For an arctic island archipelago like Svalbard, the interactions between sea, ice and land are of key importance for understanding the local climate. The location in the geomagnetic cusp region also means that solar activity and electromagnetic energy from solar wind have more direct impact, in particular in the upper atmosphere and ionosphere. Thus, the need for interdisciplinary investigations encompassing space/solar physics, meteorology, oceanography and glaciology cannot be emphasized enough.

Our final recommendation not only applies to science investigations, but also policy: decisions made to address challenges arising from the warming trend should be based on scientific data. Consequently, there is a need to maintain the existing observation grid, and to expand this to new regions (e.g., observations from Svalbard's interior regions remain few).

7. Data availability

All data used for this study are available from public archives. Links to data sources and an overview of station coordinates for each dataset are shown in Table 1.

8. Acknowledgements

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Table 1: Updated list of data sets, observatories, their geographic location and elevation above mean sea level, time of operation, data availability as well as mean temperature over the given time interval.

Dataset	Station	Latitude	Longitude	Altitude	Period	Data points	T_{avg}	Dataset provider	Metadata access (URL)	Remarks
OSTIA SST	OSTIA Barents Sea	76.8-78.5	24.4-27.0	0m	2005-09-16 2021-10-08	15264	-1.7 °C	Copernicus Climate	https://doi.org/10.48670/moi-00165	See "*Data access and mapping services*" in given URL. SATS contact person: Ragnheid Skogseth (ragnheids@unis.no)
	OSTIA North of Svalbard	80.5-82.7	17.0-19.0	0m	1981-10-01 2023-06-24	15252	-1.6 °C	Copernicus Climate	https://doi.org/10.48670/moi-00165	
	OSTIA South Cape	75.0-76.3	16.5-18.5	0m	1981-10-01 2023-06-24	15242	2.5 °C	Copernicus Climate	https://doi.org/10.48670/moi-00165	
	OSTIA West Spitsbergen	76.5-78.0	11.0-13.5	0m	1981-10-01 2023-06-24	15252	2.7 °C	Copernicus Climate	https://doi.org/10.48670/moi-00165	
Isfjorden temperatures	Isfjord mouth	78.06	13.52	-150 - -200m	1981-10-01 2023-06-24	95969	3.0 °C	Norwegian Polar Institute	https://data.npolar.no/dataset/42927488-f4e7-4470-b107-44c4f2bd0c36	
Ground temperatures	Hopen	76.51	25.01	6m	1970-01-01 2023-06-27	19517	-4.46 °C	Norwegian Centre for Climate Research	https://www.seklima.met.no	Select station and time interval, thereafter "*Mean air temperature (24h)*" in given URL. SATS contact person: Antonia Radlwimmer (Quivi@web.de)
	Ny-Ålesund	78.92	11.89	8m	1974-08-01 2023-06-27	17522	-4.69 °C	Norwegian Centre for Climate Research	https://www.seklima.met.no	
	Longyearbyen Airport	78.24	15.49	28m	1975-08-01 2023-06-27	17413	-4.59 °C	Norwegian Centre for Climate Research	https://www.seklima.met.no	
	Svea	77.89	17.72	9m	1978-05-01 2022-07-31	15508	-5.56 °C	Norwegian Centre for Climate Research	https://www.seklima.met.no	
	Edgeøya (Kapp Heuglin)	78.25	22.81	14m	1992-09-03 2023-06-26	8670	-6.04 °C	Norwegian Centre for Climate Research	https://www.seklima.met.no	
	Karl XII øya	80.65	25.00	5m	2000-08-01 2023-05-10	5709	-6.77 °C	Norwegian Centre for Climate Research	https://www.seklima.met.no	
Weather balloon	Atmosphere (balloon)	78.92	11.89	0-25km	1993-01-01 2023-07-03	ca 110000	(*)	Alfred Wegener Institute (AWI) and Norwegian Meteorological Institute	https://thredds.met.no/thredds/catalog/remotesensingradiosonde/catalog.html	SATS contact person: Brandon van Schaik (brandon.vanschaik@epfl.ch)
Mesospheric radar	Mesosphere (radar)	78.17	16.00	ca 90km	2001-10-16 2023-07-31	7080	181.3 K	Tromsø Geophysical Observatory	https://www.tgo.uit.no/	
EISCAT	Eiscat Svalbard	78.09	16.03	>100km	1999-12-01 2021-03-23	4837	486.0 K	National Polar Institute, Japan	http://esr.nipr.ac.jp/www/eiscatdata/	
Global CO_2 data	Mauna Loa, Hawaii	19.53	-155.58	3400m	1974-05-19 2023-07-16	15131	-	National Oceanographic and Atmospheric Administration (NOAA)	https://gml.noaa.gov/ccgg/trends/data.html	
Solar wind and F10.7	Solar Measurement	(*)	(*)	(*)	1980-01-01 2023-08-01	14151	-	NASA CDAWeb	https://cdaweb.gsfc.nasa.gov/index.html	

(*) As in Haaland et al. 2023, we divide balloon measurements into 11 pressure altitude levels up to ca 25 km altitude. Each pressure level contains approximately 10000 averages, and overall average temperatures vary from -3.3°C near ground to -57.4°C in pressure level 0 (i.e., atmospheric pressure below 100 mBar, corresponding to altitudes above ca 15 km).

9. References

Donlon CJ, Martin M, Stark J, Roberts-Jones J, Fiedler E, Wimmer W (2012) The Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) system. Remote Sensing of Environment 116:140–158. https://doi.org/10.1016/j.rse.2010.10.017

Fritz T, Fung S (2005) The Magnetospheric Cusps: Structure and Dynamics. Springer Dordrecht.

Good S, Fiedler E, Mao C, Martin MJ, Maycock A, Reid R et al. (2020) The Current Configuration of the OSTIA System for Operational Production of Foundation Sea Surface Temperature and Ice Concentration Analyses. Remote Sensing 12:720. https://doi.org/10.3390/rs12040720

Haaland S, Radlwimmer A, van Schaik B, Schillings A, Bjoland L (2023) Seasonal asymmetries and long-term trends in atmospheric and ionospheric temperatures in polar regions and their dependence on solar activity. In: Gevers et al (eds) SESS report 2022, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 26-43. https://doi.org/10.5281/zenodo.7371477

IPCC (2023) Contribution of Working Groups I, II and III to the Sixth Assessment Report of the Intergovernmental Panel on Climate hange. In Climate Change 2023 (pp. 25–115). IPCC, United Nations, Geneva Switzerland. https://doi.org/10.59327/IPCC/AR6-9789291691647

Nilsen F, Skogseth R, Vaardal-Lunde J, Inall M (2016) A Simple Shelf Circulation Model: Intrusion of Atlantic Water on the West Spitsbergen Shelf. J. Phys. Oceanography 46:1209–1230. https://doi.org/10.1175/JPO-D-15-0058.1

NOAA (2023). Global Monthly Mean CO_2 Atmospheric Measurements. National Oceanographic and Atmospheric Administration, USA. Retrieved from https://gml.noaa.gov/ccgg/trends/global.html

Onarheim IH, Eldevik T, Smedsrud LH, Stroeve JC (2018) Seasonal and regional manifestation of Arctic sea ice loss. Journal of Climate 31:4917–4932. https://doi.org/10.1175/JCLI-D-17-0427.1

Platt SM, Hov Ø, Berg T, Breivik K, Eckhardt S, Eleftheriadis K et al. (2022) Atmospheric composition in the European Arctic and 30 years of the Zeppelin Observatory, Ny-Ålesund. Atmospheric Chemistry and Physics 22:3321–3369. https://doi.org/10.5194/acp-22-3321-2022

Rantanen M, Karpechko AY, Lipponen A, Nordling K, Hyvärinen O, Ruosteenoja K, Vihma T, Laaksonen A (2022) The Arctic has warmed nearly four times faster than the globe since 1979. Communications Earth & Environment 3:168. https://doi.org/10.1038/s43247-022-00498-3

Rolnick D, Donti PL, Kaack LH, Kochanski K, Lacoste A, Sankaran K et al. (2022) Tackling climate change with machine learning. ACM Computing Surveys (CSUR) 55:1–96. https://doi.org/10.1145/3485128

Van Der Maaten L, Postma EO, van den Herik HJ (2009) Dimensionality reduction: A comparative review. Journal of Machine Learning Research 10:1-41.

A holistic approach to snow observations and models in Svalbard (Snow 23)

2

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1. Introduction

Snow plays a crucial role in Svalbard and significantly impacts ecology and human activity. Ongoing climate change (Isaksen et al., 2022) affects the snow cover and will have even higher impact in the future. Accurate measurements of snow parameters are thus important. Various projects addressing Svalbard's snow cover will give improved measurements of snow parameters, including the essential climate variables (ECVs) snow covered area, snow depth and snow water equivalent[1]. This SESS report reviews some of the initiatives, to assess the path forward.

SIOS Snow Pilot[2] is funded by the Research Council in Norway via SIOS Knowledge Centre in 2022-2023 based on previous SESS report recommendations. It establishes time series of snow cover fraction from satellite sensors and develops three in situ supersites (Figure 1) for snow cover monitoring via standardized time lapse cameras and standardized ground penetrating radar equipment for snow depth and snow water equivalent transects. Despite limited funding, these infrastructures are now largely established, but funding for future continuous operations has not been secured yet.

SIOS SnowInOpt (2023-2024) is funded by SIOS under the infrastructure optimisation call[3]. The project has four main objectives: 1) Implement standards for Ground Penetrating Radar (GPR) measurements, 2) Carry out GPR measurements, 3) Develop machine learning methods for GPR analysis and 4) develop a prototype method for measuring snow depth in Svalbard using ICESat-2.

The project "Cryosphere Integrated Observation Network on Svalbard" (CRIOS)[4] focuses on building automatic measuring network on glaciers in Svalbard providing near real-time weather, snow and ice data via the internet. Five glaciers are instrumented.

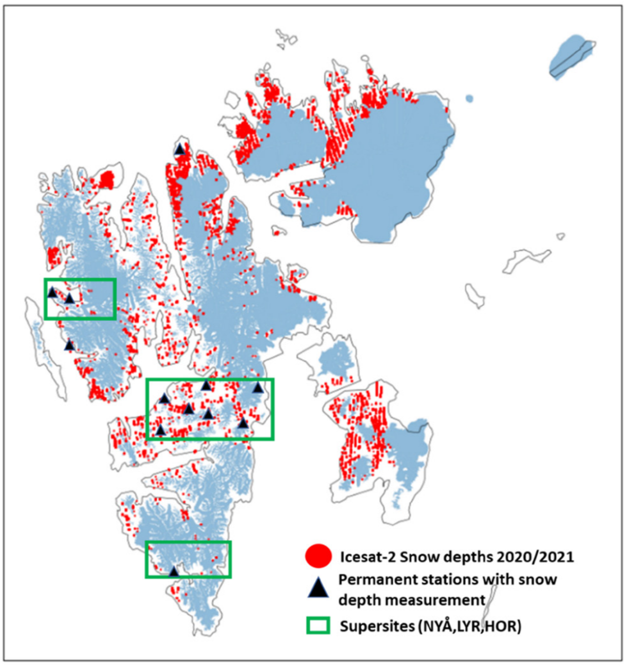

Figure 1: Map of Svalbard with the 3 current supersites. For data sources see Table 1.

Table 1: Data used to produce Figure 1-3. The datasets have been processed from Level-1 data provided by the satellite ground segments, into geophysical products (snow depth and snow cover fraction) described in section 2. In Figure 2 snow cover is visualized using CVL 3D visualization tools[5].

Sensor	Organization	Link
Icesat-2 (Figure 1&Figure 2)	NSIDC	https://doi.org/10.5067/ATLAS/ATL03.005,
Sentinel-2 (Figure 3)	ESA&EU	https://scihub.copernicus.eu/, service migrated to https://dataspace.copernicus.eu/ (Nov 1, 2023).

1 WMO https://gcos.wmo.int/en/essential-climate-variables/snow/ecv-requirements
2 https://sios-svalbard.org/SnowPilot2022
3 https://sios-svalbard.org/OptimisationCall
4 https://sios-svalbard.org/CRIOS; funded by the EEA Financial Mechanism
5 https://cvl.eo.esa.int/

2. The state of the art in snow science

In this section we review relevant snow parameters and observation techniques, as well as models available in Svalbard. Then we review which types of snow-related data are already available in the SIOS data management system, and try to assess the maturity and FAIRness of the datasets.

Snow extent (and snow cover fraction) observed with remote sensing is by far the most mature snow parameter (Dietz et al., 2011). Snow cover is treated separately in the SATMODSNOW report with an update of Malnes et al. (2021) by Vickers et al. (2024). The report focuses on long term time series of snow cover mainly by optical sensors from late 1980 to present and compares with model data for the same period. The findings show a clear need to harmonize models and satellite observations since there are substantial differences. Optical sensors have significantly improved since the start of the satellite era: daily acquisitions with high spatial resolution are now available. There is, however, a need to improve calibration between the different sensors and understand scale differences between the high- and low-resolution sensors. Salzano et al. (2023) in the PASSES report has addressed this issue using time-lapse cameras to calibrate and validate satellite methods. Upcoming work will seek to utilize the variety of spatial scales observed simultaneously to improve results from the past (e.g. reconstructing snow cover in the past at high resolution). In the context of AI-technology we anticipate that correlation with other parameters such as precipitation and temperature can result in high-resolution predictions of the snow cover in the future (Richiardi et al., 2023; Daudt et al., 2023). Other sensors such as Synthetic Aperture Radar (SAR) can also be utilized to fill gaps in the time-series when optical data are obstructed due to clouds or polar night.

Snow depth has been challenging to measure using satellites. Optical remote sensing can be used via photogrammetric methods and digital elevation models to derive information about snow depth but is challenging due to variable snow properties (roughness) and poor light conditions and requires high-resolution optical images, mostly limited to airborne surveys (Bührle et al., 2023). Passive microwave sensors are widely used to estimate snow depth but are currently limited by their relatively low resolution and therefore cannot address areas with high topographic variability (Tanniru et al., 2023). Another approach to derive snow depth from space, is to use satellite altimetry, and in particular laser altimetry. NASA's Ice, Cloud, and land Elevation Satellite-2 (ICESat-2), launched in 2018, carries a laser altimeter that allows for detailed measurements of surface heights with a footprint of ~11 m, and 70 cm sampling interval horizontally along track under cloud-free conditions. During summer, in snow-free areas, ICESat-2 surface heights provide a reference surface in combination with high-resolution digital elevation models. During winter, ICESat-2 senses the snow surface, allowing estimations of snow depth when referenced to snow-free elevations. The SIOS Interoperability project SIOS SnowInOpt aims to develop a processing algorithm to derive snow depth from ICESat-2 measurements. The algorithm uses the geolocated photon height data, in combination with the 2-m resolution Arctic Digital elevation model. We have preliminary results for 2019-2023 in the extended Ny-Ålesund and Adventdalen areas. Figure 2 shows an example of ICESat-2 derived snow depth for Adventdalen, averaged over March/April 2023. We will use field campaign data based on GPR to validate the snow depth estimates. If ICESat-2 snow depth products prove to provide robust snow depth estimates, this can be a high-quality source for snow depth data across Svalbard, and may significantly benefit modelling and upcoming satellite missions that measure snow parameters.

Drone-borne GPR-campaigns have been carried out nearby Longyearbyen for several years during SIOS Infranor. Drone-borne GPR could potentially cover wider areas than GPR on snowmobile (also slopes inaccessible by snowmobile) and also be used to measure snow layer structure and snow

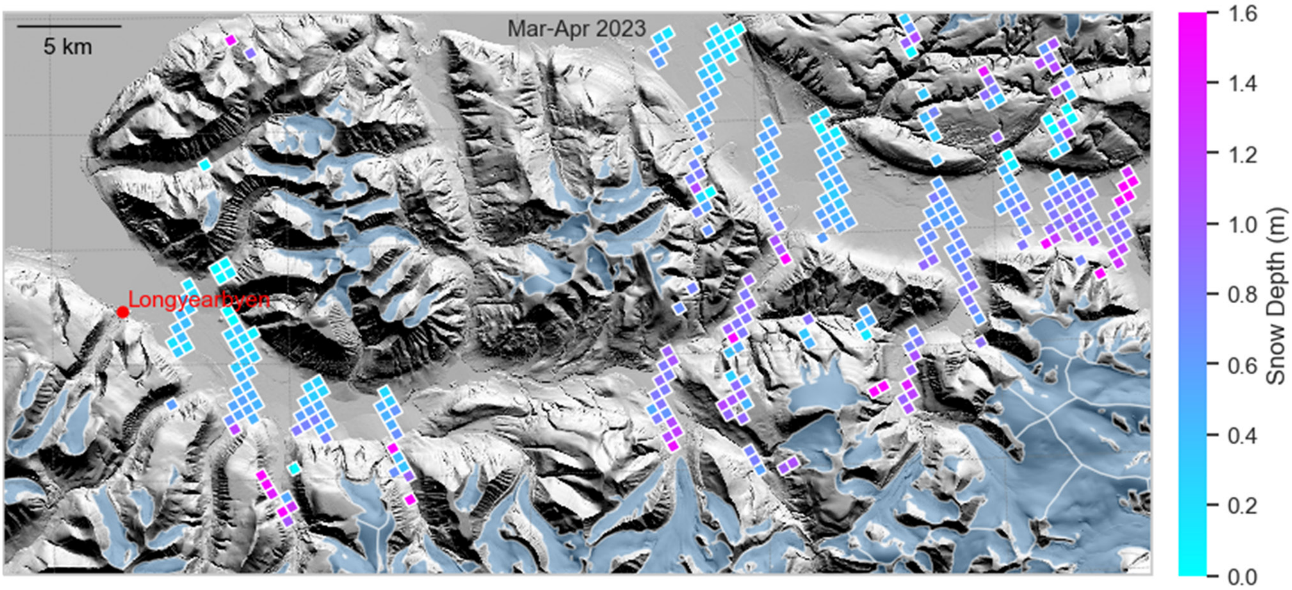

Figure 2: Average snow depth estimates from ICESat-2 in Adventdalen and Sassendalen during March/April 2023. Blue shaded areas indicate glaciers. For data sources see Table 1.

water equivalent. To reduce the current cost of these campaigns, the sensor should be improved/miniaturized to allow more automatic sensing.

In 2022, within the SIOS SnowPilot framework, the first coordinated GPR snow depth surveys in unglaciated areas for calibration of satellite products were conducted using snowmobile. GPR transects around Ny-Ålesund and Hornsund were supplemented with snow depth probing and snow pits for snow water equivalent retrieval. For Hornsund, this was the first use of a High Frequency 1.6 GHz antenna to retrieve snow depth in the shallow snowpack in the tundra.

Snow water equivalent (SWE) is the product of snow depth and snow density and is the third snow-related ECV identified by the World Meteorological Organization (GCOS). This parameter has previously been impossible to measure with sufficient resolution in Svalbard using satellites, whereas on a global scale the results are excellent (CCI-Snow). SWE is measured using passive microwave sensors with coarse resolution unsuitable for mountainous and coastal regions like Svalbard. Ground measurements using standard techniques like bulk density measurements combined with Magnaprobe sensors provide SWE for limited regions. These can also be extended using GPR, and the SIOS project SnowPilot has established a network of supersites in Ny-Ålesund, Longyearbyen and Hornsund where standardized equipment and measurement protocols will provide at least annual transects that can be used for calibration/validation activities, with the aim to obtain monthly measurements during the winter months.

In addition to transects, continuous point-measurements of SWE are needed to relate temporal variability with the spatial patterns. Up to now, the only site with systematic (every 5 days) time series of manual SWE measurements is the Polish Polar Station Hornsund. Since 2019 a gamma-sensor instrument operates in Ny-Ålesund but could also be deployed at representative sites in Longyearbyen and Hornsund. Other technologies such as snow scales and fibre-optic mats to weigh snow are being considered in SIOS infrastructure proposals. Other promising technology for continuous SWE retrieval is Global Navigation Satellite System interferometric reflectometry (GNSS-IR). In summer 2023, GNSS-IR antennas for the retrieval of snow depth and SWE were installed in Hornsund, Longyearbyen and Ny-Ålesund within CRIOS project.

Upcoming L-band SAR missions (NISAR and ROSE-L) will relatively soon make SWE-retrievals available at a suitable resolution (< 1 km). NISAR, expected to be launched in 2024, will unfortunately not cover Svalbard, so ROSE-L will be very valuable when launched in 2028. The principle for L-band SAR is to accurately measure the phase change when radar waves penetrate snow cover as compared with snow-free ground (Guneriussen et al., 2000). The phase change is proportional to SWE. L-band is regarded as much better than C-band (e.g. Sentinel-1) since the radar signal has higher coherency. We expect several initiatives to address SWE using L-band SAR in Svalbard in the coming years.

