SESS REPORT 2024

The State of Environmental Science in Svalbard – an annual report

SIOS
SVALBARD INTEGRATED ARCTIC EARTH OBSERVING SYSTEM

SESS REPORT 2024

The State of Environmental Science
in Svalbard – an annual report

Elaine Runge, Roland Neuber, Ewa Łupikasza,
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The State of Environmental Science in Svalbard
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Contents

Foreword 6

Authors from following institutions contributed to this report: 7

Executive Summary 10

Summaries for stakeholders 14

1 Secular shift of the magnetic dip pole and its consequences for auroral boundaries (PoleMotion) 38

2 Geology of Svalbard: Deep-time and Deep-Earth (SVALGEOL) 52

3 Surging glaciers in Svalbard: Current knowledge and perspectives for monitoring (SvalSurge) 84

4 Methane in Svalbard (SvalGaSess) 106

5 The Atlantification process in Svalbard: a broad view from the SIOS Marine Infrastructure network (ARiS) 138

6 Microbial communities as sentinels of environmental changes in Svalbard (MicroSIOS) 152

7 Terrestrial and freshwater invertebrate science in Svalbard in a changing world: from regional to pan-Arctic scales (STAFIEN - Svalbard Terrestrial and Freshwater Invertebrate Ecology Network) 182

8 Operationalisation of COAT in SIOS – an example of adaptive ecosystem-based monitoring in practice (COAT) 198

9 Understanding and analysing recurrent warm events in Svalbard: a comprehensive review on land cryosphere (AWARE) 212

10 Assessing anthropogenic and natural aerosol sources in the Arctic: A baseline to detect changes due to climate change (AAA-Source) 228

11 Towards an integrated data-driven infrastructure (InfraNor) 246

12 SIOS' contribution to the ICARP IV process (SICAR) 270

Frequently asked Questions 278

Foreword

When this 7th SESS report is released we will read 2025 in our calendars.

Back in 2005, when I was research director at the Norwegian Polar Institute, I was contacted by a State Secretary at Norway's Ministry of Environment to discuss the possibility of establishing a research infrastructure project in Svalbard that could be relevant for European Strategy Forum for Infrastructures (ESFRI) roadmap, which was imminent at the time. Thus began the journey that we today call SIOS.

At the time, Svalbard's existing research infrastructure was both fragmented and bewildering. Two notable organisations for scientific cooperation were already in place to help scientists navigate the complex, heterogeneous and multi-national character of research in Svalbard. The Ny-Ålesund Science Managers Committee (NySMAC) and Svalbard Science Forum (SSF) were doing – and continue to do – excellent work. But the SIOS initiative remains a journey towards an enhanced and stimulating cooperation to build an efficient research infrastructure. Efficiency is sought both in planning, investment and utilisation for the sake of enhancing science opportunities in Svalbard.

In moments of weakness one can question what has been achieved in 20 years. But a look through the SESS reports generates a surge of confidence and even pride. The scientists have eagerly and meticulously approached the task of providing ideas and suggestions regarding how to develop Svalbard research infrastructures to enhance the scientific output in an Earth system science perspective. Their response to the challenge posed is overwhelming. Including this report, 282 recommendations have been formulated by the scientific community.

These recommendations are to some extent wish lists, but have been constructively crafted. All contributions to the SESS reports are peer reviewed and are much more than wishes; they point out pathways for enhancing research and research infrastructure in Svalbard.

In December 2024 we received an evaluation of the SIOS Knowledge Centre's performance from the Norwegian Research Council[1]. It contains accolades regarding the SESS report and emphasises its paramount significance. The Research Council recommends investing even more resources in the SESS report process.

The evaluation emphasises the need for institutions and stakeholders to engage even more strongly and identify inter-institutional common interests amongst the recommendations of the SESS reports. To date, all too few of the recommendations have been put into practice. The obstacles are at the institutional and funding levels. The scientists are mindful of their responsibilities to write proposals and procure funding but acknowledgement at the institutional level is a prerequisite for success when planning infrastructure investments. The long-term sustainability of the astounding creativity and production that the SESS reports manifest depend on the institutions and stakeholders listening to the advice from the scientific community.

I want to thank all contributors to this SESS report, and all the previous reports as well. I want to thank the SIOS-KC for the persistent and tireless effort they put into making the annual SESS report possible. The SESS reports are a defining and shining star of SIOS.

Longyearbyen, December 2024

Kim Holmén

1 https://www.forskningsradet.no/siteassets/publikasjoner/2024/sios-eval-report-2024.12.06-final-fix.pdf

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Executive Summary

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The annual State of Environmental Science in Svalbard (SESS) report has emerged as an essential tool to summarise, complement, and develop the Earth observing system in Svalbard. SESS report chapters present overviews of the latest state-of-the-art research covering Earth system environments, whilst recommending future research and infrastructure investment, tailored to those specific parts of the Earth system. They are therefore essential for knowledge sharing within the polar community and beyond.

The 7th SESS report addresses a range of themes, some of which have been lacking in previous reports. In addition to ten research chapters, the current report also describes preparations for the next polar year and how Norwegian infrastructure investments have contributed to SIOS. The diversity of this year's report reflects the profound effects of environmental change on Svalbard and the scientific community's urgent drive to capture those effects from different angles. This complexity is further reflected in the increasingly diverse and multi-layered diagram of the themes covered by SESS reports since 2018.

The current report spans the entire scientific realm, from deep in the ground, via ocean, land, and their ecosystems, to the upper atmophere, serving as a testament to the interdisciplinarity of this year's edition and to what SIOS aims to achieve within the polar community.

"Secular shift of the magnetic dip pole and its consequences for auroral boundaries (PoleMotion)" – addresses the consequences of long-term variations in the geomagnetic field. It explores decades of magnetic field observations from Svalbard and observations of auroral boundaries, along with potential impacts on the auroral oval over Svalbard. Long-term changes of the local magnetic field in Svalbard are also examined, as are their effects on navigation and infrastructure.