2.1. Additional snow parameters

In addition to the classical ECVs there is also a need to observe other parameters such as wet snow/liquid water in snow, albedo, snow surface temperature. More complex observations – avalanche activity, snow layering, snow chemistry etc – should also be studied. Wet snow (Vickers et al., 2022) and avalanche activity (Eckerstorfer et al., 2019) are currently monitored in Svalbard and delivered to SIOS DSBM. For some of these fields, both satellite and in situ measurements exist, and could be coordinated in the future.

2.2. Models

A few snow models cover all of Svalbard. In the SATMODSNOW project, the models EBFM (van Pelt et al., 2018) and SeNorge (Saloranta, 2016) were used, but in general the spatial scales are too coarse to the capture the dynamics of seasonal snow in Svalbard. Upcoming high-resolution initiatives such as SURFEX/Crocus have been tested for the Ny-Ålesund region (Zweigel et al., 2022) and the CryoGrid model forced by CARRA for all of Svalbard (1991-2020) with 2.5 km resolution (Schmidt et al., 2023). Current models do not really assimilate detailed datasets from remote sensing, and as shown in SATMODSNOW this may results in errors. Long term time series only exist for the snow cover parameter, and not for snow depth and SWE. Since snow cover is a more qualitative parameter than the others, it is harder to assimilate.

2.3. SIOS Core Data

SIOS has identified the following snow-related core data[6] (Snow depth, Snow water equivalent, Snow cover and Snow/ice temperature). A search in the SIOS Data Access Portal[7], based on the description in the meta-data fields, yields a number of datasets (Table 2). It should be noted searches for some of the parameters give many hits, but when the datasets and their meta-data are inspected, we find that the parameter in question is mentioned, although it is not the one being measured. This uncovers a clear need to tag SIOS Core data and a standardised approach to identify variables to avoid erroneous hits in the search procedure. For example, SCD 2.8 includes snow cover data, but some time lapse cameras provide photos, not digitized estimates of snow cover fraction within the camera's field of view (FOV). The FOV should also be defined by a polygon to ease comparison with Earth Observation data.

In addition to more precise dataset tagging, users would benefit from more clarity about a few other information pieces. Table 2 shows that users might need to know whether a dataset is based on model, satellite or in situ data, as well as the dataset's temporal and spatial extent. This is usually a pre-requisite in FAIR data (Findable, Accessible, Interoperable, and Reusable). One way to improve the preciseness in the description of the datasets could be to adhere to the Global Change Master (GCMD) keywords[8].

The approach described above for counting actual snow datasets in the SIOS Data Access Portal can clearly be questioned. Browsing 183 metadata fields opens for errors.

We have also inspected the Cryosphere Virtual Laboratory data portal[9] which incorporates the SIOS Data Access Portal but has a larger

6 https://sios-svalbard.org/CoreData_Cryosphere
7 https://sios-svalbard.org/metsis/search
8 https://www.earthdata.nasa.gov/learn/find-data/idn/gcmd-keywords
9 cvl.eo.esa.int/

Table 2: SIOS Core data related to snow. The table was developed by searching the SIOS Data Access Portal for datasets on the Snow Essential Climate Variables (ECVs). We organised the results into different categories based on inspection of individual datasets. Many datasets mention ECVs in the metadata without containing any data on those specific ECVs. This accounts for discrepancy between the number of datasets displayed and the total for the categories in the three rightmost columns.

Parameter SIOS DAP	ID	# datasets displayed	Dataset source		
			Model	Satellite	In situ
Snow cover	SCD 2.8	22	1	5	2
Snow depth	SCD 2.9	64	-	-	37 (*)
Snow water equivalent	SCD 2.10	6	2	-	4
Snow temperature	SCD 2.11	89	-	-	4
Total		183	3	5	47

(*) 9 field campaigns, 13 snow depth time series from meteorological stations, 15 glacier stations

geographical footprint. In general, we find many more snow related datasets here (406 vs. 183), but the chance that the data are not relevant is even higher here partly since many global datasets are not relevant to Svalbard but also since several of the satellite-based datasets do not provide snow ECVs even if these are mentioned in the metadata.

2.4. Digital twins

EU launched the Destination earth (DestinE) framework[10] in 2023 which aims at developing a highly accurate digital model of the entire earth. The model will monitor, simulate, and predict interrelations between natural phenomena and human activity using accurate earth observation data, high-performance computers and models, and artificial intelligence. The ambitions are clearly high, and though it is unclear how an accurate model will be achieved, this type of EU ambition pushes the scientific community to utilize the infrastructure and methods being developed. The snow community in Svalbard has already started to prepare digital twins (Figure 3), and several have been submitted to address snow and other components of the cryosphere (sea ice, glacier, permafrost). The vision is a holistic approach where models and observations interact in real-time and are able to assimilate past and current observations using AI-technology to recognize the detailed patterns and interrelations between large scale meteorological phenomena and small scale differences in the snow cover on the ground. Climate simulations could also be involved to make detailed predictions about snow cover in the future.

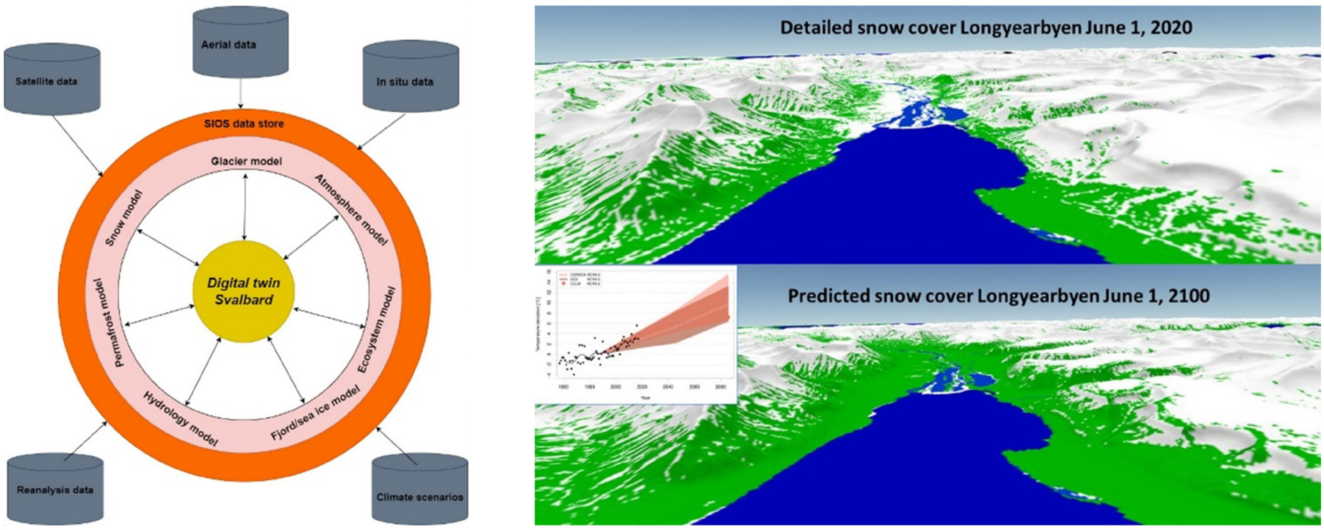

Figure 3: Left: Concept design for a digital twin for the water cycle in Svalbard. Right: 3D Visualization of the snow cover in Longyearbyen on June 1, 2020 and June 1, 2100. The first is based on Sentinel-2 data, whereas the last is inferred from time-series of Sentinel-2 (2016-2022) and a climate scenario. For data sources see Table 1.

10 https://digital-strategy.ec.europa.eu/en/policies/destination-earth

3. Contributions to interdisciplinarity

Snow is an important part of the extended water cycle. The water cycle is highlighted in the SESS Synthesis report (Christensen et al., 2023) as the most important earth system research component integrating interdisciplinarity across most of the spheres (atmosphere, hydrosphere, cryosphere, ecosphere). Combining skills from the observation community and the modelling community is necessary to obtain a holistic approach to snow science in Svalbard and improve the snow parameterizations. Collaborations with other disciplines, across the spheres, but also with social and health scientists could also be achieved by joining forces, e.g. in projects related to geohazards like snow avalanches, using drones to study polar bear dens and study relations between rain-on-snow events and lichen as reindeer forage.

4. Unanswered questions

This chapter incorporates some of the recommendations from two chapters in the current SESS report (Vickers et al., 2024; Salzano et al., 2024). Based on this and work carried out in several snow-related projects we recommend that the snow community within SIOS continue the good collaboration to improve observations and modelling of the snow cover and approach the field holistically, e.g. by establishing a digital twin for the water cycle in Svalbard. The community should also seek collaboration with leading research groups in Europe to address fundamental scientific questions like how the water cycle can be closed in Svalbard and how this links to global Earth System Science.

5. Summary

The snow community within SIOS works systematically to address a variety of snow parameters with a goal to obtain as accurate and detailed observations of snow as possible, and to share them as FAIR data in the SIOS data management system. Snow cover extent is a mature parameter where many time-series exist, but we notice that harmonization and inter-calibration is still needed. Snow depth and snow water equivalent will soon be observable from space, providing even more quantitative measurements of terrestrial snow that could be useful for our total understanding. However, there is also need for extended ground observations for calibration and validation. Models and digital twins need to develop assimilation strategies that can capture the information contained in in situ and remote sensing data of the snow cover.

6. Joint recommendations

- Intercomparisons (and intercalibrations) of snow products from coarse scale (4 km, AVHRR), via medium scale (500 m, MODIS) and detailed (10–20 m, S2-MSI) to sub-meter scale (time-lapse cameras) should continue and be used to improve remotely-sensed data products across all spatial scales.
- The SIOS supersites for remote sensing of snow must be continued as a reference for upcoming satellite products and snow parameter retrieval methods. Funding of snow water equivalent transects using GPR and web-camera operations should be sought from available sources.
- Attempts should be made to map, harvest and maintain (if possible) all kinds of Earth Observation products of snow over the archipelago and validate/quantify errors in each of the datasets. Possible new sensors are VIIRS (500 m), Landsat-8 (30 m) and Planet Labs (4 m).
- The assimilation of Earth Observation data in snow hydrology and snow process models needs to be further investigated. The CryoGrid model (2.5 km) should be included.
- A digital twin framework for snow cover in Svalbard should be implemented to assimilate data in models using AI-concepts, and possibly make future predictions about the snow cover.

7. Acknowledgements

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8. References

Bührle LJ, Marty M, Eberhard LA, Stoffel A, Hafner ED, Bühler Y (2023) Spatially continuous snow depth mapping by aeroplane photogrammetry for annual peak of winter from 2017 to 2021 in open areas. The Cryosphere 17:3383–3408. https://doi.org/10.5194/tc-17-3383-2023

Christiansen HH, Baddeley L, Hoppe CJ, Loonen MJ, Storvold R, Vitale V, Zaborska A, Matero ISO, Lihavainen H (2023) Developing the Svalbard Integrated Arctic Earth Observing System–SIOS. Earth System Dynamics Discussions. https://esd.copernicus.org/preprints/esd-2023-18/

Daudt RC, Wulf H, Hafner ED, Bühler Y, Schindler K, Wegner JD (2023) Snow depth estimation at country-scale with high spatial and temporal resolution. ISPRS Journal of Photogrammetry and Remote Sensing 197:105–121. https://doi.org/10.1016/j.isprsjprs.2023.01.017

Dietz AJ, Kuenzer C, Gessner U, Dech S (2012) Remote sensing of snow–a review of available methods. International Journal of Remote Sensing 33(13):4094–4134. https://doi.org/10.1080/01431161.2011.640964

Eckerstorfer M, Vickers H, Malnes E, Grahn J (2019) Near-real time automatic snow avalanche activity monitoring system using Sentinel-1 SAR data in Norway. Remote Sensing 11(23), 2863. https://doi.org/10.3390/rs11232863

GCOS https://gcos.wmo.int/en/essential-climate-variables/snow

Guneriussen, T., Høgda, K. A., Johnsen, H., & Lauknes, I. (2001). InSAR for estimation of changes in snow water equivalent of dry snow. IEEE Transactions on Geoscience and Remote Sensing, 39(10), 2101-2108.

Isaksen K, Nordli Ø, Ivanov B, Køltzow MA, Aaboe S, Gjelten HM, Mezghani A, Eastwood S, Førland E, Benestad RE, Hanssen-Bauer I, Brækkan R, Sviashchennikov P, Demin V, Revina A, Karandasheva T (2022) Exceptional warming over the Barents area. Scientific reports 12(1):9371. https://doi.org/10.1038/s41598-022-13568-5

Malnes E, Vickers H, Karlsen SR, Saloranta T, Killie MA, Van Pelt W, Pohjola V, Zhang J, Stendardi L, Notarnicola C (2021) Satellite and modelling based snow season time series for Svalbard: Inter-comparisons and assessment of accuracy. In: Moreno-Ibáñez et al (eds) SESS report 2020, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 202-219. https://doi.org/10.5281/zenodo.4294072

Richiardi C, Siniscalco C, Adamo M (2023) Comparison of Three Different Random Forest Approaches to Retrieve Daily High-Resolution Snow Cover Maps from MODIS and Sentinel-2 in a Mountain Area, Gran Paradiso National Park (NW Alps). Remote Sensing 15(2):343. https://doi.org/10.3390/rs15020343

Saloranta TM (2016) Operational snow mapping with simplified data assimilation using the seNorge snow model. J Hydrol 538:314–325. https://doi.org/10.1016/j.jhydrol.2016.03.061

Salzano R, Killie MA, Luks B, Malnes E (2021) A multi-scale approach on snow cover observations and models. In: Moreno-Ibáñez et al (eds) SESS report 2020, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 252-257. https://doi.org/10.5281/zenodo.4294092

Salzano R, Salvatori, R, Luks, B, Malnes, E, Gallet, J-C (2024) Terrestrial photography applications on the snow cover: developing a data service for monitoring extreme events in Svalbard. In: Verret et al (eds) SESS report 2023, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 44–53. https://doi.org/10.5281/zenodo.10260051

Salzano R, Aalstad K, Boldrini E, Gallet JC, Kępski D, Luks B, Nilsen L, Salvatori R, Westermann S (2021) Terrestrial photography applications on snow cover in Svalbard. In: Moreno-Ibáñez et al (eds) SESS report 2020, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 236-251. https://doi.org/10.5281/zenodo.4294084

Schmidt LS, Schuler TV, Thomas EE, Westermann S (2023) Meltwater runoff and glacier mass balance in the high Arctic: 1991–2022 simulations for Svalbard. The Cryosphere 17:2941–2963. https://doi.org/10.5194/tc-17-2941-2023

Tanniru S, Ramsankaran R (2023) Passive Microwave Remote Sensing of Snow Depth: Techniques, Challenges and Future Directions. Remote Sens 15:1052. https://doi.org/10.3390/rs15041052

Van Pelt WJJ, Pohjola VA, Pettersson R, Marchenko S, Kohler J, Luks B, Hagen JO, Schuler TV, Dunse T, Noël B, Reijmer C (2019) A long-term dataset of climatic mass balance, snow conditions and runoff in Svalbard (1957-2018). The Cryosphere 13:2259–2280. https://doi.org/10.5194/tc-13-2259-2019

Vickers H, Malnes E, Eckerstorfer M (2022) A Synthetic Aperture Radar Based Method for Long Term Monitoring of Seasonal Snowmelt and Wintertime Rain-On-Snow Events in Svalbard. Front. Earth Sci. Sec.Cryospheric Sciences 10. https://doi.org/10.3389/feart.2022.868945

Vickers H, Malnes E, Karlsen SR, Saloranta T, Killie MA, van Pelt W, Notarnicola C, Stendardi L (2024) Satellite and modelling based snow season time series for Svalbard: Intercomparisons and assessment of accuracy. In: Verret et al (eds) SESS report 2023, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 54–63. https://doi.org/10.5281/zenodo.10257427

Zweigel RB, Westermann S, Nitzbon J, Langer M, Boike J, Etzelmüller B, Vikhamar Schuler T (2021) Simulating snow redistribution and its effect on ground surface temperature at a high-Arctic site on Svalbard. Journal of Geophysical Research: Earth Surface 126(3). https://doi.org/10.1029/2020JF005673

Taking a snow profile in a mountain slope. (Photo: Eirik Malnes)

Terrestrial photography applications on the snow cover: developing a data service for monitoring extreme events in Svalbard (PASSES 3)

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DOI: https://doi.org/10.5281/zenodo.10260051

1. Introduction

The availability of Earth Observation (EO) data in remote areas poses a critical challenge that affects our ability to comprehensively describe processes occurring in the Arctic. Fortunately, satellite data have become increasingly accessible in regions like Svalbard, thanks to new missions supported by international and national space agencies. However, in-situ observations in the Arctic demand substantial logistical efforts, highlighting the need for an intermediary layer of observations to bridge the gap between these distinct data sources (Salzano et al. 2021b). Ensuring temporal alignment between satellite overpasses and field-based campaigns is a primary task, one that can be resolved by deploying automated stations with higher temporal resolution compared to spaceborne or airborne platforms. The COVID-19 pandemic also underscored the importance of having backup solutions in case of disruptions to fieldwork (Jawak et al. 2021). In line with these considerations, SIOS has supported the transition from a survey focused on terrestrial photography applications (Salzano et al. 2021a) to a time-lapse camera network specifically designed for cryospheric studies, particularly snow cover monitoring. Building upon the recommendations of the PASSES initiative, the SIOS Snow Pilot project played a vital role in establishing a time-lapse camera network in Svalbard, following the guidelines outlined in Salzano et al. (2022). This update chapter encompasses several key elements: an updated survey of terrestrial applications for snow cover monitoring, the conceptual framework of the service associated with the time-lapse camera network, and the potential synergies offered by time-lapse cameras in describing the snow melting process during the snow season, in conjunction with satellite and in-situ observations.

2. Moving from single applications to an integrated data service

2.1. The updated survey

Analysing published papers that employ time-lapse cameras in Svalbard provides valuable statistics for comprehending the evolution of applications and technologies in remote regions. The results presented in this survey were obtained using the same methodology as defined in Salzano et al. (2022). To gather these scientific publications, we employed the Scopus platform and used the query string "(time-lapse OR camera OR photography OR webcam) AND Svalbard" to search within paper titles, abstracts, and keywords. As of 31 August 2023, we identified a total of 186 articles (the list is available online (Salzano et al. 2023), with institutes from Norway, the United Kingdom, France, Italy, Sweden, the United States, and Poland being the most prominently represented. The observed trend exhibits growth, doubling every ten years, with two significant increments occurring in 2007 and 2019. The initial surge in publications can be attributed to the widespread adoption of digital cameras over film devices. The second notable increase may be attributed to the development of smart CMOS sensor modules, the growing utilization of IoT solutions, and potentially the impact of the COVID-19 pandemic. This observed pattern aligns with the broader trend of more publications on the application of time-lapse cameras for monitoring snow cover. Overall, the numbers are notably higher, as the applications extend far beyond the scope of Svalbard, encompassing a diverse range of research areas.

2.2. Establishing a time-lapse camera network in Svalbard.

The PASSES initiative is a success story, demonstrating how individual applications, backed by various national institutions, came together to shape a shared protocol, and collaborate on establishing a regional sensor network under the auspices of SIOS (Figure 1). The consortium behind the Snow Pilot project, with support from SIOS, used the knowledge and recommendations outlined in the SESS reports (Salzano et al. 2021a; 2022) as a starting point. The development of the time-lapse camera network entailed diverse contributions, including establishing necessary infrastructure, designing a streamlined data processing chain, and conceptualizing the service itself. The first component involved identifying architectural nodes and optimizing existing observing facilities.

Three sites were selected based on the survey of existing applications and those facilities were integrated to increase the observing capacities and to fill the identified gaps. The network will cover an ideal N-S transect across Svalbard (Figure 2) with large flat areas easily recognizable by satellite platforms (Ny-Ålesund, Adventdalen and Hornsund).

The optimisation of the network in Ny-Ålesund will be finalised in 2024 by adding a new camera system to enhance coverage over the Bayelva catchment, which is already partially covered by sensors operated by the Norwegian Polar Institute (NPI) and the National Research Council of Italy (CNR) at the Amundsen-Nobile Climate Change Tower. Furthermore, the network will expand to year-round coverage of Adventdalen, where monitoring will involve installing a device within a UNIS facility

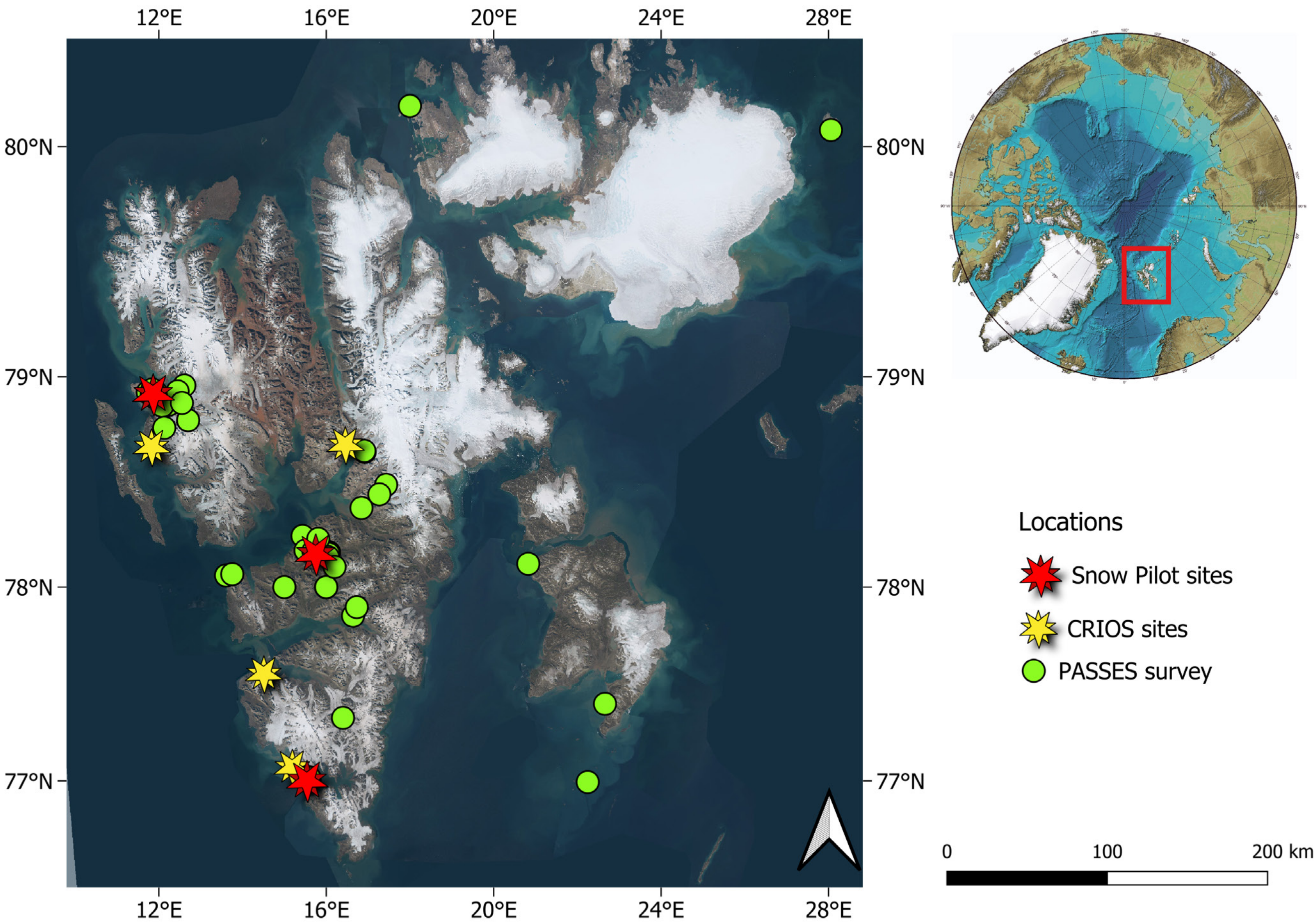

Figure 1: Locations of all current cameras in the network as identified by the survey in 2023. In addition, new cameras installed through two recent projects, the SIOS snow pilot[1] and CRIOS[2].

1 https://sios-svalbard.org/SnowPilot2022
2 https://crios.pl/

with support from NPI. Lastly, the Hornsund area will complete the transect, featuring a redesigned asset operated by the Institute of Geophysics of the Polish Academy of Sciences (IG PAS). The logistics for these installations is an ongoing challenge, complicated by permitting and safety issues that we aim to resolve soon. While the Snow Pilot project contributed the network's most advanced hardware (three Harbotronics Cyclapse systems with the 24.2-megapixel sensor resolution), data processing has been designed to manage a wide range of image formats. The designed infrastructure will be the backbone of an additional Cryosphere Integrated Observation Network on Svalbard (CRIOS) that will be operational in 2024.

Designing the data processing chain necessitated an analysis of various tasks, with a focus on identifying solutions primarily based on open-source libraries. The description of each chain component, as well as the identified software solution, is available at the PASSES website[3].

2.2.1. Image pre-screening

The first task involves image pre-screening to identify and discard corrupted images and those affected by bad weather conditions. This is achieved by examining metadata associated with each image file, including image size and pixel resolution. This initial check helps us detect data corruption and issues related to server accessibility. Additional

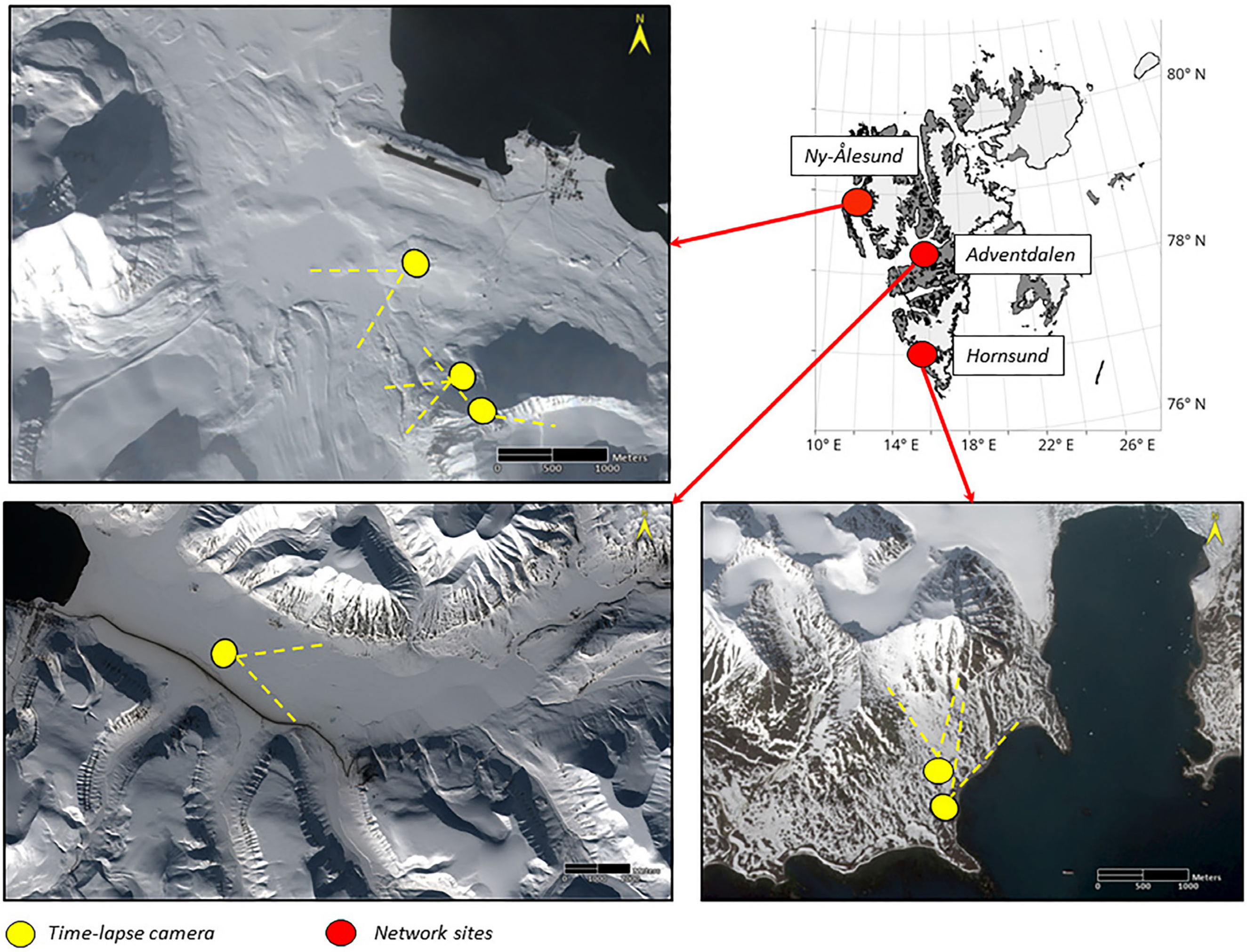

Figure 2: Camera views in the three selected sites contributing to the Svalbard camera network. While the Snow pilot site in Hornsund started to acquire images in summer 2023, the other sites will be installed and activated in 2024.

3 https://passes.cnr.it/Algorithm.html

analysis of RGB values and image patterns supports identification of scenes with low illumination or intense cloud cover. An additional filter is used to remove any image with lens interferences, such as raindrops or ice crusts.

2.2.2. Image radial distortion correction

Image radial distortion is a major issue associated with sensor specifications. The removal of such distortion requires calibration of the time-lapse camera using a reference chessboard. This procedure involves capturing at least six images of the chessboard at close range from the camera, with different orientations. The ultimate goal of this task is to determine intrinsic lens features for correcting lens distortion.

2.2.3. Image othoprojection

Geometrical projection requires information about the camera orientation and sensor specifications. The orthorectification process corrects the perspective view using methods outlined by Corripio (2004), and it relies on a digital elevation model. Ground control points are essential for assessing the accuracy of this correction.

2.2.4. Image segmentation

Image segmentation is based on the spectral similarity approach, as proposed by Salzano et al. (2019). This module measures spectral variations in a 3D colour space, where the reference endmembers are the theoretical "white" snow and a theoretical "black" target. Parameters estimated in this vector system include the spectral angle, and the Euclidean distance, calculated with respect to references. While spectral similarity is an independent spectral feature, the Euclidean distance of the vector is brightness-dependent. Considering all three-colour components allows for discriminating between snow, shadowed snow, and non-snow areas. Pixel density helps in delineating cluster limits, which are determined based on frequency distribution and Mahalanobis distance.

2.2.5. Image classification

Classification of surface types (snow, non-snow, and shadowed snow) depends on a set of rules that describe a decision tree (Salzano et al. 2019). This tree examines frequency distributions of pixels in the new spectral space, evaluates homogeneity of reflective behaviour, and assesses cluster fragmentation.

2.2.6. Data service prototype

The data service prototype operates in two modes: near-real time and full analysis. In the near-real time option[4], users can select and view camera system images in RGB format. This mode provides rapid processing without the need for projection and offers an estimated snow cover fraction. The snow cover identification is based on an automated linear classifier that relies on thresholding of the blue channel (BT), as introduced by Salvatori et al. (2011). This method involves counting the frequency of the blue component and defines the snow–not-snow boundary by examining increments in the blue-channel histogram. However, it is important to note that this method has limitations and may be affected by factors such as lighting conditions, surface roughness, and camera distance, which can impact its accuracy in snow cover estimation.

The second mode generates a yearly data product by combining the classification output with the ortho-projection procedure. This delivered product pertains to the fractional snow-covered area (FSCA) and is presented as a grid. The grid is derived from specific satellite products, including Sentinel-2, Landsat 8, or MODIS. The data format adheres to the NetCDF standard format, with metadata defined in accordance with the ISO 19115 guidelines and the Climate & Forecast convention.

2.3. The contribution for assessing the impact of extreme events on the snow cover

The availability of highly time-resolved datasets on seasonal snow cover is crucial for comprehensively

4 https://passes.cnr.it/Classification.html

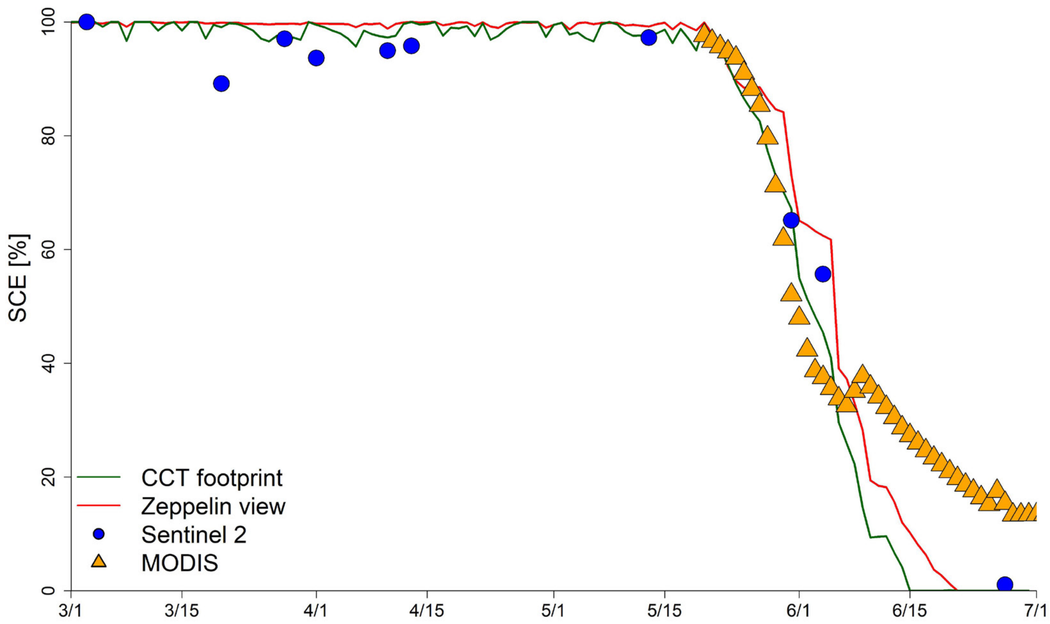

Figure 3: Comparison between snow-off day estimations obtained by satellite observations (Sentinel-2 and MODIS), and by terrestrial photography with the CCT instrument footprint (about 20 m) and the Zeppelin webcam over Ny-Ålesund in 2022. Data for terrestrial photography and Sentinel-2 are from Salzano et al. (2023), those related to the MODIS sensor were obtained from Vickers et al. (2020).

assessing the evolution of the Arctic ecosystem, as it allows us to combine data from various spatial and temporal scales. In cryospheric studies, a key metric for understanding the snow season is the end of the melting season, which can be determined using various EO data sources. Satellite data offer reliable observations but come with specific limitations depending on the spaceborne platform. Instruments like MODIS on the Terra and Aqua platforms provide medium spatial resolution (ranging from 250–500 metres) and offer daily overpasses, with the main limitation being occasional cloud cover in Svalbard. On the other hand, platforms like Sentinel-2 and Landsat 8-9 provide higher spatial resolution (around 10–30 metres), allowing for more detailed surface cover descriptions. However, their revisiting time is less frequent, and they are susceptible to cloud cover interference. From this perspective, terrestrial photography plays a significant role in continuously describing surface conditions. It serves as a ground-truth reference, offering a more reliable spatial representation when compared to data from in-situ automated stations (Figure 3).

The contribution of novel EO infrastructures is expected to play an increasingly vital role in coming years, as phenomena associated with climate change in the Arctic emerge. One such phenomenon is the rising frequency and intensity of warm spells, even at high latitudes. These extreme events involve the recurrent influx of wet and warm air masses into Arctic coastal regions, leading to periods of unpredictable and prolonged warmth in the lower atmosphere. These warm spells can also bring about liquid precipitation, leading to what is known as "rain-on-snow" events. What makes warm spells particularly concerning is their occurrence during the winter season before the snow melting season begins. A case study from Ny-Ålesund illustrates this scenario (Salzano et al. 2023). A rain-on-snow event on March 16, 2022 resulted in the first significant reduction in snow cover and the release of a significant amount of water in late March (see Figure 4). Automated stations recorded that this initial warming event did not lead to a significant reduction in snow water equivalent (SWE), indicating that, at least in flat areas, only moisture and ripening processes occurred within the snowpack. Subsequent solid precipitation events continued until mid-May when another warm spell impacted the area, marking the onset of the actual melting season. By the end of the melting season, the SWE content had completely

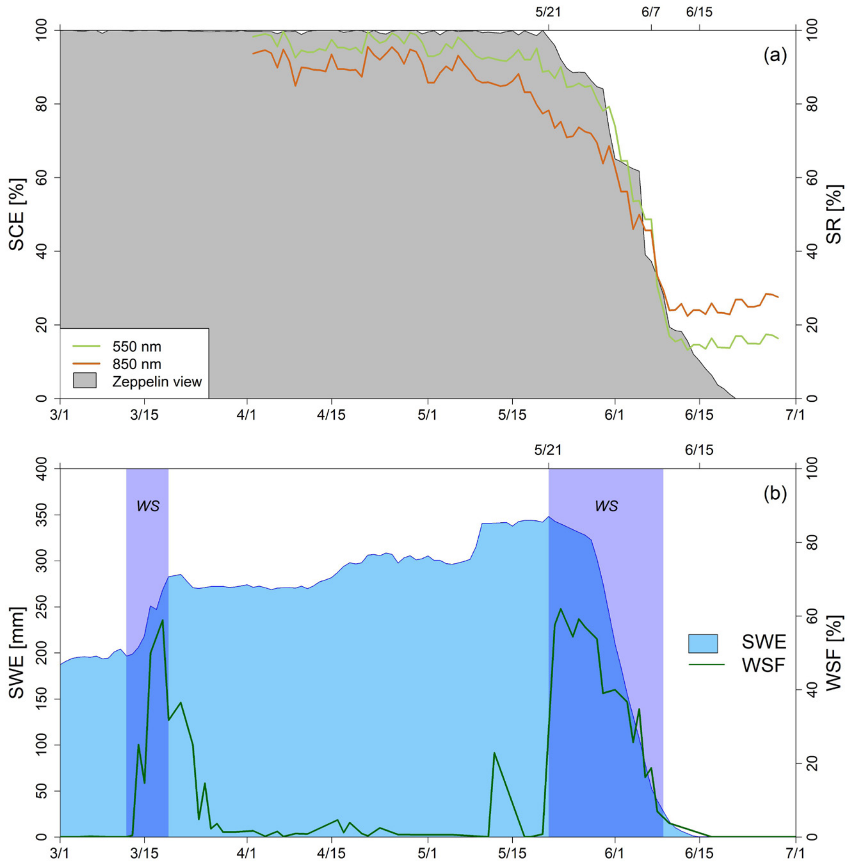

Figure 4: Evolution of snow cover extent (SCE) obtained by terrestrial photography in Ny-Ålesund in 2022. While surface reflectance (SR) and snow water equivalent (SWE) were observed by an automated station located close to the Amundsen-Nobile Climate Change Tower (Salzano et al. 2023), the wet snow fraction (WSF) was retrieved by microwave remote sensing (Vickers et al. 2022). Warm spells (WS) are marked with vertical blue areas.

diminished, indicating widespread melting across the area. The optical properties of the surface snow remained relatively stable, with high spectral reflectance (SR), until early May. Minor fluctuations in spectral components occurred before this time, typically associated with fresh snowfall and wind transport. From May onwards, a gradual reduction in both visible and near-infrared spectral reflectance was observed due to ongoing snow melt.

The evolution of SWE and SR closely aligned with observations from terrestrial photography, providing insights into the timing of snow melting at various spatial scales. Considering the footprint of sensors, limited to a 20-metre radius from the observation platforms where automated stations were deployed, both SWE and Snow Cover Extent (SCE) indicated that the snow melting period was essentially complete by June 15th. Results obtained from both satellite and terrestrial platforms, looking at the entire catchment area, showed the snow cover was essentially gone on June 21, six days later. It is worth noting that satellite data provided more detailed surface information compared to terrestrial photography. Spaceborne platforms are equipped with highly efficient multi-spectral sensors, particularly suited for distinguishing between different surface types, especially in the near-infrared wavelength domain. For further insights into the observed dynamics, microwave sensors, as described by Vickers et al. (2022), were employed. These sensors allowed measurement of the Wet Snow Fraction (WSF), confirming the impact of warm spells during the snow season. The first event was characterised by a significant temperature decrease in the following days, coupled with significant wind, surface water refreezing, and the formation of an ice crust over the snow cover. The second event completed the melting process, resulting in the complete disappearance of the snow cover.

3. Contributions to interdisciplinarity

The presented chapter completes the description of terrestrial photography applications on the snow cover. The presented data chain is a flexible tool for processing data from different sensors. The near-real-time processing will be active in 2024 thanks to the Snow Pilot project. Guidelines about calibrating cameras are available on the PASSES webpage[5]. The presented infrastructure will support cryospheric studies and remote sensing applications, but several contributions to other disciplines are already feasible.

The description of snow seasonality will contribute to studies about Arctic ecosystems, providing metrics suitable for assessing the state of permafrost and vegetation. Atmospheric studies will gain information on the occurrence and impact of phenomena such as warm spells and rain-on-snow events. Finally, data integration will surely be involved in studies about surface hydrology, providing solutions for assessing the evolution of the surface drainage system.