"Geology of Svalbard: Deep-time and Deep-Earth (SVALGEOL)" – gives an overview of Svalbard's geology and assesses its influences on local and global society. Different geoscientific datasets are outlined, followed by a study covering the pre-Quaternary period and the integration of data from Earth's surface to its interior, both elucidating the variations in global climate over time.

"Surging glaciers in Svalbard: Current knowledge and perspectives for monitoring (SvalSurge)" – discusses the benefits and limitations of different approaches used to monitor and detect glacier surges in Svalbard. The authors provide a new and updated database of Svalbard's surge-type glaciers, highlighting the surge-type behaviour of some of the larger glaciers and potential impacts on different Earth systems.

"Methane in Svalbard (SvalGaSess)" – presents the rising atmospheric methane concentrations and the limited understanding of the processes that drive methane emissions in the Arctic. The potential to use Svalbard as an example of under-studied ice-covered low-land locations is highlighted. Improved knowledge about methane production, removal and transport helps create reliable estimates of present-day and future methane emissions throughout the archipelago. This is vital to help society manage greenhouse gases.

"The Atlantification process in Svalbard: a broad view from the SIOS Marine Infrastructure network (ARiS)" – discusses how oceanic water masses in

the Svalbard region change due to influx of Atlantic Water and interactions between water masses on the continental slope, the shelf and in the fjord systems (called "Atlantification"). It presents marine time series spanning the last two decades.

"Microbial communities as sentinels of environmental changes in Svalbard (MicroSIOS)" – gives an overview of microbial communities in Svalbard, focusing on poorly studied connections with climate change, chemical pollution, antibiotic resistance, and spread of pathogenic species. Insights into the use of microbial variables as proxies of environmental changes are outlined.

"Terrestrial and freshwater invertebrate science in Svalbard in a changing world: from regional to pan-Arctic scales (STAFIEN)" – summarises current knowledge and investigates the significance of invertebrates in the Arctic. It identifies key knowledge gaps, opportunities and data requirements concerning the regional invertebrate fauna and examines how SIOS could contribute to closing those gaps.

"Operationalisation of COAT in SIOS – an example of adaptive ecosystem-based monitoring in practice (COAT)" – The COAT project is an ecosystem-based long-term biosphere monitoring tool essential to assessing impacts on terrestrial ecosystems. Here, the essence of the climate monitoring network and the five biotic monitoring modules are presented, along with a description of their status.

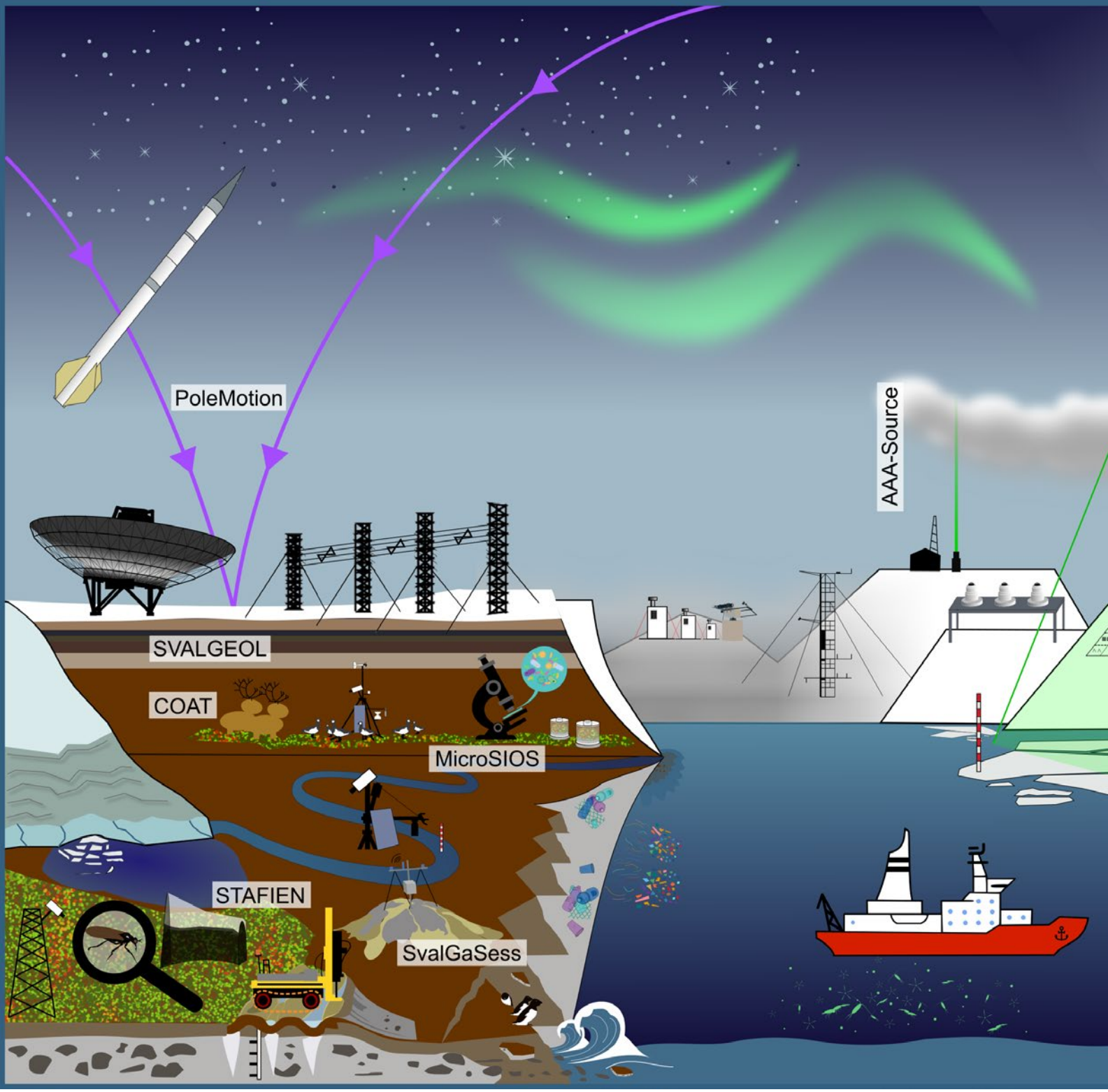
"Understanding and analysing recurrent warm events in Svalbard: a comprehensive review on land cryosphere (AWARE)" – focuses on extreme temperature events (heatwaves) and their implications for Svalbard's fauna and inhabitants. While rain-on-snow events can be detected with satellite remote sensing and atmospheric analysis, assessing their repercussions on Svalbard's environment, economy, and communities requires further investigation and close cooperation between scientific disciplines.