4. Unanswered questions

PASSES has matured considerably since 2020 and will soon provide the scientific community working in Svalbard with versatile infrastructure that serves various purposes. The network will be completed in 2024 once various safety and permission issues have been solved. The camera in Hornsund is active since summer 2023, the remaining in Adventdalen and Bayelva will be installed in winter-spring 2024. This update underscores the crucial role of integrating terrestrial photography with satellite remote sensing. While the potential for cryospheric studies is evident, further integration of the infrastructure would also open new avenues for vegetation studies.

5. Recommendations for the future

Terrestrial photography offers many opportunities for research on snow cover and related topics, but several problems and knowledge gaps limit its full use. We suggest the following actions that the SIOS community can take to support research in this field:

1. Promote projects that use time-lapse cameras, especially in the more remote areas of Svalbard. Use fog and edge computing to enable the use of IoT systems, aiming to overcome data transfer limitations.
2. Support the maintenance of the Svalbard camera system network with a multi-sensor data service for processing images captured for snow cover applications.
3. Foster the integration of terrestrial photography with satellite remote sensing by developing machine learning and artificial intelligence techniques.
4. Encourage the use of time-lapse cameras across disciplines where high-resolution temporal information can be useful for various purposes, including glaciology, hydrology, plant and animal ecology, coastal processes, sea ice tracking, and satellite imagery calibration and validation (Cal/Val).

5 https://passes.cnr.it/Calibration.html

6. Data availability

Dataset	Parameter	Period	Location	Metadata access (URL)	Dataset provider
Survey about time-lapse cameras applications on snow in Svalbard	Time-lapse cameras	1980–2023	Svalbard	https://metadata.iadc.cnr.it/geonetwork/srv/eng/catalog.search#/metadata/9511477e-82d0-4ad2-a0f1-5d01792058ef	IADC
Fractional Snow-Covered Area (FSCA) in Ny-Ålesund	FSCA	2022	Ny-Ålesund	https://metadata.iadc.cnr.it/geonetwork/srv/eng/catalog.search#/metadata/8ca8d01c-2e4d-4e1d-bf7c-450a58a9da63	IADC

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8. References

Corripio JG (2004) Snow surface albedo estimation using terrestrial photography. Int J Remote Sens 25(24):5705-5729 https://doi.org/10.1080/01431160410001709002

Jawak SD, Andersen BN, Pohjola VA, Godøy Ø, Hübner C, Jennings I et al. (2021) SIOS's Earth Observation (EO), Remote Sensing (RS), and Operational Activities in Response to COVID-19. Remote *Sens 13(4):712* https://doi.org/10.3390/rs13040712

Salvatori R, Plini P, Giusto M, Valt M, Salzano R, Montagnoli M, Cagnati A. Crepaz G, Sigismondi D (2011) Snow cover monitoring with images from digital camera systems. Ital J Remote Sens 43 (2):137–145. https://doi.org/10.5721/ItJRS201143211

Salzano R, Aalstad K, Boldrini E, Gallet JC, Kępski D, Luks B, Nilsen L, Salvatori R, Westermann S (2021a) Terrestrial photography applications on snow cover in Svalbard. In: Moreno-Ibáñez et al (eds) SESS report 2020, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 236-251. https://doi.org/10.5281/zenodo.4294084

Salzano R, Killie MA, Luks B, Malnes E (2021b) A multi-scale approach on snow cover observations and models. In: Moreno-Ibáñez et al (eds) SESS report 2020, Longyearbyen, Svalbard Integrated Arctic Earth Observing System, Longyearbyen pp. 252–256. https://doi.org/10.5281/zenodo.4294092

Salzano R, Aalstad K, Cerrato R, Luks B, Salvatori R, Westermann S (2022) Improving terrestrial photography applications on snow cover in Svalbard with satellite remote sensing imagery. In: Feldner et al (eds) SESS report 2021, Longyearbyen, Svalbard Integrated Arctic Earth Observing System, Longyearbyen pp. 56–65. https://doi.org/10.5281/zenodo.5751867

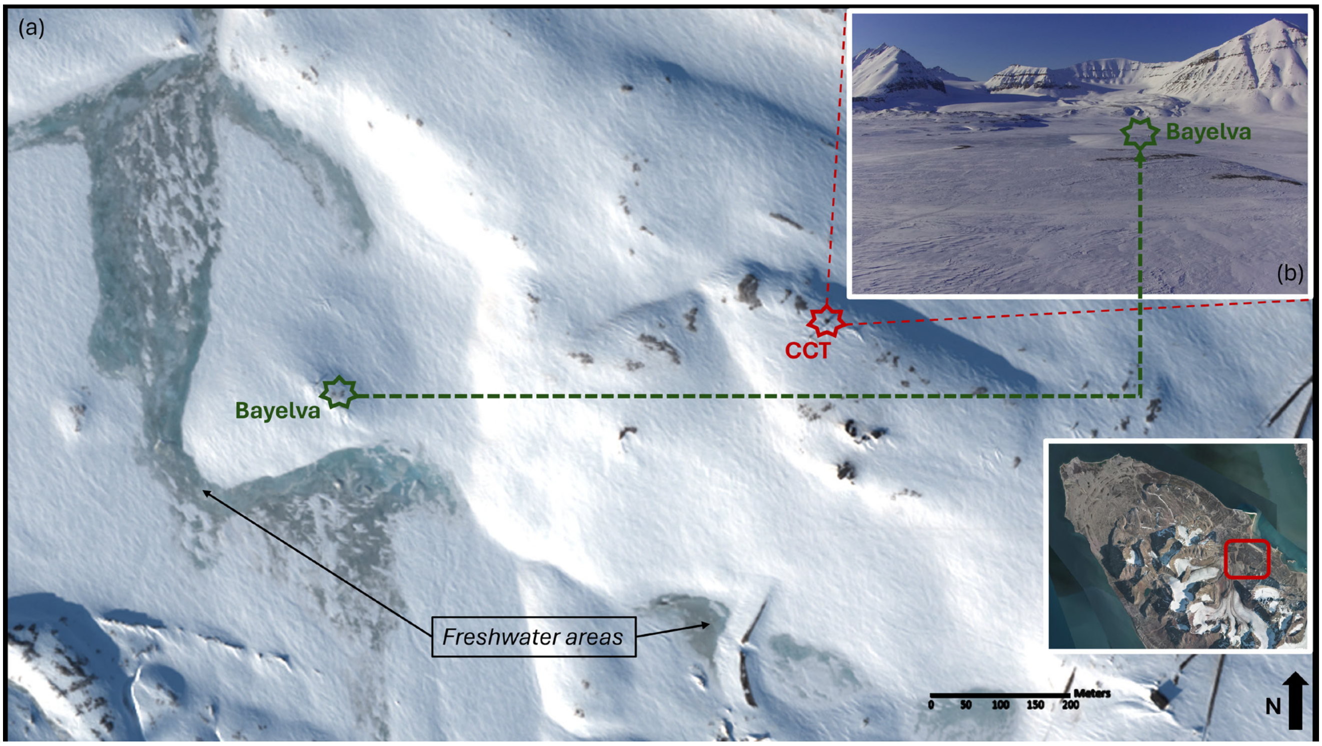
Salzano R, Salvatori R, Cerrato R (2023) Svalbard time-lapse cameras [Data set]. Zenodo. https://doi.org/10.5281/zenodo.10125304

Salzano R, Cerrato R, Scoto F, Spolaor A, Valentini E, Salvadore M, Esposito G, Sapio S, Taramelli A, Salvatori R (2023) Detection of Winter Heat Wave Impact on Surface Runoff in a Periglacial Environment (Ny-Ålesund, Svalbard). *Remote Sens 15(18):4435*. https://doi.org/10.3390/rs15184435

Salzano R, Salvatori R, Valt M, Giuliani G, Chatenoux B, Ioppi L (2019) Automated Classification of Terrestrial Images: The Contribution to the Remote Sensing of Snow Cover. *Geosciences 9(2):97* https://doi.org/10.3390/geosciences9020097

Vickers H, Karlsen SR, Malnes E (2020) A 20-Year MODIS-Based Snow Cover Dataset for Svalbard and Its Link to Phenological Timing and Sea Ice Variability. Remote Sens 12(7):1123 https://doi.org/10.3390/rs12071123

Vickers H, Malnes E, Eckerstorfer M (2022) A Synthetic Aperture Radar Based Method for Long Term Monitoring of Seasonal Snowmelt and Wintertime Rain-On-Snow Events in Svalbard. Front Earth Sci 10:2022. https://doi.org/10.3389/feart.2022.868945



The drainage system in the Bayelva catchment (a) after the extreme event in Ny-Ålesund on March 2022 (Worldview image acquired on 3 April 2022). (b) The same condition viewed from the Amundsen-Nobile Climate Change Tower (CCT) on 3 April 2022. (Photo: Roberto Salzano)

Satellite and modelling based snow season time series for Svalbard: Intercomparisons and assessment of accuracy (SATMODSNOW 2)

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1. Introduction

In Svalbard, snow cover characteristics are changing rapidly due to ongoing climate warming and associated trends of increasing temperature and precipitation. These climatic changes have resulted in earlier disappearance of seasonal snow with later onset of snow in autumn, have raised the altitude of the equilibrium line perennial snow (van Pelt et al., 2016), decreased maximum snow depths and increased the frequency of winter rain-on-snow events (Hansen et al., 2011; Peeters et al., 2019; Vickers et al., 2022). During the last few decades, datasets for snow cover and snow water equivalent in Svalbard have been built up through use of both remote sensing methods and snow models. To build a complete, consistent, and accurate picture of snow cover evolution in Svalbard, how it has been changing and is going to change in the future, there is a need to assimilate data from snow models and observations. Remote sensing can provide observations over large spatial areas at higher resolution but lacks temporal consistency due to issues such as cloud cover. While snow models can provide consistent and spatially complete data over large scales, their resolution is often too coarse to accurately represent the true spatial variability in snow cover. Moreover, snow models are often calibrated using remote sensing observations as well as large-scale numerical analysis, while remote sensing observations often rely on models for validation due to a lack of ground observations over large spatial scales. There is therefore a need to examine the similarities and differences between the different models and sensors, as well as between datasets of different spatial resolution, to determine how they can be used to complement each other and fill in knowledge gaps regarding patterns and changes in snow cover in Svalbard. This work builds on the earlier SESS report chapter SATMODSNOW (Malnes et al., 2021) where snow model products were compared with remote sensing datasets to fulfil two objectives. First, to identify where models and remote sensing datasets differ both temporally and spatially, and second, to cross-compare satellite remote sensing datasets across a range of scales. A long-term goal will be to use high resolution data from newer sensors to downscale and reconstruct long time series of snow cover patterns measured using older, lower resolution sensors. Since the report chapter SATMODSNOW was published, new snow cover datasets have become available, as well as additional years with data building on the existing datasets. In SATMODSNOW2 the earlier analyses are repeated and updated using the additional datasets that are now available. This is done not only to solidify earlier results but also to identify outstanding challenges associated with snow cover mapping and make recommendations for future snow research in Svalbard.

2. The state of snow cover datasets in Svalbard

Several remote sensing and snow model datasets provide coverage over Svalbard, spanning a time frame from 1982 to present day. In the earlier SATMODSNOW report (Malnes et al., 2021) a rigorous description of the available datasets was provided in sections 2.1 and 2.2. In this update we have primarily focused on the datasets that have been updated with additional years of data as well as giving an overview of new datasets that have been analysed since the earlier report. In terms of the two remote sensing datasets, 3 additional years of MODIS data have been included (2020-2022) while the AVHRR dataset includes 4 additional years of binary snow cover extent (SCE) data, now providing coverage for 2000–2019. The MODIS snow cover fraction dataset with its 500 m spatial resolution, forms the basis for the comparisons with other remote sensing and model datasets in this report. The seNorge snow model (Saloranta, 2016), which earlier covered only full years from 2013–2019, now also includes 3 additional years, while the Energy Balance-Firn Model (EBFM) provided by Uppsala University (van Pelt et al., 2012; van Pelt et al., 2019) includes 5 more years and covers the same time frame as the MODIS dataset (2000–2022).

In addition, the snow project of the ESA Climate Change Initiative (CCI) programme has resulted in the production of a Daily Snow Cover Fraction on Ground (SCFG) product with worldwide coverage, including Svalbard, at 1 km resolution and is based on MODIS Terra data. A thorough overview of this product as well as the algorithms used to retrieve SCFG are presented by Nagler et al. (2022). While the data source is the same as for the MODIS dataset referred to in this report, the differing retrieval and cloud masking approaches, as well as land and water masks applied to each product, renders a comparison of the two datasets necessary. This study uses version 2.0 of the SCFG product which covers 2000–2020. Since there are no forests in Svalbard, there should be no difference between the SCFG and MODIS snow cover fraction (SCF) product, which would otherwise observe the top of the canopy. In this study, the CCI SCFG data are remapped to match the 500 m MODIS SCF grid.

To extend the time series of MODIS snow cover fraction, Notarnicola (2022) proposes a hybrid model to merge satellite data and model simulation through a machine learning approach. More specifically, the modelled data are derived from the simulation of the Famine Early Warning Systems Network (FEWS NET) Land Data Assimilation System (FLDAS, https://ldas.gsfc.nasa.gov/fldas), which is produced on a monthly basis with global coverage at a spatial resolution of 0.1° x 0.1° (10 km × 10 km). The model simulations are available from 1982 to present. In the period of overlap with MODIS time series, SCF time series of modelled and MODIS data were compared, and a machine learning approach based on Artificial Neural

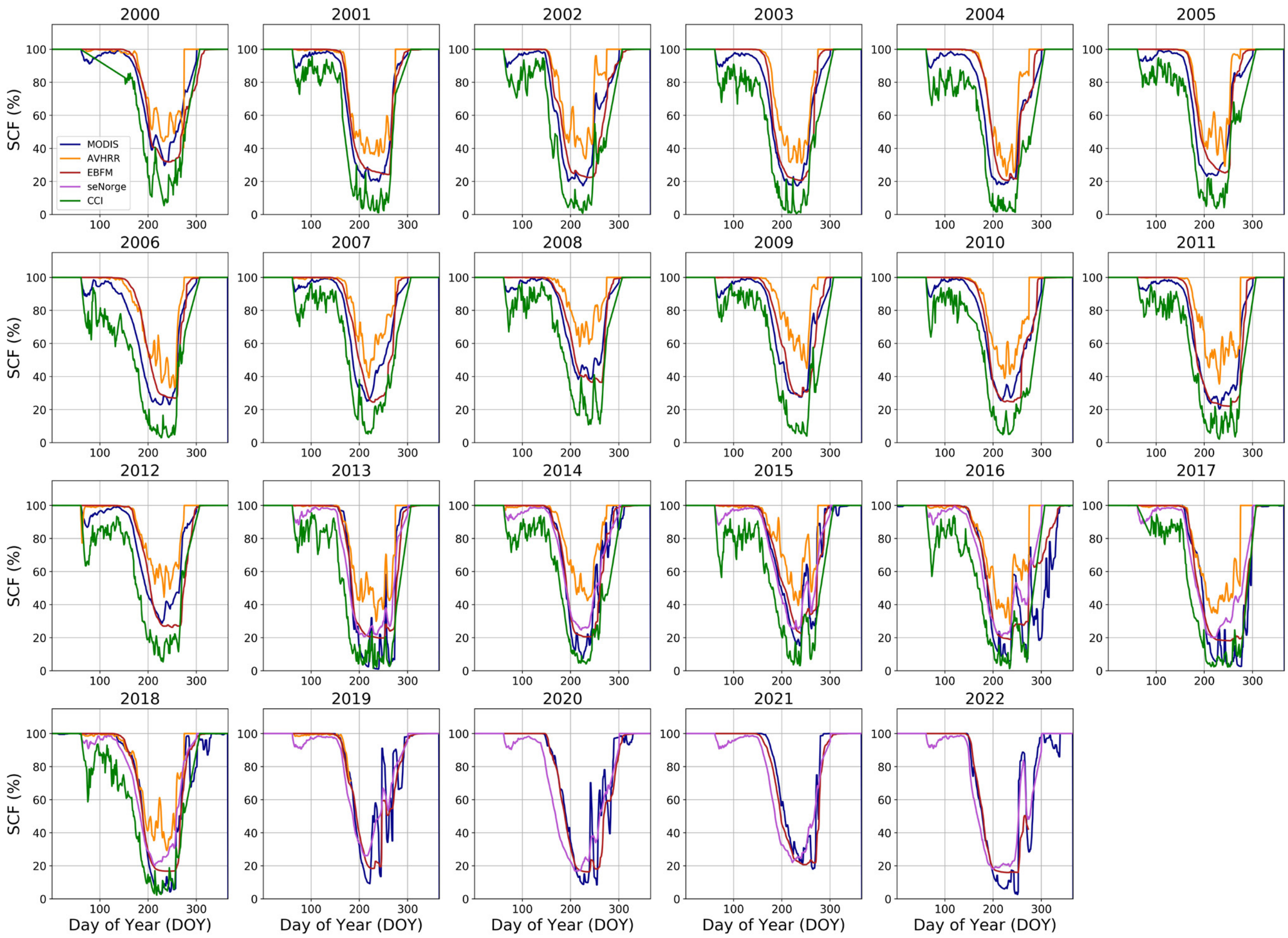

Figure 1: Time series of snow-covered fraction (SCF) for all datasets

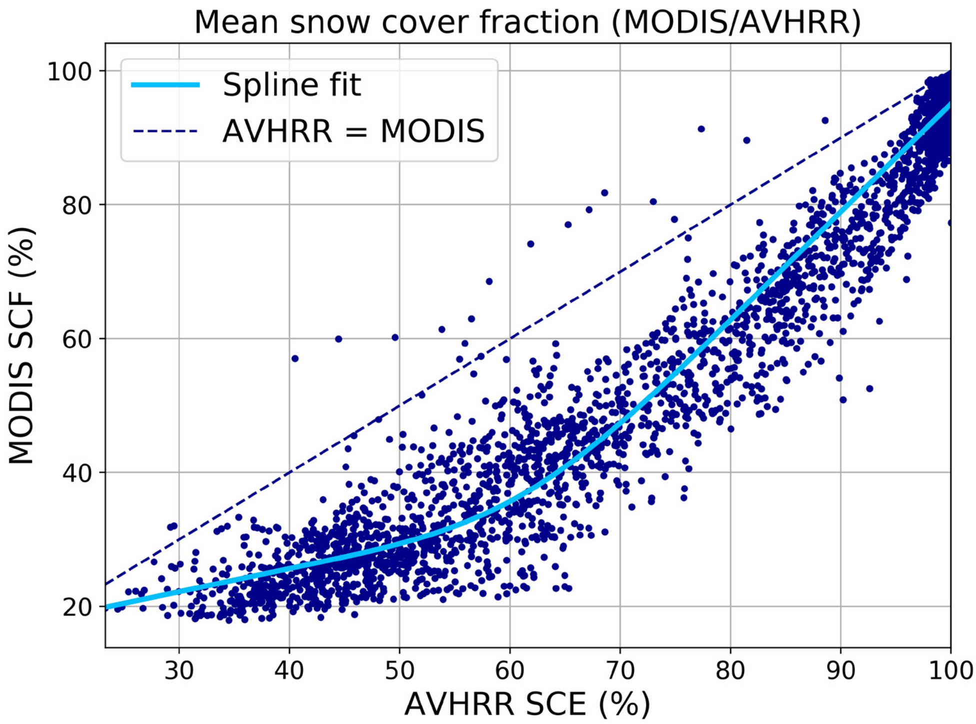

Figure 2: Scatter plot illustrating the relationship between the MODIS land-averaged SCF and AVHRR land-averaged SCE for the 20 overlapping years of data. Each point represents a daily value.

Networks was used to calibrate the modelled data with MODIS observations to reduce biases and improve the spatial representativeness due to the model coarse resolution. While this dataset is based on the MODIS time series, a major difference in the calculation of the yearly mean SCF is the inclusion of glaciated areas since Notarnicola (2022) focused on snow cover in mountain areas only, while the MODIS dataset of Malnes et al. (2021) considers snow on land areas only.

For all datasets, we have focused on (i) comparisons of the land-averaged snow cover fraction, which is calculated for each day of year and all the years of each dataset and (ii) differences in the number of days with snow cover. The methods used to obtain the land averaged SCF, and duration of snow cover, are already outlined in section 2.3 of the original SESS report chapter (Malnes et al., 2021).

2.1. 2.1 Comparison to other remote sensing datasets

2.1.1. AVHRR (20 years) 2000–2019 (+4 years)

The additional 4 years of binary snow-covered extent (SCE) data did not bring about any new changes to the earlier derived relationship between MODIS and AVHRR, or the spatial variation in the difference in number of days with snow across the archipelago. We find that the land-averaged SCE in AVHRR is greater than the land-averaged SCF in the MODIS dataset throughout the year, as shown by the time series comparison in Figure 1. This is likely attributable to the large difference in resolution of the two datasets, with the coarse resolution AVHRR sensor not allowing partially covered grid cells to be resolved. The scatter plot in Figure 2 displays the relationship between the MODIS SCF and AVHRR SCE, with a dashed line indicating where values would be equal in both datasets.

2.1.2. CCI SCFG (20 years) 2000–2019

In Figure 3, we illustrate the relationship between the 500 m MODIS SCF product and the ESA CCI SCFG product based on a 1 km grid. The figure also shows the daily cloud cover fractions for the two datasets. The 500 m MODIS SCF is consistently greater than the corresponding 1 km CCI SCFG, with the greatest difference in snow cover at sub-maximum values, typically on the order of around 20% greater than CCI SCFG. The corresponding cloud cover fractions show a significant contrast

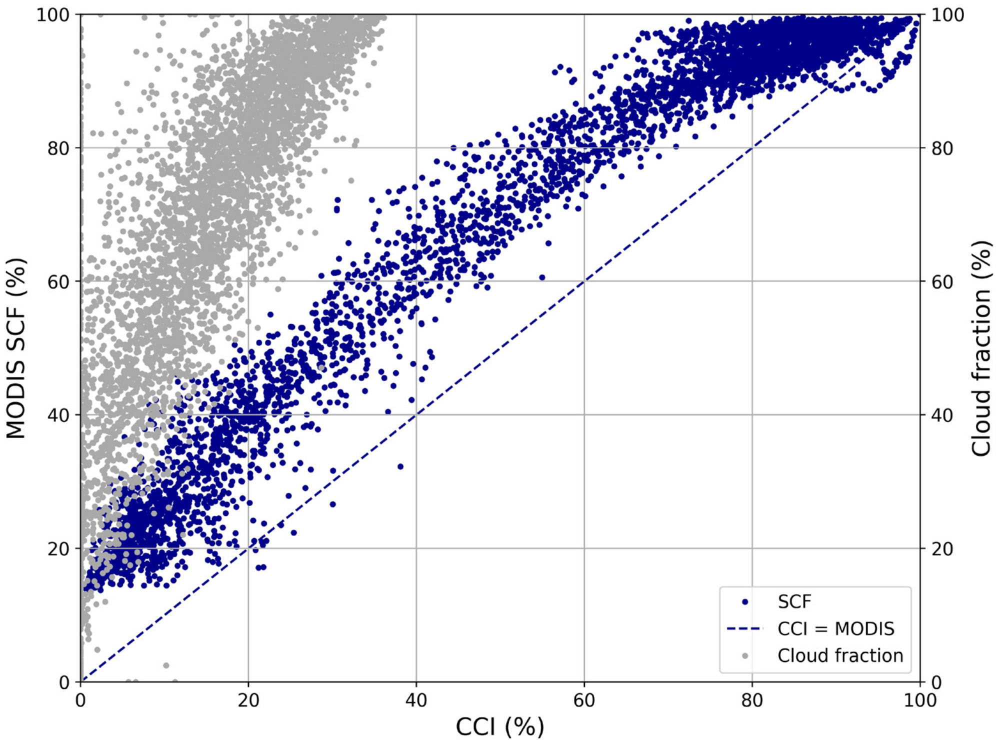

Figure 3: Scatter plot illustrating the relationship between the 500 m MODIS SCF, and the ESA CCI 1 km MODIS SCFG dataset (dark blue) and the cloud pixels (grey) detected in each dataset.

in cloud detection in the two datasets, with cloud cover being much greater in the MODIS 500 m product compared to the CCI SCFG product, which generally always detected below 40% cloud cover fraction, while the MODIS 500 m product detected much greater cloud cover of up to 100% on many occasions. However, if snow-covered pixels in the MODIS 500 m product have been incorrectly classified as cloud, giving rise to high cloud detection, one would expect a correction to result in less cloud but greater snow cover, increasing the difference between the two datasets, suggesting that this may not necessarily be the main driver of the observed snow cover fraction differences.

2.1.3. Hybrid model

The "hybrid" dataset which uses machine learning methods to combine MODIS and model measurements provides yearly averages of the land-averaged SCF for mountainous areas of Svalbard, where the SCF is averaged over the hydrological year (1 October – 30 September). Averaged daily land SCF using the MODIS 500 m data was averaged across the hydrological year to compare with this dataset. Figure 4 illustrates the time series for the period 2000–2019. Yearly variations in mean SCF for the two datasets are correlated with each other; however, the hybrid MODIS-model SCF product is typically 5-10% greater than the 500 m MODIS product. Note that the main differences between the datasets are that the hybrid model (i) does not include any cloud gap filling procedure and (ii) includes glaciers in the yearly average, whereas the MODIS 500 m product is based on non-glacial land areas.

2.2. Comparison with snow model datasets

2.2.1. seNorge (10 years) 2013–2022 (+3 years)

For seNorge, the additional 3 years of data increases the number of data points for comparison by nearly 50% with respect to the 7 years of data that were used in the earlier SESS report. However, the relationship between the land-averaged snow-

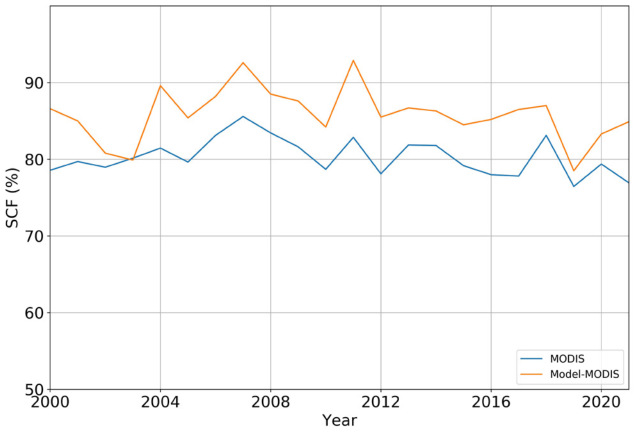

Figure 4: Time series of the hybrid MODIS–model SCF and the 500 m MODIS product.

covered area obtained from the seNorge dataset, and the land-averaged snow cover fraction from the MODIS dataset remains largely unchanged compared with the earlier result, as illustrated by Figure 8a of Malnes et al. (2021). For snow cover fractions at the minimum end of the scale, MODIS was typically greater than the seNorge dataset, while the opposite is true at the time of year when snow cover fraction was typically at maximum. Time series of the land-averaged snow cover fraction (Figure 1) reveal that some years exhibited a mismatch in timing of snowmelt onset and onset of snow in autumn between the two datasets, such that snowmelt occurred earlier in MODIS while snow covered area was still at a maximum in seNorge, giving rise to higher snow cover area in seNorge compared to MODIS, but the onset of snow in autumn was also later in seNorge, meaning that MODIS snow-covered fraction was increasing while seNorge snow-covered area was still at a minimum. However, the time series of land-averaged snow cover fraction masks information on the spatial variation in differences in timing of snowmelt/snow-on; Figure 5 displays the difference in number of days with snow cover (SCA or SCF > 50%) between the seNorge dataset and MODIS dataset. Here it can be seen that across Edgeøya, the seNorge dataset typically has a greater number of days with snow cover compared to MODIS, whereas across low elevation areas in Nordenskiöld Land, seNorge exhibits fewer days with snow compared to MODIS, with differences typically in the range of ±20–40 days.

2.2.2. EBFM (23 years) 2000–2022 (+5 years)

Similar to the results of the comparisons between the MODIS SCF and the AVHRR and seNorge datasets, we found that the additional 5 years of snow water equivalent (SWE) data did not change the statistical relationship between the MODIS SCF and SCF derived from the EBFM SWE data; for low SCF days in the EBFM dataset, corresponding MODIS values were typically higher, while for high SCF days in the EBFM dataset, the MODIS values were lower than EBFM. This is likely due to the same reasons as for the seNorge dataset, where the model snow cover can be seen to start snowmelt slightly later than MODIS in several years (2004–2007, 2020–2021), and onset of snow cover lags MODIS in the autumn most years of the overlapping dataset. The result of this time lag in snowmelt and snow onset between the two datasets is a difference in number of days with snow cover that varies spatially across the archipelago as illustrated in Figure 5 (right panel). The EBFM dataset exhibits fewer days with snow compared to MODIS across large parts of Nordenskiöld Land, Nordaustlandet and Edgeøya; however, there are parts of northern Spitsbergen, eastern coastal areas of Nordenskiöld Land and western coastal areas of Edgeøya where there are a greater number of days with snow cover derived from EBFM SWE data compared to the MODIS dataset.

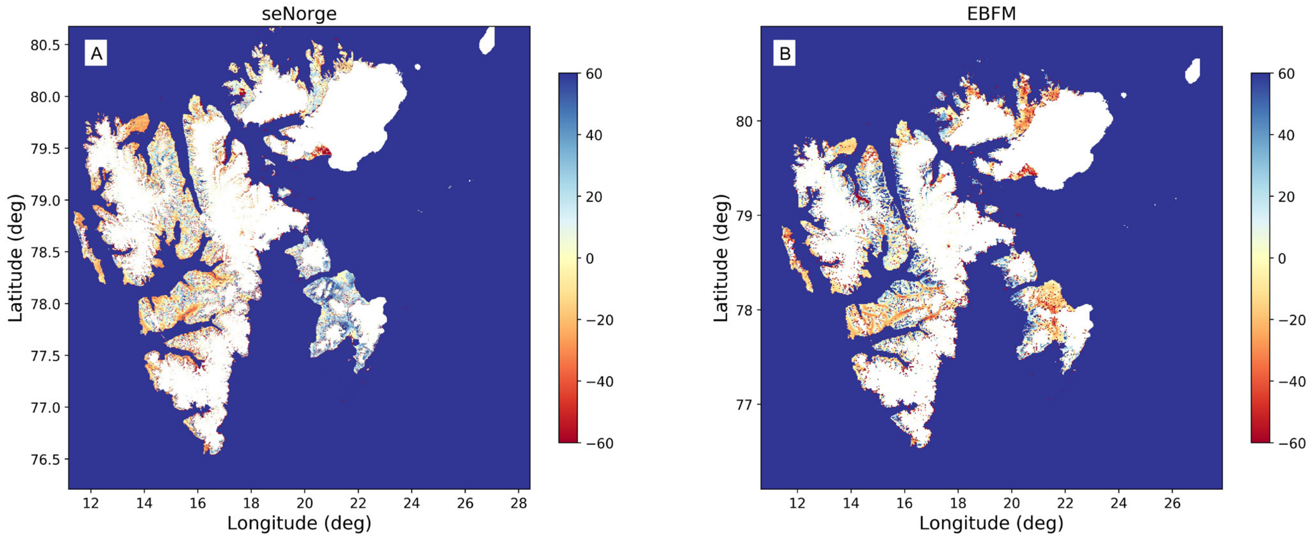

Figure 5: The difference in number of days with snow cover, comparing (a) the seNorge dataset to MODIS and (b) the EBFM model to MODIS. For both models, positive values (blue hues) indicate a greater number of days with snow while negative values (orange-red hues) indicate a greater number of days with snow cover in MODIS.

3. Contributions to interdisciplinarity

Snowmelt patterns – both temporal and spatial – are important for the transport of nutrients into rivers and fjords through surface runoff, as well as determining the timing of onset of vegetation growth in the spring. Seasonal snow cover acts as an important insulator for permafrost; wintertime snowmelt resulting from rain-on-snow events can contribute to degradation of permafrost as well as result in ice crusts that can present a physical barrier to forage for reindeer. Thus, datasets that allow monitoring of snowmelt in both space and time will be of value to research into terrestrial and marine ecological systems in Svalbard.

The long time series of snow models and observations are of importance to climate studies where spatial variations in trends in timing of snow disappearance and onset reflect spatial variations in changes in the large-scale drivers of snowmelt, including those of atmospheric and oceanic origin.

Advancements made since Malnes et al. (2021) primarily comprise the additional years of data made available to the SIOS database, as well as the inclusion of the ESA CCI SCFG dataset.

4. Unanswered questions

On a long-term perspective, the goal is to integrate both model and observations to produce an accurate representation of snow cover dynamics in Svalbard. Differences between different snow models, and between snow models and observations, do not uncover which dataset is more accurate than another; this requires a more thorough validation of each model and remote sensing method using ground observations. This should enable the development of an optimal method for assimilating observations into models or vice versa. However, since the current availability of consistent time series of ground observations of snow parameters across Svalbard is poor in terms of spatial coverage, development of the ground based observational network is greatly needed.

The findings of this study reveal that the differences in snow cover between models and remote sensing datasets vary spatially across the archipelago, and that models are systematically late with respect to timing of snowmelt and snow onset. However, without substantial improvement in availability of ground truth measurements, an improvement in both model and remote sensing products is not very probable at present.

5. Recommendations for the future

- Integrate high-resolution datasets e.g. Sentinel 2 with artificial intelligence (AI) methods to downscale coarse resolution data and thus provide more detailed information on snow cover dynamics.
- Increase the availability and diversity of ground truthing datasets. These could include more unmanned aerial vehicle (UAV) borne surveys providing high resolution snow observations as well as measurements of snow temperature and liquid water content.
- Integrate Synthetic Aperture Radar (SAR) wet snow datasets with snow cover from optical sensors (Vickers et al., 2022) to improve snow cover detection during the melting period on overcast days. SAR can also provide information on melting phases (Marin et al., 2020) which is important in the context of water resource management.

6. Data availability

Dataset	Parameter	Period	Location	Metadata access (URL)	Dataset provider
MODIS	Snow cover fraction	2000-2022	Svalbard	https://thredds.met.no/thredds/arcticdata/infraNOR.html?dataset=norcesnowcover-agg	NORCE
AVHRR	Snow cover extent	1982-2019	Svalbard	https://thredds.met.no/thredds/catalog/metusers/mariak/sios_SvalSCE_dataset/catalog.html	METNO
EBFM	Snow water equivalent	1957-2022	Svalbard	https://doi.org/10.6084/m9.figshare.13142840.v2	Uppsala University
seNorge	Snow covered area	2012-2022	Svalbard	www.senorge.no	NVE Jess Joar Andersen (jea@nve.no)
CCI	Snow cover fraction on ground	2000-2019	Worldwide	https://catalogue.ceda.ac.uk/uuid/8847a05eeda646a29da58b42bdf2a87c	ESA CCI
Hybrid MODIS/model	Snow cover fraction	1982-2022	Worldwide	Available on request	EURAC claudia.notarnicola@eurac.edu

7. Acknowledgements

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8. References

Hansen BB, Isaksen K, Benestad RE, Kohler J, Pedersen ÅØ, Loe LE, Coulson SJ, Larsen JO, Varpe, Ø (2014) Warmer and wetter winters: Characteristics and implications of an extreme weather event in the High Arctic. Environ Res Lett 9:114021. https://iopscience.iop.org/article/10.1088/1748-9326/9/11/114021

Malnes E, Vickers H, Karlsen SR, Saloranta T, Killie MA, Van Pelt W, Pohjola V, Zhang J, Stendardi L, Notarnicola C (2021) Satellite and modelling based snow season time series for Svalbard: Inter-comparisons and assessment of accuracy. In: Moreno-Ibáñez et al (eds) SESS report 2020, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 202–219. https://doi.org/10.5281/zenodo.4294072

Marin C, Bertoldi G, Premier V, Callegari M, Brida C, Hürkamp K., Tschiersch J, Zebisch M, and Notarnicola C (2020) Use of Sentinel-1 radar observations to evaluate snowmelt dynamics in alpine regions. The Cryosphere 14:935–956. https://doi.org/10.5194/tc-14-935-2020

Nagler T, Schwaizer G, Mölg N, Keuris L, Hetzenecker M, Metsämäki S (2022) ESA Snow Climate Change Initiative (Snow_cci): Daily global Snow Cover Fraction - snow on ground (SCFG) from MODIS (2000-2020), version 2.0. NERC EDS Centre for Environmental Data Analysis, 23 March 2022. https://dx.doi.org/10.5285/8847a05eeda646a29da58b42bdf2a87c

Notarnicola C (2022) Overall negative trends for snow cover extent and duration in global mountain regions over 1982–2020. Sci Rep 12:13731. https://doi.org/10.1038/s41598-022-16743-w

Peeters B, Pedersen AO, Loe LE, Isaksen K, Veiberg V, Stien A, Kohler J, Gallet J-C, Aanes R, Hansen BB (2019) Spatiotemporal patterns of rain-on-snow and basal ice in high Arctic Svalbard: Detection of a climate-cryosphere regime shift. Environ Res Lett 14:015002. https://iopscience.iop.org/article/10.1088/1748-9326/aaefb3

Saloranta TM (2016) Operational snow mapping with simplified data assimilation using the seNorge snow model. J Hydrol 538:314–325. http://dx.doi.org/10.1016/j.jhydrol.2016.03.061

Van Pelt WJ, Kohler J, Liston GE, Hagen JO, Luks B, Reijmer CH, Pohjola VA (2016) Multidecadal climate and seasonal snow conditions in Svalbard. J Geophys Res Earth Surface 121:2100–2117. http://dx.doi.org/10.1002/2016JF003999

Van Pelt WJJ, Oerlemans J, Reijmer CH, Pohjola VA, Pettersson R, van Angelen JH (2012) Simulating melt, runoff and refreezing on Nordenskiöldbreen, Svalbard, using a coupled snow and energy balance model. The Cryosphere 6:641–659. https://doi.org/10.5194/tc-6-641-2012

Van Pelt WJJ, Pohjola VA, Pettersson R, Marchenko S, Kohler J, Luks B, Hagen JO, Schuler TV, Dunse T, Noël B, Reijmer C (2019) A long-term dataset of climatic mass balance, snow conditions and runoff in Svalbard (1957-2018). The Cryosphere 13:2259–2280. https://doi.org/10.5194/tc-13-2259-2019

Vickers H, Malnes E, Eckerstorfer M (2022) A Synthetic Aperture Radar Based Method for Long Term Monitoring of Seasonal Snowmelt and Wintertime Rain-On-Snow Events in Svalbard. Front Earth Sci 10:868945. https://doi.org/10.3389/feart.2022.868945

Photo: Christiane Hübner

Arctic haze in a climate changing world: the 2010–2022 trend (HAZECLIC 2)

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1. Introduction

The Arctic region is warming at more than twice the rate of the global average, a phenomenon referred to as Arctic amplification – AA (Serreze and Barry 2011). Arctic ecosystems and inhabitants are heavily impacted by increased seasonal mean temperature, decreased sea ice thickness and extent, and permafrost destabilization (AMAP 2017). The triggers and feedback mechanisms of AA are not clearcut yet, and current climate models do not cover the complex local processes at play, particularly aerosol–climate interactions (Schmale et al. 2021). A key to understand the contribution of aerosols to AA is to characterize regional and seasonal processes including aerosol sources, transformation and resulting climate effects.

One of the most distinctive features of aerosol patterns in the High Arctic, including Svalbard, is a typical annual cycle with a maximum aerosol mass in late winter and early spring, commonly referred to as Arctic haze (Quinn et al. 2007). Haze chemical composition has been monitored on the seasonal scale at several sites in the Arctic since the early 1980s. No change in sulphate concentrations was observed during the 1980s, but in the 1990s they began to decline due to the decrease in S emissions from Eurasia, western Europe and North America (AMAP 2006). In the 2000s and 2010s, sulphate decline along the year is instead barely detectable (Sharma et al. 2019).

Nevertheless, monthly analysis showed that sulphate decrease from year to year mostly occurs during haze months and this was reasonably ascribed to anthropic sulphate. Here we confirm that this assumption is correct, by applying the same monthly analysis exclusively to the anthropic fraction of sulphate, as assessed by a chemical source apportionment method (Amore et al. 2022), also including more recent data (now covering the 2010–2022 time period). We also show that anthropic sulphate levels remain relatively constant in summer, suggesting that it is hitting its background level.

2. The state of Arctic haze in Svalbard

Arctic aerosol is generally characterized by a strong seasonality, resulting in different processes and sources dominating at different times of the year: anthropic pollution from long-range transport in winter/spring and natural emissions from regional sources in summer/autumn. Aerosol in Svalbard follows such a cycle, with a maximum in mass and species concentration in spring, due to Arctic haze, and a maximum in aerosol particle number in summer due to increased new particle formation processes (AMAP 2006).

As also reported in the original HAZECLIC chapter (Traversi et al. 2021), sulphate is the main component of the haze, and is usually taken as the chemical marker of this phenomenon. In that chapter, sulphate trends were studied at two sites in Ny-Ålesund (Gruvebadet – GVB and Zeppelin - ZEP) allowing the detection of a decreasing trend along the 2010–2020 period, mostly related to a decrease during the haze months, whereas a slight increase during summer was observed. As reported in topical papers (Sharma et al. 2019), a similar decrease was observed at several Arctic sites and was caused by the decline in S emission from the former Soviet Union, North America and western Europe during the 1990s.