"Assessing anthropogenic and natural aerosol sources in the Arctic: A baseline to detect changes due to climate change (AAA-Source)" – discusses current Arctic aerosol composition and sources and presents existing data on its main and trace components. It aims to inform citizens and policymakers about the present-day aerosol composition in the Arctic and enable modellers to predict the future state of Arctic aerosols.

"'Towards an integrated data-driven infrastructure (InfraNor)'" – The InfraNor project illustrates the importance of national investments in research infrastructure in Svalbard and its surrounding oceans. Emphasis is on upgrading existing and establishing new infrastructure to achieve a more coherent dataset among sites with similar instruments, thus enabling comprehensive research on urgent Earth system science questions. New technology can also reduce the footprint of future scientific activities in Svalbard.

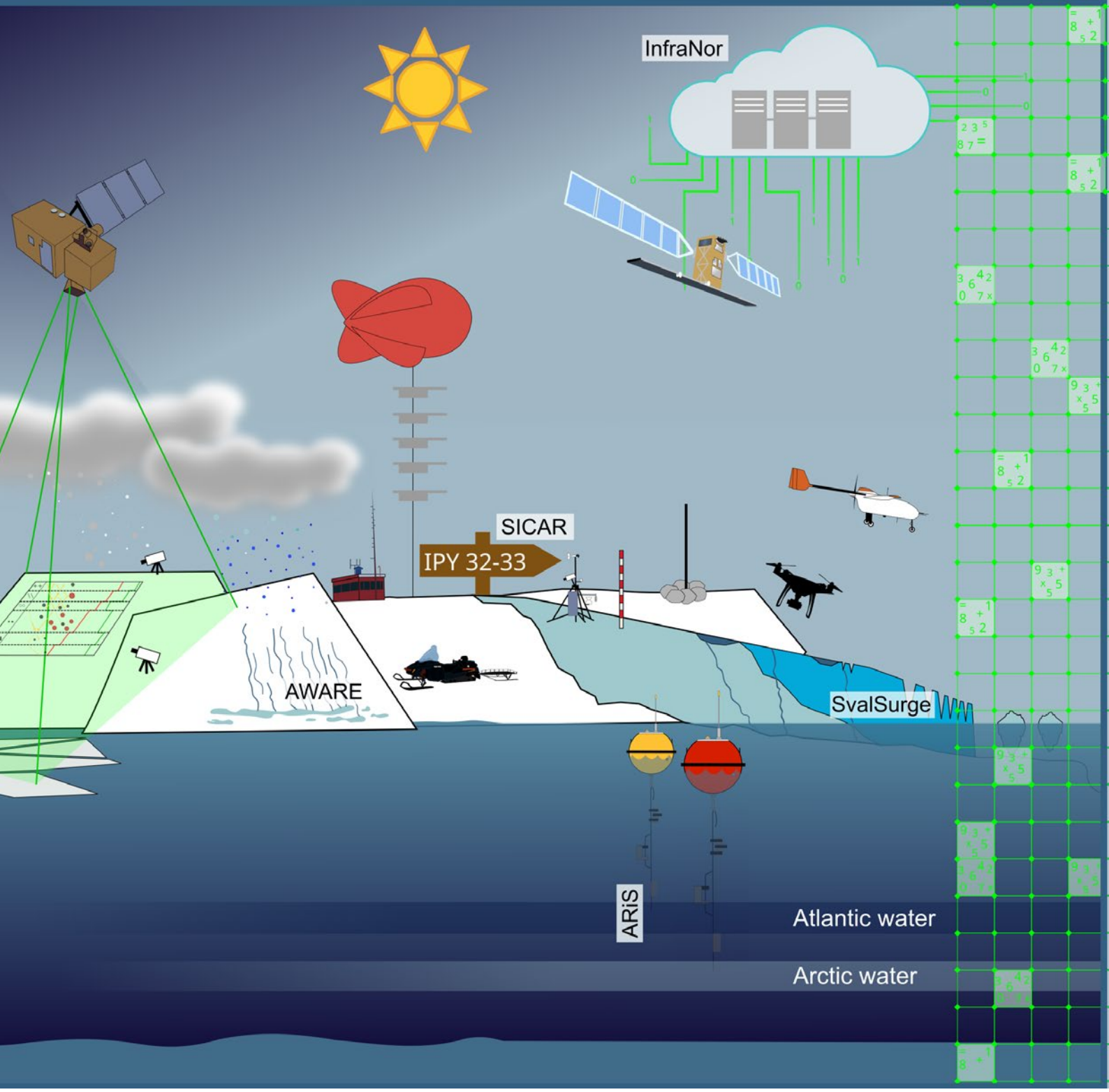
"SIOS' contribution to the ICARP IV process (SICAR)" – ICARP IV invites community-wide engagement to prepare for research planning for the next decade. SIOS' input was based on a workshop with group and panel discussions, and recommendations from previous SESS reports, weighted for pan-Arctic relevance.

We thank all authors for their dedication and contributions to this 7th SESS report. Its thematic diversity emphasises the importance of an interdisciplanary approach to monitoring recent and future developments in Svalbard and beyond.



Legend

- Svalbard grazers
- Seabirds
- Zoo- and Phytoplank-ton
- Plastic litter
- Magnetic field lines
- Snow covered land
- Sea ice and land fast sea ice
- Glaciers
- Partly ice-covered lake
- Coastal erosion
- Rain on snow
- Permafrost degradation, ground instability and ice wedges
- Pingo with measurement station
- Geological time scales
- Microscope with bacteria
- Insect and magnifying glass
- Malaise trap
- 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 the chapters in the current report are shown. (Figure: Floor van den Heuvel)

CHAPTER 1

EISCAT Svalbard radar with aurora. (Photo: Katie Herlingshaw)

Secular shift of the magnetic dip pole and its consequences for auroral boundaries (PoleMotion)

Click here for full chapter

HIGHLIGHTS

- The Earth's northern magnetic dip pole has moved 1500 km over 30 years.
- Geomagnetic field changes have led to an equatorward shift of the auroral oval over Svalbard.
- Magnetic field observations in Svalbard show an unexpected increase in strength despite models suggesting a weakening dipole moment.

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The Earth's northern magnetic dip pole has shifted approximately 1500 km over the past 30 years, moving several tens of kilometres annually due to changes in the flow of metal alloys within Earth's interior. The geomagnetic field influences the aurora's location, leading to questions about whether it shifts with the magnetic pole. This work investigates long-term geomagnetic field variations and their impact on the auroral oval, as observed in Svalbard. Observations of the magnetic field at Hornsund, Svalbard, reveal a magnetic field rotation consistent with the dip pole motion.

Using satellite remote sensing, we show that the aurora over Svalbard is slowly but consistently moving equatorward. Observations using the EISCAT Svalbard radar seem to confirm this motion, though more investigations are needed before definitive conclusions can be drawn from EISCAT.

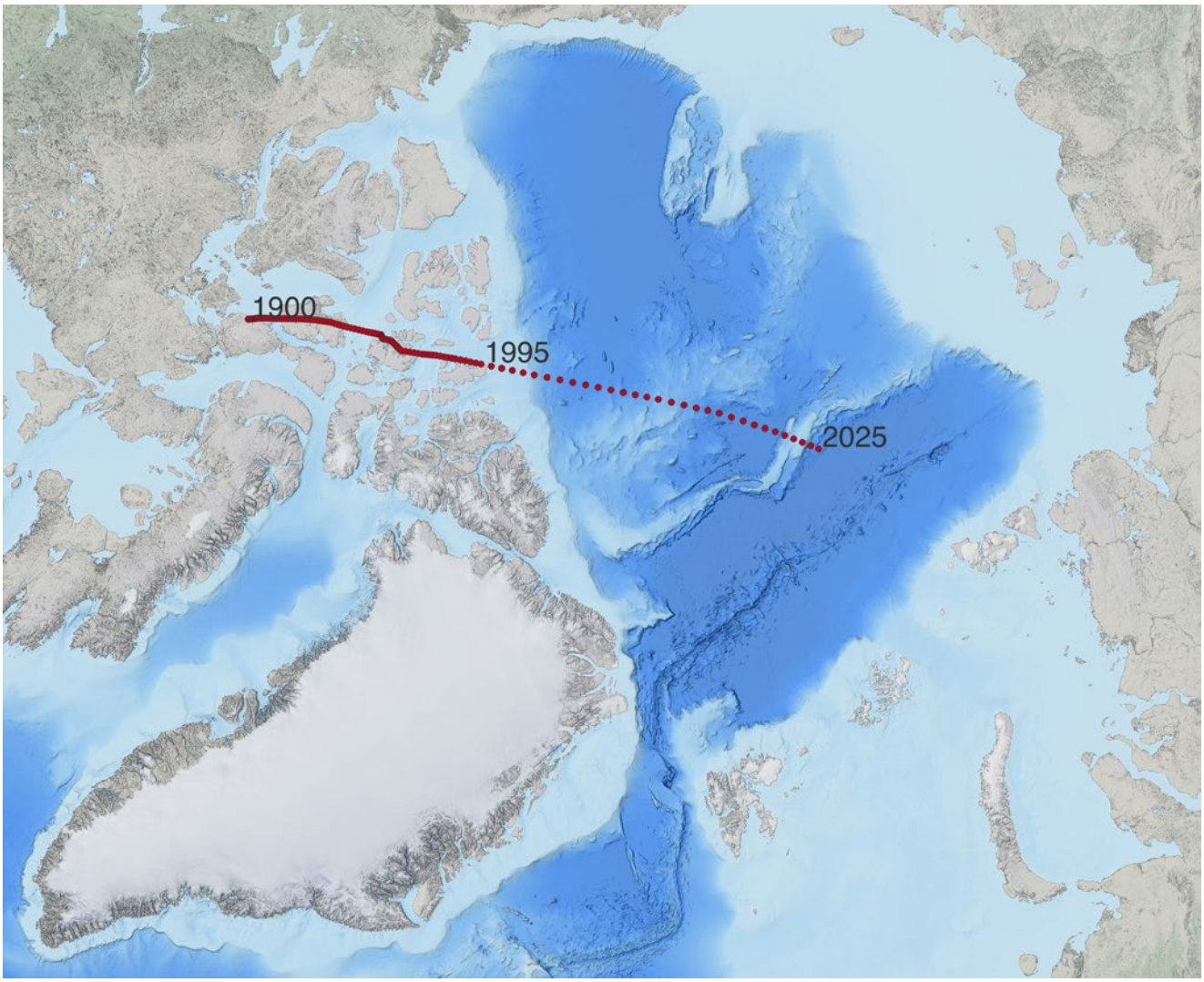
Variations in the local magnetic field have significant societal implications, particularly for navigation and infrastructure in Svalbard. The magnetic field remains crucial for navigation, and any changes

in magnetic field direction imply that maps and navigation aids need to be updated. For example, runway designations and approach procedures at airports are based on magnetic orientation. These must be revised as the magnetic field changes. At Longyearbyen airport, runway designations were recently changed due to changes in the geomagnetic field.