Despite being mainly anthropic in origin, sulphate in the haze arises also from natural sources. The anthropic fraction was estimated both for GVB and ZEP sites via a simple chemical source apportionment method, as described in Amore et al. (2022). Four different source contributions to sulphate were quantified for each sample, namely sea salt, crustal, biogenic and anthropogenic. It has to be noticed that biogenic contribution at ZEP is affected by a larger uncertainty than at GVB since methanesulphonic (MSA) concentration, which was the indicator used to assess this fraction, is not available from ZEP. We chose to use MSA concentrations from GVB as best possible approximation. Interestingly, sulphate from crustal sources is present all through the year. This can be ascribed to resuspension of dust both from local sources (when the surrounding areas are ice-free, from late spring to early autumn) and to long-range sources, including Arctic haze (Quinn et al. 2002). The dust source areas in the Arctic were studied in detail by using different back trajectory models (including HYSPLIT and LAGRANTO) by Stohl (2006). In particular, Tobo et al. (2019) observed that air masses that spent a relatively long time over Svalbard in summer 2016 were enriched in larger dust particles, hinting to a significant contribution of local sources. Also, Crocchianti et al. (2021) reported a contribution of local and long-distance dust in spring and summer 2015.

Figure 1 shows the data distribution as box plots covering the 2010–2022 time period for both GVB and ZEP. The two sites show comparable levels in general for all the apportioned components, with mean and median values in the same order of magnitude. A particularly good agreement at the sites can be observed for the anthropic fraction, showing mean values at GVB only 2% higher than ZEP and similar median levels as well (around 11% difference). A larger gap is shown for biogenic fraction, which exhibits the lowest concentrations, thus carrying larger uncertainties, besides being biased by the lack of MSA data at ZEP. The comparability of the two data sets shows the robustness of the sampling, measurement, and data elaboration methods at the two observatories, which so far have been deploying different strategies in terms of sampling protocols and analytical methods.

Figure 2 shows anthropic sulphate levels along the time period covered by both records (2010–2022). We can observe that both absolute concentration levels and the seasonal pattern of this fraction agree well at GVB and ZEP. We present here the raw data obtained by applying the source apportionment method to each measured sample and, despite the different temporal resolution (in some years) and different sample collection and analysis methods, the records appear to be comparable. Neither the GVB nor the ZEP series shows an obvious decline in anthropic sulphate over the years, confirming that this species is reaching its lower limit, although the overall picture appears different in close-up (see monthly analysis in Figure 3). The possible correspondence of short-term events at GVB and ZEP is worthy of interest, especially as it may enable definition of structure of the atmospheric boundary layer (ABL) but accurate data elaboration (resampling and outlier treatment) would be required to compare the records on the short scale with statistical significance.

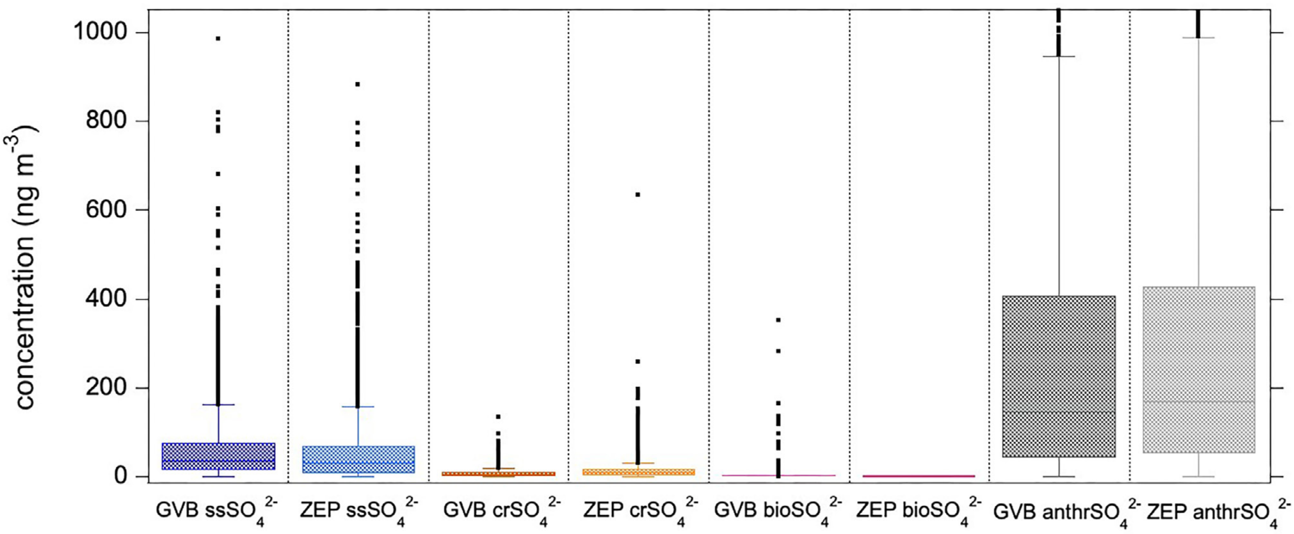

Figure 1: Data distribution plots of the different sulphate contributions (sea salt, crustal, biogenic, anthropic) at GVB and ZEP observatories in the 2010–2022 time period.

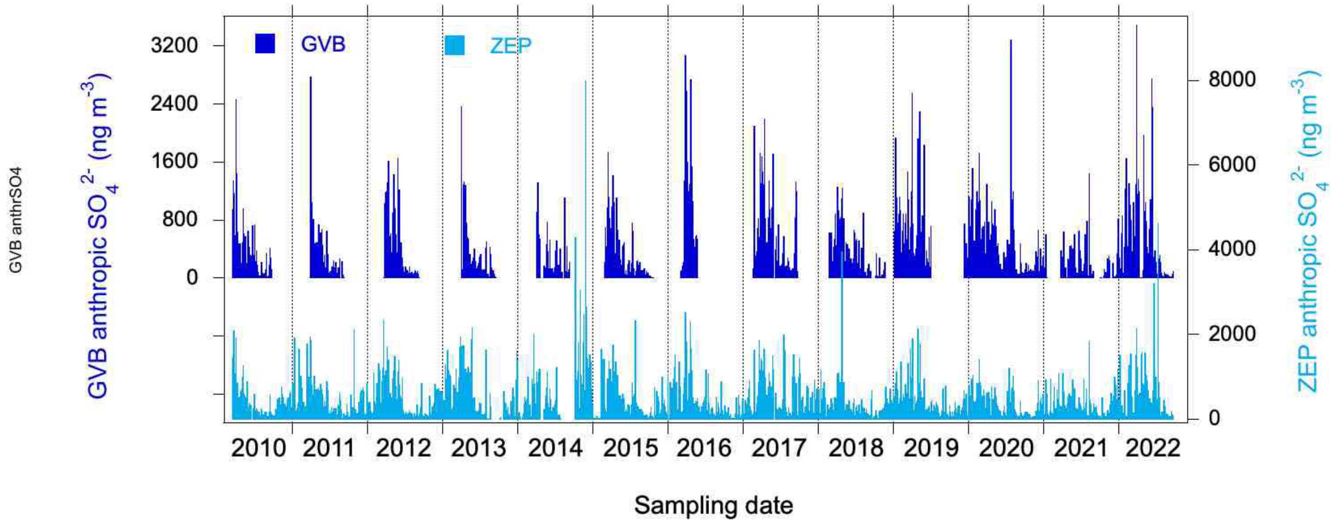

Figure 2: Temporal profile of anthropic sulphate at GVB (dark blue) and ZEP (light blue) observatories as reconstructed by chemical atmospheric series in the 2010–2022 time period.

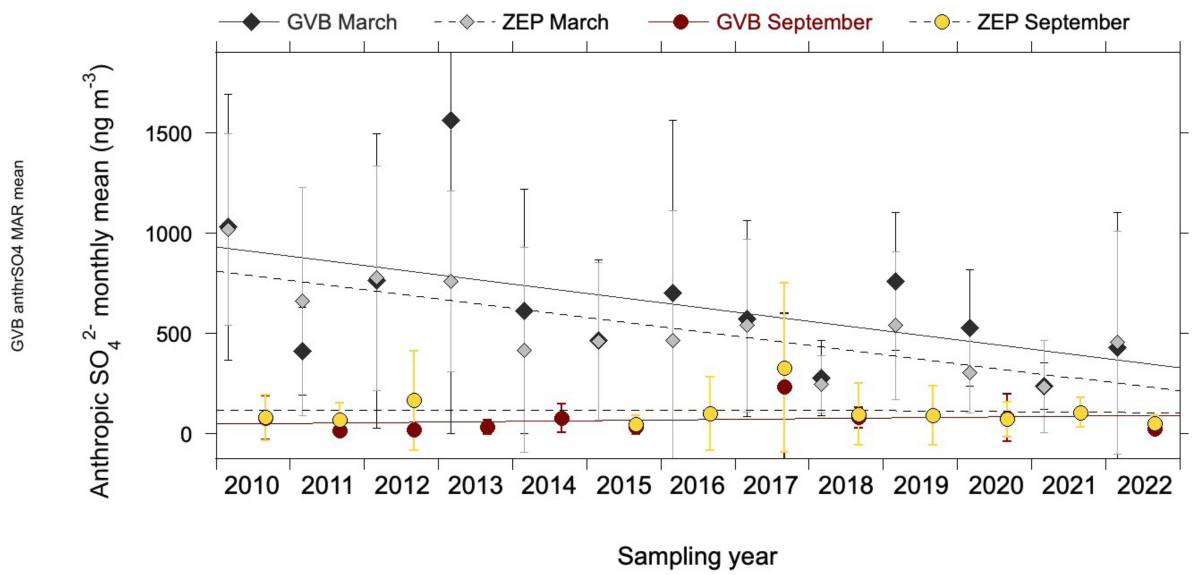

Figure 3: March and September monthly averages of anthropic sulphate in every year between 2010 and 2022 at GVB (black and brown) and ZEP (grey and yellow) observatories. Vertical bars represent monthly standard deviation.

The good agreement of anthropic sulphate series (as well as the other fractions) at GVB and ZEP can also be seen in the monthly averages of the four sources' contributions to sulphate in spring and summer periods (Figure 4). Since year-round measurements were started at GVB only in 2018, we chose to consider only the time from March to September, which is covered by observations at both sites throughout the 2010–2022 period. The pattern of the haze is quite evident in Figure 4, with anthropic sulphate reaching 630 (GVB) and 570 (ZEP) ng m^{-3} in April, decreasing significantly in May (by 36% and 23%, respectively) and reaching the lowest summer levels in August (95 ng m^{-3} at GVB and 125 ng m^{-3} at ZEP), 5-7 times lower than peak values. The proportion of natural sulphate is markedly lower during the haze months (13% and 15% of total sulphate at ZEP and GVB in March and April) and closer to that of anthropic sulphate in September (33% and 42% at ZEP and GVB). This feature deserves some attention because of the mentioned importance of the natural baseline and its climate change-driven variability.

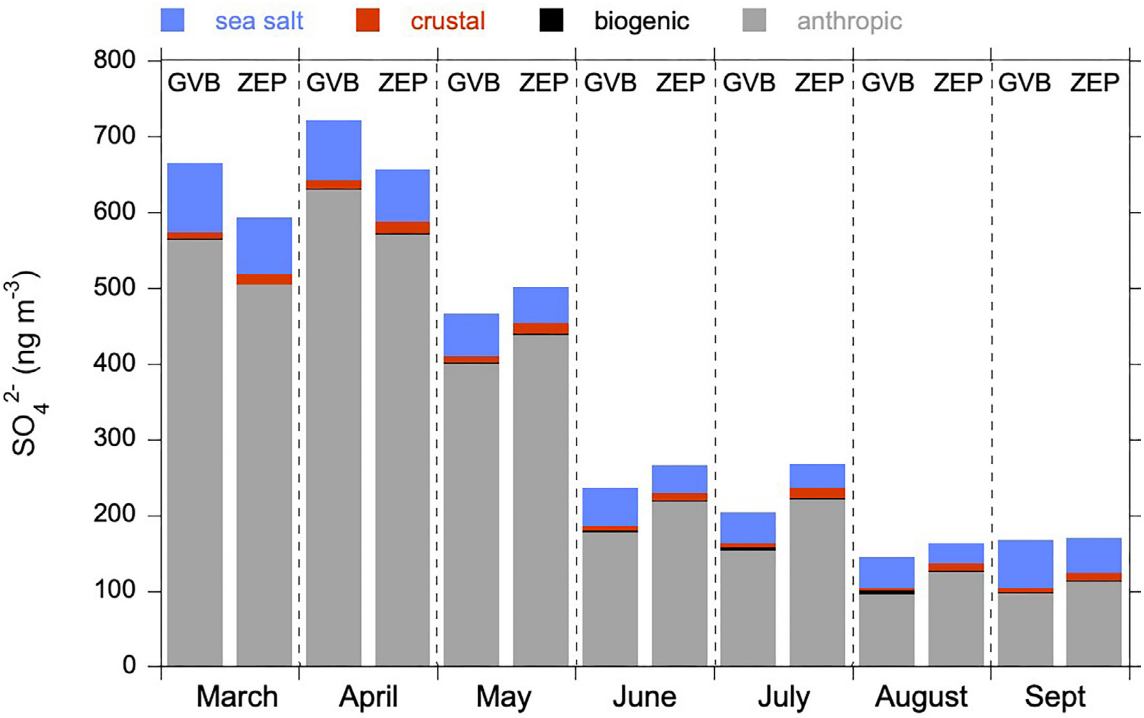

Figure 4: Stack column plot displaying the monthly averages of sulphate contributions (sea salt – blue; crustal – red; biogenic – black; anthropic – grey) at GVB and ZEP for the entire period 2010–2022.

Anthropic sulphate shows no clear trend through the 2010–2022 period, neither at GVB nor at ZEP, where the dataset is larger and more complete (Figure 2). The detection of recent trends is complicated by the effect of natural variations on seasonal and annual time scales. Hence, to remove seasonal variability from the trend analyses, we compared average monthly concentrations, similarly to Traversi et al. (2021). We selected March and September as representative of two different scenarios: haze-on and haze-off, respectively. Unlike the previous SESS Report we can observe here (Figure 3) the behaviour of the exclusively anthropogenic sulphate at different times of the year. Anthropic sulphate in March features a net decrease at both sites, with a similar slope along the investigated 13 years, reaching concentrations in 2022 which are about two thirds to half of those measured in 2010 at both sites. GVB shows a larger inter-annual variability than ZEP and its linear correlation is worse (R^2 = 0.263 at GVB, R^2 = 0.618 at ZEP). This difference in variability may possibly be caused by GVB being more sensitive than ZEP to local production sources and short-range transport (Graßl et al. 2022). Nevertheless, anthropic sulphate series at both sites hint that sulphate concentrations were still actively declining also in the last decade. Conversely, no clear trend can be detected in the September averages over the 2010–2022 time period. Both sites exhibit essentially constant levels of anthropic sulphate in this month, all through the years. Previous results (Traversi et al. 2021) showed a slight increase total sulphate concentrations in September at both sites. Now that we have added two years of data, identified the anthropic fraction (which actually accounts for the largest part of sulphate, even in September) and based our calculations solely on that fraction, anthropic sulphate does not show a significant increase in September over the last decade.

According to these results, it appears that the anthropic contribution during haze-off times (as in September) has reached its lower limit, a sort of “background level” that does not decrease further as years go on. Conversely, during haze-on times (as in March), the anthropic contribution is still decreasing, possibly due to stricter air quality policies, globally leading to fewer aerosols and precursors being transported to the Arctic. Such an effect is promising, in principle, especially considering that more intense socioeconomic activities in the Arctic will probably lead to enhanced local emissions, directly affecting cloud coverage and local albedo.

3. Contributions to interdisciplinarity

The data yielded by the simultaneous observation of two sites (GVB and ZEP) both located in Ny-Ålesund at different altitudes and differently related to the ABL, can be useful for a number of modelling studies (vertical structure of the ABL, anthropic and natural aerosol sources, atmospheric circulation processes on different geographical scale, Ice Nucleating Particle production).

Interaction with the glaciological community working in Arctic sites would be welcome to constrain the aerosol deposition processes (besides production and transport), hence its impact on the cryosphere. This connection could also work the other way round, with current aerosol observations serving as calibration tools for past chemical records archived in firn and ice cores.

Major improvements to the Earth observing system in Svalbard since the publication of our previous chapter (Traversi et al. 2021):

- Two additional years (2021 and 2022) added to the data sets enlarging the currently available chemical series from Svalbard to 13 years; this update will allow better characterization of long-term trends and short-term events and the spatial and temporal variability of aerosol sources.

- Refinement of the sulphate proxy by apportioning different anthropic and natural contributions by means of a simple chemical source apportionment method.

4. Unanswered questions

Although the Arctic haze has received much attention in the past (AMAP 2006, 2015), key questions are still unsolved. The ongoing long-term observations at Ny-Ålesund can provide pivotal information on the following pending questions (see also section 5):

1. Discrimination of the two modes of the Arctic haze: the so-called “chronic Arctic haze” (the low variance climatological annual cycle) and the episodic events of long-range transported pollutants.

2. Address numerous modelling issues for Arctic processes. Continuous observations at high resolution can help in constraining current models. The available model estimates of anthropogenic aerosol are affected by various uncertainties such as lack of feedback from variability in natural aerosol input, treatment of aerosol mixing state and hygroscopicity, contribution of precursor gases to secondary organic aerosol formation (Schmale et al. 2021), interaction between sea salt aerosol (which can significantly contribute to wintertime Arctic aerosol budget) and other inorganic aerosol components which have a dominant anthropic (haze) origin such as sulphate and nitrate.

3. More detailed characterization of the vertical structure of the ABL in the Kongsfjorden area, not only during spot campaigns but all through the year, since the GVB observatory can be considered representative of ground-level aerosol concentrations and is well within the ABL whereas

ZEP observatory has a more complex relationship with the ABL (often above the ABL during winter season and only sometimes within it in summer) (Graßl et al. 2022).

4. Better definition of the "moving natural aerosol baseline" (Schmale et al. 2021). This novel research focus is related to the knowledge of the anthropic aerosol emissions (including the Arctic haze) since the "natural" processes are affected by the environmental changes induced, in their turn, by the anthropic activity. The "moving baseline" concept reflects the continuous changes that natural aerosol emission and production processes undergo upon being perturbed by the ongoing climate change (Schmale et al. 2021). Such interplay between anthropic forcing and natural processes can be better understood by apportioning aerosol natural sources by means of specific markers and experimental and modelling efforts. In this context, particular attention should be paid to marine biogenic trace gases (DMS) and related aerosol oxidation products (MSA and sulphate) (see also Recommendations 2 and 3). In fact, Svalbard is becoming a warmer environment, and retreating sea ice there could increase the number of NPF events in the future, since most precursor gases originate from biogenic sources within the nearby ocean. The growth of these particles can lead to reflective low-level clouds over the "dark" sea surface.

5. Recommendations for the future

The data and results presented in this update chapter allow us to reiterate two previous recommendations and propose a new one.

1. The continuous long-term measurements at two strategic sites (GVB and ZEP) should be maintained. Given that these two observatories are both located in Ny-Ålesund but at different elevations, the simultaneous observation of key aerosol chemical markers can help discriminating the impact of the haze both at ground level and above the ABL, thus gaining a local and long-range signature of this phenomenon. In this view, it is recommended to harmonize the protocols for aerosol sampling and measurements between the two sites. A preliminary effort in this direction is being accomplished within the Italian PRA "BETHA-NyÅ" project (2021–2024).

2. The natural Arctic "baseline" should be unraveled (see also section 4.). As outlined in the previous section, an accurate evaluation of the "moving natural aerosol baseline" is needed to better understand how anthropic activities impact the environment. This requires a more detailed knowledge about natural Arctic aerosol emissions, their evolution and transport, as well as of their effects on cloud microphysics. To this aim, the measurement of MSA also at ZEP observatory would provide an asset to quantify the biogenic contribution to sulphate budget in at Ny-Ålesund area. In fact, MSA is a univocal marker of marine biological activity, also in relation to sea ice dynamics (Becagli et al. 2019) and sulphate/MSA ratio has been used here just to assess the contribution of this source at GVB site.

Based on the results here presented and on the latest developments of the research in the Arctic the following new recommendation is proposed:

3. Upgrade the GVB observation facility with the measurement of trace gases using on-line instruments. Expanding the current observation set at Gruvebadet (mainly devoted to the aerosol phase) with year-round continuous measurements of key gaseous species would provide an extended overview of the gas–aerosol–cloud interaction, which is crucial for a better understanding of climate change in the Arctic. One of the main effects of climate change is the loss of Arctic Sea ice, which was found to cause an increase in the phytoplankton net primary production in the last two decades. This is likely to lead to an increase in the emissions of primary biogenic precursors such

as DMS, which undergo chemical transformation in the atmosphere. The oxidation products of DMS (MSA and H_2SO_4), together with NH_3 and amines, act as aerosol precursors contributing to NPF processes and thus influencing cloud formation and radiative balance (Xavier et al. 2022).