Workers updating the runway signage at Longyearbyen airport due to changed magnetic field. (Photo: Ine Therese Pedersen)

RECOMMENDATIONS

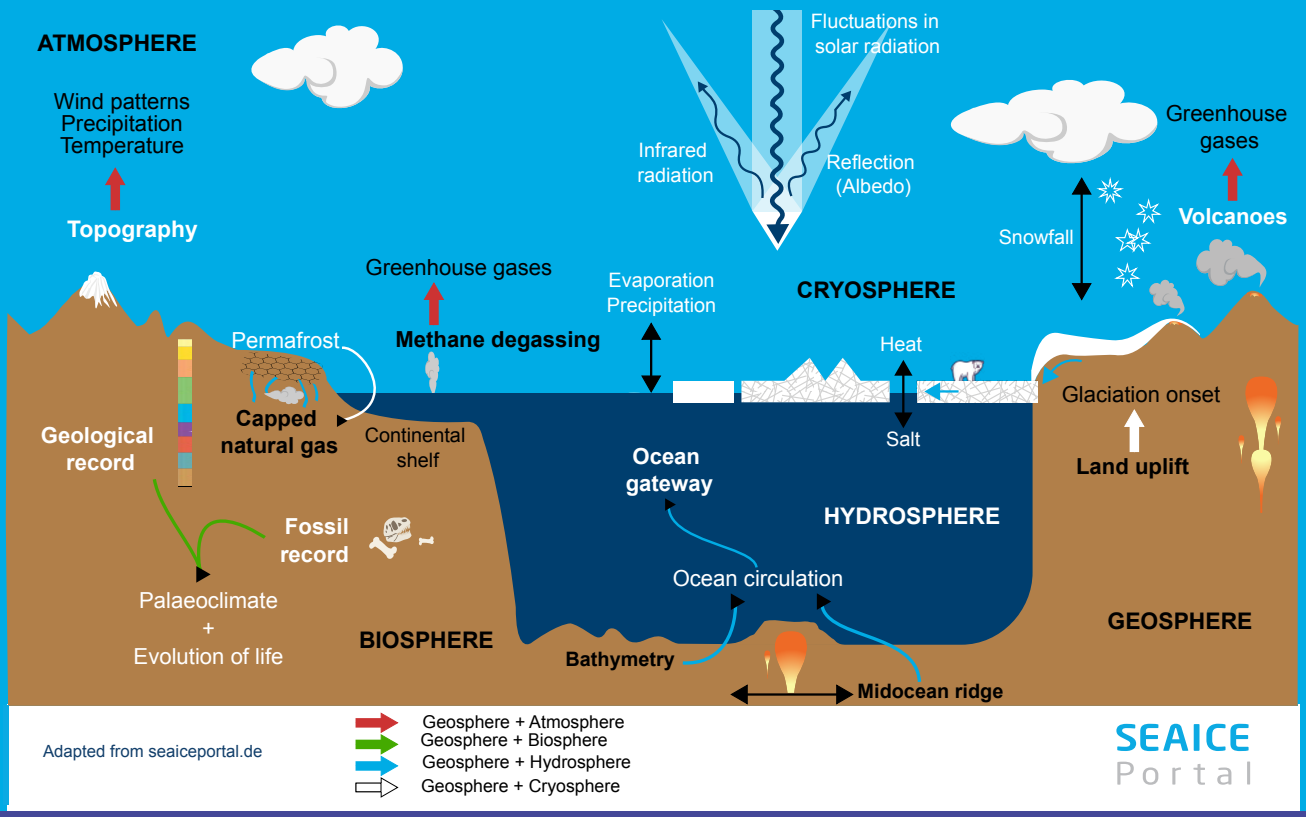
- Harmonise Data Formats and Integration: Standardise and harmonise the data formats for magnetic field measurements from Svalbard and make them accessible through the SIOS Data Access Portal.
- Standardise Satellite Data Formats and Documentation: Ensure that all remote sensing data, especially from satellites, are available in a single, well-documented file format with proper metadata.
- Enhance Ground-Based Instrumentation Compatibility: Develop strategies to ensure that data from the next generation of ground-based instruments, like the EISCAT 3D radar, are comparable with existing systems despite differences in their operational characteristics.



Map showing the movement of the magnetic dip pole over the last 125 years. Since 1995, the dip pole has moved approximately 1500 km. (Map: Lindis Bjoland)

CHAPTER 2

Interaction of the geosphere with the atmosphere, biosphere, hydrosphere and cryosphere. Colours of the arrows indicate main sphere interaction described by the processes. Figure adapted from the SEAICE Portal, Alfred Wegener Institute (2024).



Geology of Svalbard: Deep-time and Deep-Earth (SVALGEOL)

Click here for full chapter

HIGHLIGHTS

- Svalbard's settlements and infrastructure are controlled by the surrounding geology and associated coal resources
- Svalbard's rocks allow us to study climate evolution over the past 500 million years
- Deep-Earth processes in Svalbard's crust and mantle are associated with earthquakes, land uplift and past volcanism

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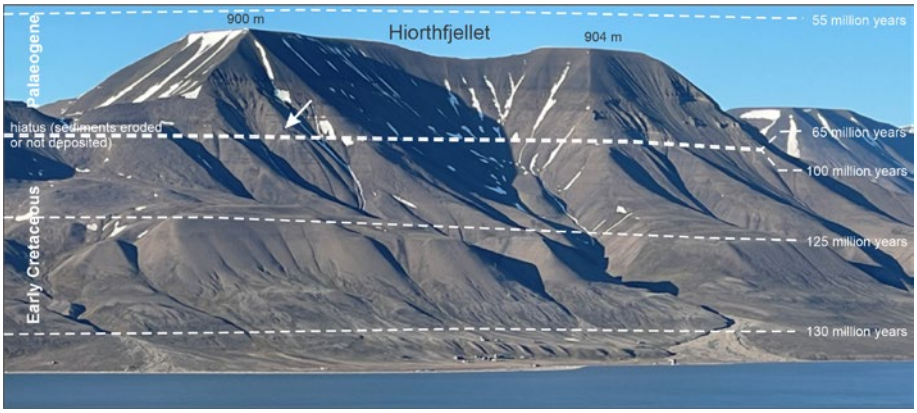
Geology is omnipresent in Svalbard, defining among other parameters the location of all major settlements. The SVALGEOL chapter provides an overview of the geology of Svalbard, and how it influences local and global society. We briefly describe the history of geological exploration and mapping of Svalbard, before outlining the various data sets geoscientists use in their work. We then focus on two key aspects of geology: the study of "deep-time" (i.e., rocks older than 2.58 million years; the pre-Quaternary period) and the study of "deep-Earth" (i.e., integration of data from Earth's surface to the interior). By investigating the Earth System at the scale of millions to billions of years, geologists can decipher how the global climate has varied through time. Furthermore, studying different proxies allows us to investigate the processes linking the geosphere with the biosphere (e.g., evolution of life, recovery following mass extinctions). By using field and various geophysical data, geologists can understand the properties of the Earth from its surface to its core, and the processes causing them. Furthermore, by coupling deep, shallow and surface observations with a time component, geoscientists can characterise the underlying processes that also influence society (e.g., natural gas emissions, permafrost development, geothermal potential, earthquakes).

RECOMMENDATIONS

We recommend that the geosphere is more tightly integrated into SIOS activities. Specifically, in arenas where a geoscientific "geospatial" approach can be used as a foundation to characterise relationships between the geosphere and other spheres. We have outlined five major recommendations in the SVALGEOL chapter, each with a series of concrete implementations, namely:

- GEOSPHERE: Further promote and support the geosphere as a key element within the SIOS community.
- DATA MANAGEMENT: Support geoscientists in making their heterogeneous data sets findable, accessible, inter-operable and re-usable (i.e., FAIR).
- STORAGE: Actively support proper documentation, re-use and long-term storage of physical geological material.
- DATA PRODUCTS: Transform geoscientific data into products with societal or scientific relevance.
- CONNECTION: SIOS should use its role as a platform to further connect the geosphere with other scientific communities.

Geologists studying Devonian outcrops at Søre Bolleneset in Dicksonfjorden as part of the UNIS AG-X51 course on Arctic Tectonics and Volcanism in October 2022 (see Senger et al. (2024d) for details on the course). The QR codes point to short videos giving insights into geoscientific fieldwork, such as the Svalbox data acquisition campaign to Van Keulenfjorden in 2021 and an international research expedition to Woodfjorden in 2023. (Photo: Fenna Ammerlaan)



The mountain Hiorthfjellet (seen here as viewed from the shooting range) provides a spectacular backdrop for everyday life in Longyearbyen and illustrates the societal relevance of geology (i.e., coal mine entrance, white arrow) and the largest "gap" of 34 million years in the geological record between the Early Cretaceous and the Palaeogene (Photo: Kim Senger). Annotations inspired by Piepjohn et al. (2012).

CHAPTER 3

The terminus of Borebreen in April 2024 during the peak of its surge. In winter 2023/24, the glacier doubled in speed and the front destabilised, forming a chaotic pattern of crevasses. (Photo: Richard Hann)

Surging glaciers in Svalbard: Current knowledge and perspectives for monitoring (SvalSurge)

Click here for full chapter

HIGHLIGHTS

- We have compiled a new database of glacier surges in Svalbard and key surge characteristics.
- There are considerable observational gaps in documenting surges, including velocity changes and impacts of surges on glacier mass balance.
- We need to extend the observational time series of glacier surges through palaeo-glaciological analysis and interpreting historical archives.

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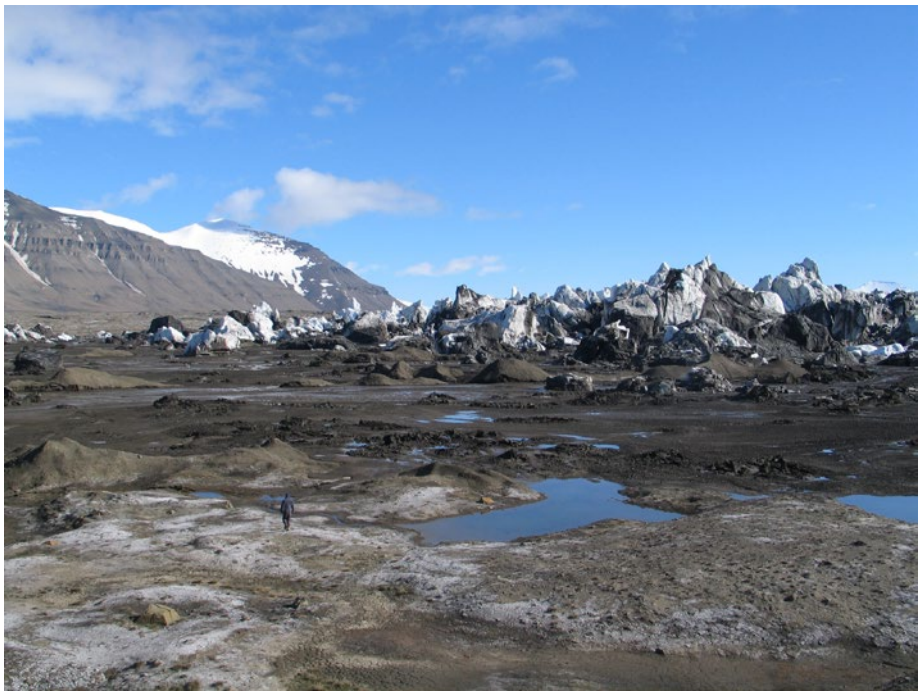
Glacier surges are cycles of long-lasting slow flow followed by a relatively short phase of fast flow where a glacier undergoes a 10/100-fold increase in velocity. These cycles are driven by internal ice dynamics and are not related to external forcing. In this chapter, we review the benefits and limitations of different approaches for monitoring and detecting glacier surges in Svalbard. Since 2000, satellite monitoring has enabled detection of most large surges, and the launch of the Copernicus Sentinels since 2014 has further enhanced our monitoring capabilities. In the satellite era (1970s onwards), surges have been detected based upon tracking the speed of glaciers over time, elevation changes, and more recently automatically detecting surface changes related to a surge such as increased crevassing. Geophysical sensors are critical for observing subglacial conditions and further work is required to improve deployment strategies on

heavily crevassed glaciers. Furthermore, we have compiled a new and updated database of surge-type glaciers in Svalbard and find that 36% of glaciers display surge-type behaviour, rising to 51% when removing glaciers smaller than 1 km^2. Only 9% of glaciers have been directly observed to surge. Surges have a significant impact on glacier mass balance, but their impact is variable in time. Therefore, we need to closely monitor when surges occur and how much ice is discharged downglacier and subsequently lost. This has implications for regional mass balance, sea level rise, and the influx of freshwater into the ocean which alters ocean circulation patterns and marine ecology.