The recommended enlargement of GVB facility might be implemented via off-line or on-line instruments, depending on what is economically feasible. On-line instrumentation would certainly imply a higher cost in the start-up phase but would be more convenient in terms of human resources and consumables, besides having the potential to yield a continuous high-resolution record. A preliminary successful effort has already been accomplished at GVB and ZEP within the Ny-Ålesund Aerosol Cloud Experiment (NASCENT) (Pasquier et al. 2022).

6. Data availability

Dataset	Parameter	Period	Location	Metadata access (URL)	Dataset provider
PM10 chemistry at GVB*	Apportioned sulphate concentration in PM10 (anthropic, sea salt, crustal, biogenic)	2010–2022	GVB, Ny-Ålesund	Italian Arctic Data https://metadata.iadc.cnr.it/geonetwork/srv/eng/catalog.search#/metadata/a72d871b-01f0-4b20-993d-d6855eefb0d6	Rita Traversi rita.traversi@unifi.it Mirko Severi Mirko.severi@unifi.it Silvia Becagli Silvia.becagli@unifi.it
PM10 chemistry at ZEP**	Anthropic sulphate concentration in PM10	2010–2022	ZEP, Ny-Ålesund	https://ebas-data.nilu.no/Pages/DataSetList.aspx?key=650ADEFD22EB414580B96BB622396E85	EBAS NILU

* GVB: Gruvebadet

** ZEP: Zeppelin Observatory

7. Acknowledgements

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8. References

AMAP (2006) Arctic Pollution 2006. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. vii+28 pp.

AMAP (2015) AMAP Assessment 2015: Black carbon and ozone as Arctic climate forcers. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. vii + 116 pp.

AMAP (2017) Adaptation Actions for a Changing Arctic: Perspectives from the Bering-Chukchi-Beaufort Region. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. xiv + 255pp

Amore A, Giardi F, Becagli S, Caiazzo L, Mazzola M, Severi M, Traversi R (2022) Source apportionment of sulphate in the High Arctic by a 10 yr-long record from Gruvebadet Observatory (Ny-Ålesund, Svalbard Islands). Atmospheric Environment 270:118890. https://doi.org/10.1016/j.atmosenv.2021.118890

Becagli S, Amore A, Caiazzo L, Di Iorio T, di Sarra A, Lazzara L, Marchese C, Meloni D, Mori G, Muscari G, Nuccio C, Pace G, Severi M, Traversi R (2019) Biogenic aerosol in the Arctic from eight years of MSA data from Ny Ålesund (Svalbard Islands) and Thule (Greenland). Atmosphere 10:349. https://doi.org/10.3390/atmos10070349

Crocchianti S, Moroni B, Waldhauserová PD, Becagli S, Severi M, Traversi R, Cappelletti D (2021) Potential Source Contribution Function Analysis of High Latitude Dust Sources over the Arctic: Preliminary Results and Prospects. Atmosphere 12:347. https://doi.org/10.3390/atmos12030347

Graßl, S, Ritter C, Schulz A (2022) The Nature of the Ny-Ålesund Wind Field Analysed by High-Resolution Windlidar Data. Remote Sens 14:3771. https://doi.org/10.3390/rs14153771

Pasquier JT, David RO, Freitas G, Gierens R, Gramlich Y, Haslett S, et al (2022) The Ny-Ålesund Aerosol Cloud Experiment (NASCENT) Overview and First Results. BAMS 103:11, E2533-E2558. https://doi.org/10.1175/BAMS-D-21-0034.1

Quinn P, Miller T, Bates T, Ogren J, Andrews E, Shaw G (2002) A 3-year record of simultaneously measured aerosol chemical and optical properties at Barrow, Alaska. J Geophys Res 107(D11): NO. D11, 10.1029/2001JD001248. https://doi.org/10.1029/2001JD001248.

Quinn PK, Shaw G, Andrews E, Dutton EG, Ruoho-Airola T, Gong SL (2007) Arctic haze: current trends and knowledge gaps. Tellus 59B:99–114. https://doi.org/10.1111/j.1600-0889.2006.00236.x

Schmale J, Zieger P. Ekman AML (2021) Aerosols in current and future Arctic climate. Nat. Clim. Chang. 11:95–105. https://doi.org/10.1038/s41558-020-00969-5

Serreze MC, Barry RG (2011) Processes and impacts of Arctic amplification: A research synthesis. Global Planet. Change 77(1):85–96. https://doi.org/10.1016/j.gloplacha.2011.03.004

Sharma S, Barrie LA, Magnusson E, Brattstrom G, Leaitch WR, Steffen A, Landsberger S (2019) A factor and trends analysis of multidecadal lower tropospheric observations of arctic aerosol composition, black carbon, ozone, and mercury at Alert, Canada. J Geophys Res Atmos 124(24):14133–14161. https://doi.org/10.1029/2019JD030844

Stohl A (2006) Characteristics of atmospheric transport into the Arctic troposphere. J Geophys Res 111:D 11306. https://doi.org/10.1029/2005JD006888

Tobo Y, Adachi K, DeMott PJ, Hill TCJ, Hamilton DS, Mahowald NM, Nagatsuka N, Ohata S, Uetake J, Kondo Y, Koike M (2019) Glacially sourced dust as a potentially significant source of ice nucleating particles. Nat Geosci 12:253–258. https://doi.org/10.1038/s41561-019-0314-x

Traversi R, Becagli S, Severi M, Caiazzo L, Mazzola M, Lupi A, Fiebig M, Hermansen O, Krejci R (2021) Arctic Haze in a climate changing world: the 2010-2020 trend. In: Moreno-Ibáñez et al (eds) SESS report 2020, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 104-117. https://doi.org/10.5281/zenodo.4293826

Xavier C, Baykara M, Wollesen de Jonge R, Altstädter B, Clusius P, Vakkari V et al (2022) Secondary aerosol formation in marine Arctic environments: a model measurement comparison at Ny-Ålesund. Atmos. Chem. Phys. 22:10023–10043. https://doi.org/10.5194/acp-22-10023-2022

Polar Night in Ny-Ålesund. (Photo: Simonetta Montaguti, CNR-ISP)

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

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1. Introduction

Plastic pollution has emerged as a global threat (MacLeod et al. 2021). The exponential increase in plastic production has resulted in widespread contamination (Rochman et al. 2013). Plastics, including microplastics (MPs) (<5 mm), mesoplastic (5 mm−2.5 cm), macroplastic (2.5 cm−1 m) and megaplastic (>1 m), have infiltrated every corner of the planet, from urban centres to remote areas, including the Arctic.

Arctic regions face significant challenges from human-induced factors, including climate change, (Meredith et al. 2019; Zemp et al. 2019), pollution (Dietz et al. 2019), and invasive species (Goldsmit et al. 2018). MPs have emerged as an additional complicating factor (Halsband and Herzke 2019; Kim et al. 2023), further straining these already stressed environments (Figure 1). In our previous chapter (Singh et al. 2021), we examined the status of MPs pollution in Svalbard, identifying research gaps and emphasizing the importance of regular monitoring of MPs levels. We also highlighted the need to understand their sources and impacts. Since then, new insights into MPs in Svalbard have emerged. For example, one study on algae suggested MPs integration into Arctic food chains (Bergmann et al. 2023). Another study detected MPs in water, sediment, and even walruses (Carlsson et al. 2021), emphasizing their widespread presence and impact on Arctic wildlife. By referencing Arctic Monitoring and Assessment Programme (AMAP) reports (AMAP 2021a, 2021b), and incorporating these new findings, this updated chapter aims to advance our understanding of this issue in Svalbard, and potentially prompt effective measures to protect the fragile ecosystems of Svalbard and the Arctic as a whole.

Figure 1: Plastic pollution in Svalbard (Photo: Geir Wing Gabrielsen)

2. The state of MPs in different environmental compartments

Atmosphere: Research on atmospheric MPs is expanding, with evidence of their dispersion in the atmosphere from various global locations like the Ecuadorian Andes, French Pyrenees, Italian Alps, U.S. conservation areas, Arctic snow, Nunavut in the Canadian Arctic, and Germany's Isle of Helgoland. However, since the study by Bergmann et al. (2019), nothing has been published on atmospheric MPs in Svalbard, highlighting the need for further investigation.

Ice and Snow: Kanhai et al. (2020) updated our understanding of MPs in Arctic Central Basin sea ice cores and underlying waters (Appendix 1).

Lower MPs concentrations were found in surface waters (0-18 particles/m^3) (n=22) compared to sea ice cores (2-17 particles/L) (n=22). No consistent vertical distribution was observed in the sea ice cores. These findings suggest the Siberian shelves, seas in the western Arctic, and the Central Arctic Basin as potential sources of MPs. Understanding MPs in Arctic Ocean compartments is vital for assessing risks to polar organisms. Despite study limitations, these authors highlight the Arctic Sea ice's role as a complex MPs reservoir, source, and transport pathway.

Open Ocean: Since our previous chapter, four new studies have provided additional insights into the distribution of MPs in the Arctic Ocean and adjacent waters (Appendix 1). Tošić et al. (2020) explored the Barents Sea, revealing a wide range of MPs concentrations, varying from 0.97 to 6.42 items/m^3 (n=3). These variations were influenced by complex oceanic patterns and fishing activities. Yakushev et al. (2021) sampled waters in the Eurasian Arctic. They reported an average of 0.004 item/m^3 (n=48) in surface samples and 0.8 item/m^3 (n=60) in subsurface samples. This study also unveiled differences in MPs characteristics among various water masses, suggesting their potential as regional markers. Pakhomova et al. (2022) conducted a comparative analysis across regions, highlighting significantly elevated MPs concentrations ranging from 7–7.5 µg/m^3 in the Central Atlantic and the Barents Sea, in contrast to the North Atlantic and Siberian Arctic Ocean with concentrations of 0.6 µg/m^3. These findings underscore the diverse sources, distribution patterns, and influencing factors contributing to MPs presence in these waters. In a more recent study, Emberson-Mar et al. (2023) focused on the Barents Sea, collecting sub-surface water samples along transects. They found MPs concentrations ranging 0.007–0.015 m^3 (n=6). Notably, this study detected higher concentrations closer to land and towards the ice edge, attributed to factors like melting sea ice and long-range transport from Europe.

Fjord and Bay Waters: Two studies investigated MPs in fjords and coastal waters following the MIRES project (Appendix 1). Bao et al. (2022) studied surface water (0–0.4 m) and water column (0–200 m) of Rijpfjorden, identifying a total of 1,010 MPs particles and 14 mesoplastics among the 41,038 particlesanalysed. The range of MPs was 0.15 ± 0.19 n/m^3 in surface water (n=6) and 0.15 ± 0.03 n/m^3 in the water column (n=2). This study identified 10 different polymers, including polyurethane, polyethylene, polyvinyl acetate, polystyrene, polypropylene, and alkyd varnish. It is believed that melting sea ice contributes to the presence of MPs, with alkyd varnish (accounting for 49%) suggesting shipping activities as a significant source. Kaliszewicz et al. (2023) collected water samples from six bays in the Barents Sea and freshwater lakes in the remote Kola Peninsula to investigate MPs contamination in this isolated Arctic region. MPs were found in all samples (n=18), with levels below 4,800 items/m^3 in the Barents Sea and below 3,900 items/m^3 in the lakes. Contributing factors to MPs presence in the lakes included landfill waste, protective clothing, and wind dispersion. The Norwegian Current played a pivotal role in transporting contaminants and MPs to the studied bays within the Barents Sea.

Freshwater: No new information has emerged concerning MPs in freshwater lakes in Svalbard since our previous report was published. It is essential to address this knowledge gap to gain a comprehensive understanding of MPs sources, their fate in Arctic lakes, and potential environmental consequences.

Sediment: Four new studies expanded our knowledge of MPs in sediment (Appendix 1). Choudhary et al. (2022) studied MPs in Krossfjorden and Kongsfjorden, finding high concentrations of 721±218 (n=5) and 783±530 (n=8) pieces/kg dry weight (dw) respectively. Predominant polymers were polyethylene and polypropylene, mainly fibrous. Other common polymers like polyvinylchloride and nitrile were also present, primarily in the 0.3-1 mm range. This study concluded that despite Svalbard's isolation and sparse population, the Krossfjord–Kongsfjord system showed MPs contamination from various sources such as ocean currents, sea ice, glacial melt, wind, and local human activities. Ramasamy et al. (2021) studied sediment from different locations in Kongsfjorden and found 4 to 24 MPs/kg (dw) sediment. This study stressed the need for source identification, deposition mechanisms, and understanding of MP effects in Arctic fjords. Lin et al. (2022) studied MPs and polycyclic aromatic hydrocarbons (PAHs) in Svalbard's Kongsfjorden and Rijpfjorden using surface sediment samples. They found only fibrous MPs in a range from non-detectable (ND) to 4.936 particles/kg (n=8) in Rijpfjorden and in Kongsfjorden from ND to 2.218 particles/kg. Three fibrous polymers were detected – polyester, rayon, and cellulose – suggesting that fishing debris and textiles may contribute to MPs pollution in these fjords. Kongsfjorden exhibited a stronger anthropogenic influence, while Rijpfjorden's MPs distribution seemed more influenced by ocean currents. Collard et al. (2021) studied surface sediment and core samples from Kongsfjorden to quantify anthropogenic particles (APs), including MPs. In surface sediment, APs averaged 0.33±0.05 item 100 g^{-1} (dw), with MPs averaging 0.17±0.04 item 100 g^{-1} (n=68). Sediment cores showed higher AP and MPs concentrations, averaging 1.34±0.21 and 0.75±0.12 item 100 g^{-1}. AP and MPs pollution in Kongsfjorden is mainly attributed to a sewage outlet in Ny-Ålesund. Interestingly, the site closest to the outlet had lower APs levels, possibly due to transport and accumulation in an eddy. The fjord's mouth, near the eddy, was the most polluted site in terms of APs. Roughly half of the APs were MPs, while the rest were primarily dyed fibres. This highlights the significant role of Kongsfjorden's currents in APs distribution within the sediment. These studies collectively emphasize the prevalence and sources of MPs in Arctic fjords, underlining the need for further research to understand their environmental impacts on these sensitive ecosystems.

Terrestrial environment: MPs are widespread in various environments, including the cryosphere and atmosphere. However, research gap from Svalbard's terrestrial areas is sparse. Our previous chapter stressed the need for terrestrial MPs studies here. Studying these environments is vital for assessing potential MPs risks. Notably, Hallanger et al. (2022) explored the presence of human litter, including plastic, in Arctic foxes (*Vulpes lagopus*), finding several pieces of a sour cream carton within one stomach.

2.1. Climate change and MPs distributions

In our previous chapter, we discussed how climate change, including shifting patterns, melting ice and glaciers, thawing permafrost, weather alterations, ocean current shifts, and ecosystem changes, affect MPs distribution in the Arctic. We also examined the melting cryosphere's role as a temporary MPs source. Now, we aim to delve deeper into the climate change–MPs relationship, moving beyond just how climate change influences MPs. Climate change and plastic pollution are interconnected and several climate-induced changes are known to influence the concentrations and distribution of plastic in the world (Bergmann et al. 2022). Understanding this connection can enhance our approach to tackling both issues. Hence, future research should focus on their combined environmental impact.

2.1.1. MPs and the carbon cycle: a growing concern

One pressing concern is how plastic production, closely tied to the consumption of oil, worsens climate change by creating greenhouse gases (UNEP, 2021). Plastics have accumulated in the environment to become a globally significant pool of organic carbon (Stubbins et al., 2021). Here is why this matters: in Arctic areas, permafrost holds a vast amount of organic carbon in the soil. But as it thaws due to climate change, it releases trapped MPs, turning permafrost from a carbon sink into a carbon source (Chen et al. 2021). Microbial activity also plays a role in this release, adding complexity to the MPs–carbon cycle interaction. Therefore, studying MPs in permafrost is crucial for future research. In oceans, MPs serve as surfaces for microbes to grow and form biofilms, which increases organic carbon production and results in gel-like particles (Galgani et al. 2019). While microbial communities on MPs can impact greenhouse gas cycling, their contribution to global gas surface inventories appears relatively low (Cornejo-D'Ottone et al. 2020). Nevertheless, MPs can influence the biogeochemical cycles of oceans, affecting consumers' exposure and the environmental fate of MPs (Rogers et al. 2020). Additionally, MPs alter the composition and function of microbial communities in ocean sediments, affecting carbon cycling (Seeley et al. 2020).

2.1.2. MPs and climate risk: examining the relationship

MPs pose a potential climatic risk in cryospheric regions. Studies show that cryosphere melting depends on temperature, precipitation, and the presence of light-absorbing particles like black carbon and mineral dust (Farinotti et al. 2020; Yao et al. 2022). These particles darken snow surfaces, reduce albedo (reflectivity), and accelerate melting (Kang et al. 2020). For example, increased black carbon in Arctic regions has led to reduced sea ice and intensified warming (Flanner et al. 2007; Li and Flanner 2018). MPs, like black carbon, can absorb radiation and lower albedo, hastening cryosphere melting (Revell et al. 2021). This suggests that MPs within snow may reduce glacier surface albedo, further impacting the energy balance. As glaciers melt faster, MPs could enter rivers and lakes downstream, posing ecological risks. Currently, we lack comprehensive research on the effects of airborne MPs on surface snow. Additionally, in marine environments, MPs can influence water temperatures and physicochemical properties, potentially initiating climate feedback cycles in ocean surface layers (VishnuRadhan et al. 2019).

Significantly, we still need to learn about the climatic effects of MPs on snow and ice. Questions about MPs properties, impact on radiation absorption, and comparison with particles like black carbon and dust remain. Addressing these knowledge gaps requires further research into how MPs affect cryosphere regions.

2.2. Update on food safety

Updating our understanding of the sociological impacts of MPs, particularly concerning food safety in the Arctic, is crucial. Indigenous Arctic populations have a deep historical connection to Arctic ecosystems, and possess a wealth of knowledge related to their environment. Their traditional way of life, heavily reliant on hunting and fishing for sustenance, makes them particularly vulnerable to the presence of pollutants, including MPs, in their surroundings. In contrast, Svalbard's population has access to alternative sources of traditional wild foods, such as supplies from Svalbardbutikken and mainland Norway. This diversity in food sources introduces complexity when attempting to predict how MPs are transferred to the population in Svalbard, especially through locally hunted wildlife. In Svalbard, our current understanding of MPs exposure, bioaccumulation, and the impact of consumption of locally hunted wild foods is limited. Addressing these knowledge gaps will contribute significantly to enhancing our comprehension of the potential risks associated with traditional food consumption in Svalbard, particularly in the context of MP contamination and its implications for food safety.

3. Contributions to interdisciplinarity

The issue of microplastics extends beyond specific environments; it is a widespread concern observed across all environmental compartments. Within this context, this chapter not only synthesizes updated knowledge of the microplastic pollution status in Svalbard but also identifies specific areas for further interdisciplinary research and outlines future focal points (see recommendations section).

Importantly, a recommendation from Singh et al. (2021) has been implemented in a master's thesis, contributing to refining methodologies for studying microplastics in the Arctic (Brenden 2021).

4. Unanswered questions

Three years after the first MIRES chapter was published, our knowledge has improved but not enough to answer all the questions raised there. No specific topic has attracted the interest and focus of scientific research within the field of microplastic pollution in the Arctic. The lack of development globally is undoubtedly due to the remoteness and consequent high cost of sample collection there. In particular, research on terrestrial ecosystems and/or biota is likely more challenging than marine research as the latter is usually performed on ships where working conditions are better. Here it is important to highlight that AMAP is actively developing a monitoring plan to identify essential elements and considerations for a well-coordinated environmental monitoring program focused on litter and microplastics throughout the Arctic (AMAP 2021a).

Trends: Tracking trends of MPs across different environmental compartments proves challenging due to inconsistencies in sampling methods, data protocols, lack of comprehensive data and inaccurate categorization of natural or semi-artificial polymers. Further, each study is only one point in time and can be challenging to incorporate into a holistic understanding without vast amount of data.

Sources: The sources of MPs in the Arctic are both local and long-range. Differentiating between local or long-range sources is often not possible, and the smaller the particle the less likely a source will be identified. There is a need to fully understand and to quantify possible local pollution to be able to theoretically differentiate between local and long-range sources.

Toxicological effects and ecological risks: While MPs have been identified in marine organisms, the consequences arising from plastic additives and pollutants are poorly understood. There are several experimental studies showing both toxic and non-toxic behaviour, though linking this knowledge to environmental samples or scenarios is difficult due to multiple exposure pathways and cocktail mixtures.