RECOMMENDATIONS

- Develop a portable "glacier observing system" consisting of geophysical instruments and GPS sensors that can be rapidly deployed on an actively surging glacier to study subglacial conditions and ice dynamics.
- Improve quantification of the impact of surges on mass balance, e.g., combining close-range sensors with satellite observations of surface elevation change.
- Generate long-term data sets of glaciers surges in Svalbard (e.g., velocity, volume, terminus change).
- Systematically catalogue fundamental surge behaviour (e.g., surge onset year, surge termination year, terminus change, max velocity in active phase, mean velocity in the quiescence phase).
- Analyse and document the processes that trigger a surge, through which a classification of surge triggers may be generated.

The surge front of Scheelebreen on 5 April 2022. Scheelebreen was land-terminating until the surge led to a terminus advance, transitioning the terminus to marine-terminating. 3D model can be found here: https://skfb.ly/o9nCn. (Photo: Erik Schytt Mannerfelt)



The surging front of Nathorstbreen, Van Keulenfjorden, in summer 2012. The advancing glacier pushed and thickened seafloor muds until they broke the fjord surface, grounding ice blocks that had broken off the heavily fractured front. (Photo: Harold Lovell)

CHAPTER 4

Wetlands in Adventdalen, an ideal site for active layer methane dynamics, studied here using automatic chambers in its ice wedge polygons. (Photo: Norbert Pirk)

Methane in Svalbard (SvalGaSess)

Click here for full chapter

HIGHLIGHTS

- Data from Ny-Ålesund, Svalbard contributes to the global network documenting rising atmospheric methane levels
- Methane from microbial and geological sources is slowly released from Svalbard's glacier margins, wetlands and fjords
- Major methane outbursts from beneath permafrost and glaciers have occurred in the past

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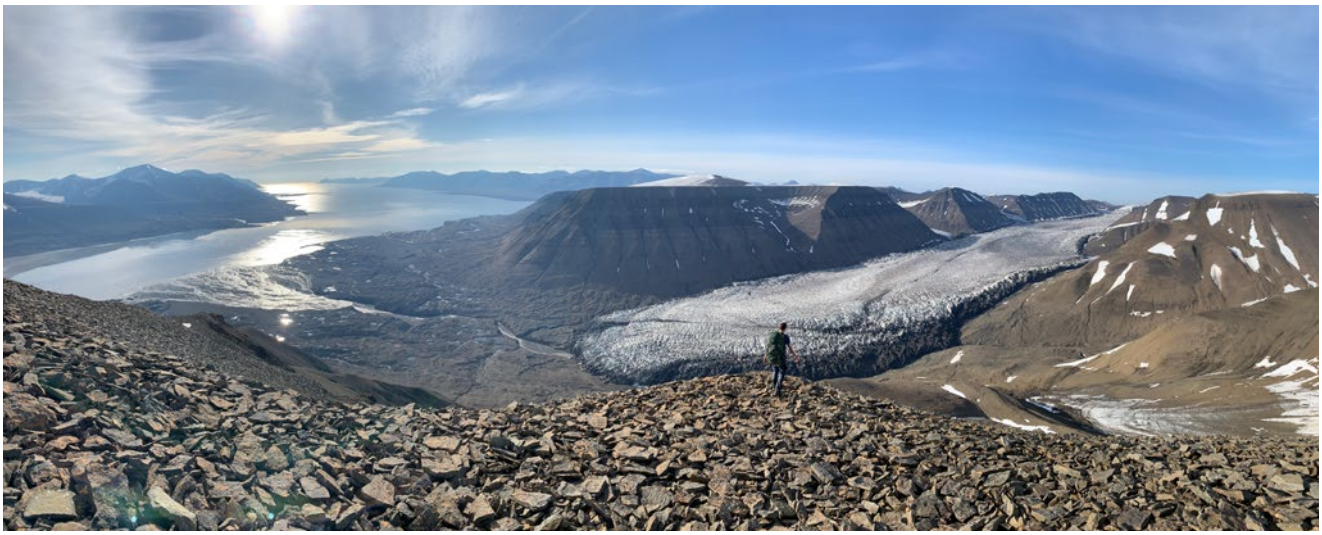
Methane is a powerful greenhouse gas whose emission into the atmosphere from Arctic environments is increasing in response to climate change. At present, the increase in atmospheric methane concentrations recorded at Ny-Ålesund and globally threatens the Paris Agreement goal of limiting warming to 2 degrees, preferably 1.5 degrees, by increasing the need for abatements. However, our understanding of the physical, chemical and biological processes that control methane in the Arctic are strongly biased towards just a few lowland sites that are not at all like Svalbard and other similar mountainous, ice-covered regions. Svalbard can therefore be used to better understand these locations.

Svalbard's methane stocks include vast reserves of ancient, geogenic methane trapped beneath glaciers and permafrost. This methane supplements the younger, microbial methane mostly produced in waterlogged soils and wetlands during the summer and early winter. Knowledge about the production, removal and migration of these two methane sources in Svalbard's complex landscapes and coastal environments has grown rapidly in recent years. However, the need to exploit this knowledge to produce reliable estimates of present-day and future emissions of methane from across the Svalbard landscape is now paramount. This is because understanding these quantities is absolutely necessary when we seek to define how society must adjust in order to better manage greenhouse gases in Earth's atmosphere.

RECOMMENDATIONS

- We recommend the initiation of systematic, interdisciplinary studies so that methane-relevant processes and budgets can be quantified for the different terrestrial and aquatic habitat types across Svalbard.
- We also propose to make Svalbard a more important node for quantifying the Arctic methane budget through infrastructural investments near settlements that promote calibration of forthcoming satellite data products and standardisation/harmonisation of emerging technology (such as low-cost sensors or drones).
- We also recommend more specific research actions targeting process uncertainty, such as fluid migration dynamics beneath permafrost, glaciers or fjords.