Fate in extreme Arctic conditions: Uncertainty exists about how MPs transform and accumulate in Svalbard's extreme Arctic conditions. The interactions between MPs and Arctic ecosystems' physical and biological elements are poorly explored, leading to unpredictable environmental effects.

Climate change and plastic dynamics: While climate change is altering the physical environment in Svalbard, its specific effects on plastic cycling and transformation in the region are not well understood and require further investigation.

Food safety and human health concerns: Limited documentation of MPs in harvested wildlife and fish raises questions about potential human health risks from ingestion and inhalation of MPs. Notably, the widespread use of clothing made from plastic fibres in Svalbard may release particles into the air over time, adding concerns about human long-term plastic exposure.

Air-to-ecosystem exchange: The transfer of MPs from the air to marine and terrestrial environments is an understudied area, leaving gaps in our understanding of how these particles move through ecosystems.

5. Recommendations for the future

The importance of long-term monitoring of plastic pollution on a global scale cannot be overstated, especially when we consider places like Svalbard. Despite its remote location, Svalbard is not immune to the effects of global plastic pollution. The plastic litter found in Svalbard is a symptom of a much larger, global problem. Long-term monitoring allows us to track the sources and pathways of plastic pollution, understand its impact on various ecosystems, and measure the effectiveness of mitigation strategies. It provides the data necessary to inform policy decisions and drive international cooperation. Ultimately, plastic pollution in Svalbard serves as a stark reminder that our actions have global consequences, reinforcing the need for sustained, global monitoring efforts.

Harmonization: Convene a workshop with experts on plastic pollution in Svalbard to come to agreements on a monitoring framework. This should be aligned with and incorporated into the AMAP Programme since standardizing and harmonizing methods is pivotal not only for Svalbard, but also for uniformity across the pan-Arctic and globally.

Collaboration: Establish a Svalbard plastic task force. Its members should meet regularly to develop methods and monitoring recommendations to ensure a concerted effort to fulfil knowledge gaps.

Mapping: Conduct a thorough mapping of MPs in Svalbard, including biota from both terrestrial and marine ecosystems. Mapping is necessary to establish reliable risk assessment and monitoring guidelines for the environment and human consumers.

Long-term monitoring: A monitoring programme should be designed to include societal needs. Scientists working on MPs can provide advice regarding plastic use in Svalbard, wastewater treatment, effects of recreational (cruises/tourists) and fishing activities.

Experiments: Experimental studies on MPs effects on Arctic key species should be promoted and the possible trophic transfer of MPs under Arctic conditions should be investigated.

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7. References

AMAP (2021a) AMAP Litter and Microplastics Monitoring Plan. Arctic Monitoring and Assessment Programme (AMAP), Tromsø.

AMAP (2021b) Arctic Climate Change Update 2021: Key Trends and Impacts. Summary for Policy-makers. Arctic Monitoring and Assessment Programme (AMAP), Tromsø.

Bao M, Huang Q, Lu Z, Collard F, Cai M, Huang P et al. (2022) Investigation of microplastic pollution in Arctic fjord water: a case study of Rijpfjorden, Northern Svalbard. Environ Sci Pollut Res 29:56525–56534. https://doi.org/10.1007/s11356-022-19826-3

Bergmann M, Collard F, Fabres J, Gabrielsen GW, Provencher JF, Rochman CM et al. (2022) Plastic pollution in the arctic. Nat. Rev. Earth Environ 3:323–337. https://doi.org/10.1038/s43017-022-00279-8

Bergmann M, Allen S, Krumpen K, Allen D (2023) High Levels of Microplastics in the Arctic Sea Ice Alga *Melosira arctica*, a Vector to Ice-Associated and Benthic Food Webs. Environ Sci Technol 57:6799–6807. https://doi.org/10.1021/acs.est.2c08010

Bergmann M, Mützel, Primpke S, Tekman MB, Trachsel J, Gerdts G (2019) White and wonderful? Microplastics prevail in snow from the Alps to the Arctic. Sci Adv 5:eax1157. https://doi.org/10.1126/sciadv.aax1157

Brenden M (2021) Method Validation in microplastic research in the Arctic. A study of microlitter in arctic sediments in Adventdalen, Svalbard. Master's thesis in Geography, Norwegian University of Science and Technology. https://ntnuopen.ntnu.no/ntnu-xmlui/bitstream/handle/11250/2823505/no.ntnu%3Ainspera%3A80616609%3A16114237.pdf?sequence=1

Carlsson P, Singdahl-Larsen C, Lusher AL (2021) Understanding the occurrence and fate of microplastics in coastal Arctic ecosystems: the case of surface waters, sediments and walrus (*Odobenus rosmarus*). Sci Total Environ 792:148308. https://doi.org/10.1016/j.scitotenv.2021.148308

Chen X, Huang G, Gao S, Wu Y (2021) Effects of permafrost degradation on global microplastic cycling under climate change. J Environ Chem Engin 9(5):106000. https://doi.org/10.1016/j.jece.2021.106000

Choudhary S, Neelavanan K, Saalim SM (2022) Microplastics in the surface sediments of Krossfjord–Kongsfjord system, Svalbard, Arctic. Mar Pollut Bull 176:113452. https://doi.org/10.1016/j.marpolbul.2022.113452

Collard F, Husum K, Eppe G, Malherbe C, Hallanger IG, Divine DV et al. (2021) Anthropogenic particles in sediment from an Arctic fjord. Sci Total Environ 772:145575. https://doi.org/10.1016/j.scitotenv.2021.145575

Cornejo-D'Ottone M, Molina V, Pavez J, Silva N (2020) Greenhouse gas cycling by the plastisphere: The sleeper issue of plastic pollution. Chemosphere 246:125709. https://doi.org/10.1016/j.chemosphere.2019.125709

Dietz R, Letcher RJ, Desforges J-P, Eulaers I, Sonne C, Wilson S et al. (2019) Current state of knowledge on biological effects from contaminants on Arctic wildlife and fish. Sci Total Environ 696:133792. https://doi.org/10.1016/j.scitotenv.2019.133792

Emberson-Marl H, Coppock R, Cole M, Godley BJ, Mimpriss N, Nelms SE et al. (2023) Microplastics in the Arctic: a transect through the Barents Sea. Front Mar Sci 10:1241829. https://doi.org/10.3389/fmars.2023.1241829

Farinotti D, Immerzeel WW, de Kok RJ, Quincey DJ, Dehecq A (2020) Manifestations and mechanisms of the Karakoram glacier Anomaly. Nat Geosci 13:8–16. https://doi.org/10.1038/s41561-019-0513-5

Flanner MG, Zender CS, Randerson JT, Rasch PJ (2007) Present-day climate forcing and response from black carbon. J Geophys Res 112:D11202. https://doi.org/10.1029/2006jd008003

Galgani L, Tsapakis M, Pitta P, Tsiola A, Tzempelikou E, Kalantzi I et al. (2019) Microplastics increase the marine production of particulate forms of organic matter. Environ Res Lett 14(12):124085. https://doi.org/10.1088/1748-9326/ab59ca

GESAMP (2015) Sources, fate and effects of microplastics in the marine environment: a global assessment (Kershaw PJ ed.). (IMO/FAO/UNESCO-IOC/UNIDO/WMO/IAEA/UN/UNEP/UNDP Joint Group of Experts on the Scientific Aspects of Marine Environmental Protection). Rep Stud GESAMP No. 90, 96 p.

Hallanger IG, Ask A, Fuglei E (2022) Occurrence of ingested human litter in winter arctic foxes (*Vulpes lagopus*) from Svalbard, Norway. Environ Pollut 303:119099. https://doi.org/10.1016/j.envpol.2022.119099

Halsband C, Herzke D (2019) Plastic litter in the European Arctic: what do we know? Emerg Contam 5:308–318. https://doi.org/10.1016/j.emcon.2019.11.001

Kaliszewicz A, Panteleeva N, Karaban K, Runka T, Winczek M, Beck E et al. (2023) First evidence of microplastic occurrence in the marine and freshwater environments in a remote polar region of the Kola Peninsula and a correlation with human presence. Biology 12:259. https://doi.org/10.3390/biology12020259

Kang S, Zhang Y, Qian Y, Wang H (2020) A review of black carbon in snow and ice and its impact on the cryosphere. Earth Sci Rev 210:103346. https://doi.org/10.1016/j.earscirev.2020.103346

Kanhai LDK, Gardfeldt K, Krumpen T, Thompson RC, O'Connor I (2020) Microplastics in sea ice and seawater beneath ice floes from the Arctic Ocean. Sci Rep 10:5004. https://doi.org/10.1038/s41598-020-61948-6

Kim S, Kim J, Kim S, Song N, La H, Yang E (2023) Arctic Ocean sediments as important current and future sinks for marine microplastics missing in the global microplastic budget. Science Advances 9:27. https://doi.org/10.1126/sciadv.add2348

Li Y, Flanner MG (2018) Investigating the impact of aerosol deposition on snowmelt over the Greenland Ice Sheet using a large-ensemble kernel. Atmos Chem Phys 18:16005–16018. https://doi.org/10.5194/acp-18-16005-2018

Lin Y, Cen Z, Peng J, Yu H, Huang P, Huang Q et al. (2022) Occurrence and sources of microplastics and polycyclic aromatic hydrocarbons in surface sediments of Svalbard, Arctic. Mar Pollut Bull 184:114116. https://doi.org/10.1016/j.marpolbul.2022.114116

Meredith M, Sommerkorn M, Cassotta S, Derksen C, Ekaykin A, Hollowed AB et al. (2019) Polar regions. In: Pörtner HO, Roberts DC, Masson-Delmotte V, Zhai P, Tignor M, Poloczanska E, et al. (eds) IPCC Special Report on the Ocean and Cryosphere in a Changing Climate. Intergovernmental Panel on Climate Change (IPCC), Geneva, pp 203–320.

Pakhomova S, Berezina A, Lusher A, Zhdanov I, Silvestrova K, Zavialov P et al. (2022) Microplastic variability in subsurface water from the Arctic to Antarctica. Environ Pollut 298:118808. https://doi.org/10.1016/j.envpol.2022.118808

Ramasamy EV, Sruthy S, Harit AK, Mohan M, Binish MB (2021) Microplastic pollution in the surface sediment of Kongsfjorden, Svalbard, Arctic. Mar Pollut Bull 173(Pt A):112986. https://doi.org/10.1016/j.marpolbul.2021.112986

Revell LE, Kuma P, le Ru E, Somerville WRC, Gaw S (2021) Direct radiative effects of airborne microplastics. Nature 598:462–479. https://doi.org/10.1038/s41586-021-03864-x

Rogers KL, Carreres-Calabuig JA, Gorokhova E, Posth NR (2020) Micro-by-micro interactions: how microorganisms influence the fate of marine microplastics. Limnol Oceanog Lett 5:18–36. https://doi.org/10.1002/lol2.10136

Seeley ME, Song B, Passie R, Hale RC (2020) Microplastics affect sedimentary microbial communities and nitrogen cycling. Nat Commun 11:2372. https://doi.org/10.1038/s41467-020-16235-3

Singh N, Granberg M, Collard F, Caruso G, Lu Z, Kögel T, Gabrielsen GW (2021) Microplastics in the realm of Svalbard: current knowledge and future perspective. In: Moreno-Ibáñez et al (eds) SESS report 2020, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 118-141. https://doi.org/10.5281/zenodo.4293836

Stubbins A, Law KL, Muñoz SE, Bianchi TS, Zhu L (2021) Plastics in the Earth system. Science 373(6550):51–55. https://doi.org/10.1126/science.abb0354

Tošić TN, Vruggink M, Vesman A (2020) Microplastics quantification in surface waters of the Barents, Kara and White Seas. Mar Pollut Bull 161:111745. https://doi.org/10.1016/j.marpolbul.2020.111745

UNEP (2021) Neglected: Environmental Justice Impacts of Marine Litter and Plastic Pollution United Nations Environment Programme Nairobi. https://www.unep.org/resources/report/neglected-environmental-justice-impacts-marine-litter-and-plastic-pollution

VishnuRadhan R, Eldho TI, David TD (2019) Can plastics affect near surface layer ocean processes and climate? Mar Pollut Bull 140:274–280. https://doi.org/10.1016/j.marpolbul.2019.01.052

Yakushev E, Gebruk A, Osadchiev A, Pakhomova S, Lusher A, Berezina A et al. (2021) Microplastics distribution in the Eurasian Arctic is affected by Atlantic waters and Siberian rivers. Commun Earth Environ 2. https://doi.org/10.1038/s43247-021-00091-0

Yao J, Chen Y, Guan X, Zhao Y, Chen J, Mao W (2022) Recent climate and hydrological changes in a mountain–basin system in Xinjiang, China. Earth Sci Rev 226:103957. https://doi.org/10.1016/j.earscirev.2022.103957

Zemp M, Huss M, Thibert E, Eckert N, McNabb R, Huber J et al. (2019) Global glacier mass changes and their contributions to sea-level rise from 1961 to 2016. Nature 568:382–386. https://doi.org/10.1038/s41586-019-1071-0

Manta sampler to collect plastic particles (MP) at the sea surface, June 2021 on a 'plastic research cruise' with RV Kronprins Haakon in Isfjorden, Svalbard. (Photo: Geir Wing Gabrielsen, NPI)

Appendix 1: MPs in different abiotic compartments of Svalbard

Location	Year	Medium	Concentration	Unit	Size range	Sampling method	Analytical method	Reference
Ice and Snow								
Arctic Sea Central Basin	2016	Sea ice core	2-17	particles/L	0.10–4.99 mm	Ice coring	Microscope (Olympus SZX10) equipped with a polariser and camera (Q Imaging Retiga 2000R) and Fourier transform infrared (FT-IR) spectroscopy	Kanhai et al. (2020)
Ocean								
Arctic Sea Central Basin	2016	Sea water under ice floe	0-18	particles/m^3	0.25–5 mm	Pump	Microscope (Olympus SZX10) equipped with a polariser and camera (Q Imaging Retiga 2000R) and Fourier transform infrared (FT-IR) spectroscopy	Kanhai et al. (2020)
Barents Sea	2018	Surface water	0.97 to 6.42	items/m^3	> 5 mm	Manta trawl	Fourier transform infrared (FT-IR) spectroscopy	Tošić et al. (2020)
Barents Sea	2019	Surface water	0.004 (avg)	item/m^3	0.2–5 mm	Neuston net	Nikon D750 camera and Tamron SP AF 28-75/2.8 XR LD lens and Fourier Transform Infrared spectroscopy (FT-IR)	Yakushev et al. (2021)
Barents Sea	2019	Subsurface water	0.8 (avg)	item/m^3	0.1–3.6 mm	Pump	Nikon D750 camera and Tamron SP AF 28-75/2.8 XR LD lens and Fourier Transform Infrared spectroscopy (FT-IR)	Yakushev et al. (2021)
Central Atlantic and Barents Sea	September 2019–February 2020	Subsurface water	7–7.5	µg/m^3	0.1–4.9 mm	Pump	Microscope (Nikon SMZ745×T, 20 × magnification), and Fourier Transform Infrared spectroscopy (µFT-IR)	Pakhomova et al. (2022)
Barents Sea	2018	Subsurface water	0.007–0.015	Microplastics/m^{-3}	0 – > 5000 µm	Pump	Olympus (SZX16) microscope (x25 magnification) and Fourier Transform Infrared Spectroscopy (FT-IR; PerkinElmer Spotlight 400).	Emberson-Mar et al. (2023)
Fjord and bay waters								
Rijpfjorden	2017	Surface water (0–0.4 m)	0.15±0.19	n/m^3	200.1–4694.1 µm	Manta net	Fourier transform infrared (FT-IR) technique and Laser Direct Infrared	Bao et al. (2022)
Rijpfjorden	2017	Water column (0–200 m)	0.15±0.03	n/m^3	200.1–4694.1 µm	Manta net	Fourier transform infrared (FT-IR) technique and Laser Direct Infrared	Bao et al. (2022)
Barents Sea	2019	Surface water	4,800 items/m^3	items/m^3	0.01–5mm	Plankton net	Raman spectroscopy	Kaliszewicz et al. (2023)

Sediment								
Kongsfjorden	2016	Surface sediment	783±530.28	pieces/kg	0.3–1 mm	Van Veen Grab sampler	Attenuated Total Reflectance Fourier Transform Infrared (ATR-FT-IR) and Perkin-Elmer PC-16 FT-IR spectrometer	Choudhary et al. (2022)
Krossfjorden	2016	Surface sediment	721.42±217.89	pieces/kg	0.3–1 mm	Van Veen Grab sampler	Attenuated Total Reflectance Fourier Transform Infrared (ATR-FTIR) and Perkin-Elmer PC-16 FT-IR spectrometer	Choudhary et al. (2022)
Kongsfjorden	2016	Surface sediment	4–24	MPs/kg	55–381 µm	Van Veen Grab sampler	Microscope (Zeiss Stemi 508) and Raman spectrometer (WITec Alpha 300RA, Germany)	Ramasamy et al. (2021)
Kongsfjorden	2017	Surface sediment	ND–2.218	particles/kg		Box corer	Visual identification by microscope (ZEISS, Scope A1, Germany) Micro Fourier Transform Infrared Spectrometer (µFT-IR)	Lin et al. (2022)
Rijpfjorden	2017	Surface sediment	ND–4.936	particles/kg	NA	Box corer	Microscope (ZEISS, Scope A1, Germany) and Micro Fourier Transform Infrared Spectrometer (µFT-IR)	Lin et al. (2022)
Kongsfjorden	2018	Surface sediment and 5 cm core	0.17±0.04 (avg) (items)	Items.100 g^{-1}	0.10–6.31 mm	Box corer	LabRam 300 spectrometer (Horiba Jobin-Yvon) d with an Olympus BX 40 confocal microscope and Fourier-Transform Infrared spectroscopy (FT-IR)	Collard et al. (2021)

ND=Not Detectable; NA=Information is not available in the manuscript

References

Bao M, Huang Q, Lu Z, Collard F, Cai M, Huang P et al. (2022) Investigation of microplastic pollution in Arctic fjord water: a case study of Rijpfjorden, Northern Svalbard. Environ Sci Pollut Res 29:56525–56534. https://doi.org/10.1007/s11356-022-19826-3

Choudhary S, Neelavanan K, Saalim SM (2022) Microplastics in the surface sediments of Krossfjord–Kongsfjord system, Svalbard, Arctic. Mar Pollut Bull 176:113452. https://doi.org/10.1016/j.marpolbul.2022.113452

Collard F, Husum K, Eppe G, Malherbe C, Hallanger IG, Divine DV et al. (2021) Anthropogenic particles in sediment from an Arctic fjord. Sci Total Environ 772:145575. https://doi.org/10.1016/j.scitotenv.2021.145575

Emberson-Marl H, Coppock R, Cole M, Godley BJ, Mimpriss N, Nelms SE et al. (2023) Microplastics in the Arctic: a transect through the Barents Sea. Front Mar Sci 10:1241829. https://doi.org/10.3389/fmars.2023.1241829

Kaliszewicz A, Panteleeva N, Karaban K, Runka T, Winczek M, Beck E et al. (2023) First evidence of microplastic occurrence in the marine and freshwater environments in a remote polar region of the Kola Peninsula and a correlation with human presence. Biology 12:259. https://doi.org/10.3390/biology12020259

Kanhai LDK, Gardfeldt K, Krumpen T, Thompson RC, O'Connor I (2020) Microplastics in sea ice and seawater beneath ice floes from the Arctic Ocean. Sci Rep 10:5004. https://doi.org/10.1038/s41598-020-61948-6

Lin Y, Cen Z, Peng J, Yu H, Huang P, Huang Q et al. (2022) Occurrence and sources of microplastics and polycyclic aromatic hydrocarbons in surface sediments of Svalbard, Arctic. Mar Pollut Bull 184:114116. https://doi.org/10.1016/j.marpolbul.2022.114116

Pakhomova S, Berezina A, Lusher A, Zhdanov I, Silvestrova K, Zavialov P et al. (2022) Microplastic variability in subsurface water from the Arctic to Antarctica. Environ Pollut 298:118808. https://doi.org/10.1016/j.envpol.2022.118808

Ramasamy EV, Sruthy S, Harit AK, Mohan M, Binish MB (2021) Microplastic pollution in the surface sediment of Kongsfjorden, Svalbard, Arctic. Mar Pollut Bull 173(Pt A):112986. https://doi.org/10.1016/j.marpolbul.2021.112986

Tošić TN, Vruggink M, Vesman A (2020) Microplastics quantification in surface waters of the Barents, Kara and White Seas. Mar Pollut Bull 161:111745. https://doi.org/10.1016/j.marpolbul.2020.111745

Yakushev E, Gebruk A, Osadchiev A, Pakhomova S, Lusher A, Berezina A et al. (2021) Microplastics distribution in the Eurasian Arctic is affected by Atlantic waters and Siberian rivers. Commun Earth Environ 2. https://doi.org/10.1038/s43247-021-00091-0

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