A methane seep at Førstehytte Pingo in Adventdalen: one of four pingos in the valley where methane is released all year. (Photo: Andy Hodson)



Vallåkrabreen in Central Svalbard, recently described in the first studies of methane release from Svalbard's glacial drainage systems and now experiencing a powerful surge. (Photo: Gabby Kleber)

CHAPTER 5

K-Lander deployment at Sørkapp, southern Spitsbergen. (Photo: Bénédicte Ferré)

The Atlantification process in Svalbard: a broad view from the SIOS Marine Infrastructure network (ARiS)

Click here for full chapter

HIGHLIGHTS

Atlantification (i.e., the increasing influence of Atlantic waters) is an ongoing process in Svalbard leading to ocean warming. Several long-term time series from marine observatories from south to north of Svalbard show both seasonal patterns, multi-year cycles and long-term changes, including sea water freshening since 2018.

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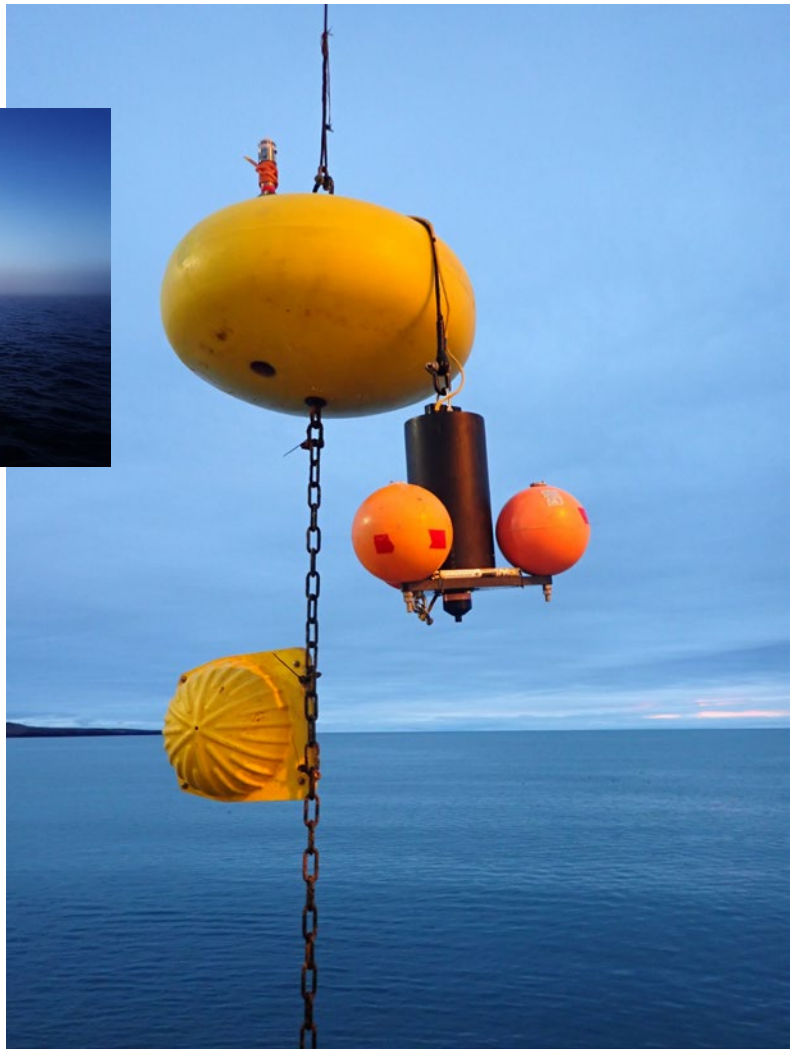
Arctic marine systems are vital to the Earth's ecological and climatic balance and harbour a unique biodiversity adapted to extreme conditions. However, they are under unprecedented threat from climate change, in particular from "Atlantification", i.e., the loss of sea ice and the increasing influence of Atlantic Water (AW) in this region. Long-term observatories are crucial to detect even small changes in these dynamic ecosystems. Svalbard, with its easily accessible infrastructure, is a strategic location for studying these changes. We have identified marine time series that clearly illustrate the signature of Atlantification in the Svalbard region over the last two decades. These time series provide insight into the propagation of AW and the interaction between the continental slope, the shelf and the fjord systems. Seasonal and multi-year temperature and salinity patterns illustrate the varying influence of AW, with long-term variability showing, among others, a freshening phase since 2018, possibly related to North Atlantic freshwater anomalies.

RECOMMENDATIONS

- MAINTAIN: Long-term deep-sea observation systems south and north of Spitsbergen to record the variability of the Atlantic Water inflow.
- PLAN: Opportunistic and systematic Conductivity-Temperature-Depth (CTD) measurements in understudied areas, possibly with Atlantic–Arctic Distributed Biological Observatories (A-DBO) collaboration.
- HARMONISE: Extensive application of oxygen sensors to monitor deep-water ventilation and ecosystem changes linked to Atlantification.
- IDENTIFY: Key sites for ocean warming monitoring, encouraging shared marine infrastructure from multiple institutes.
- INVESTIGATE: Carbon sequestration linked to polar zooplankton migration because of Atlantification.

Arctic fogbow at the marginal ice zone in summer 2023. (Photo: Manuel Bensi)



Mooring deployment in Kongsfjorden: buoyancy and ballast recovery system. (Photo: Daniel Vogedes)

CHAPTER 6

Wetlands and thawing permafrost in Adventdalen. (Photo: Agata Zaborska, IOPAN)

Microbial communities as sentinels of environmental changes in Svalbard (MicroSIOS)

Click here for full chapter

HIGHLIGHTS

- Microbial community dynamics are affected by environmental changes
- Microbial diversity is a suitable tool to monitor ecosystem health
- The study of microbiological variables is fragmentary and geographically limited in Svalbard
- The study of bacterial antibiotic resistance should be harmonised

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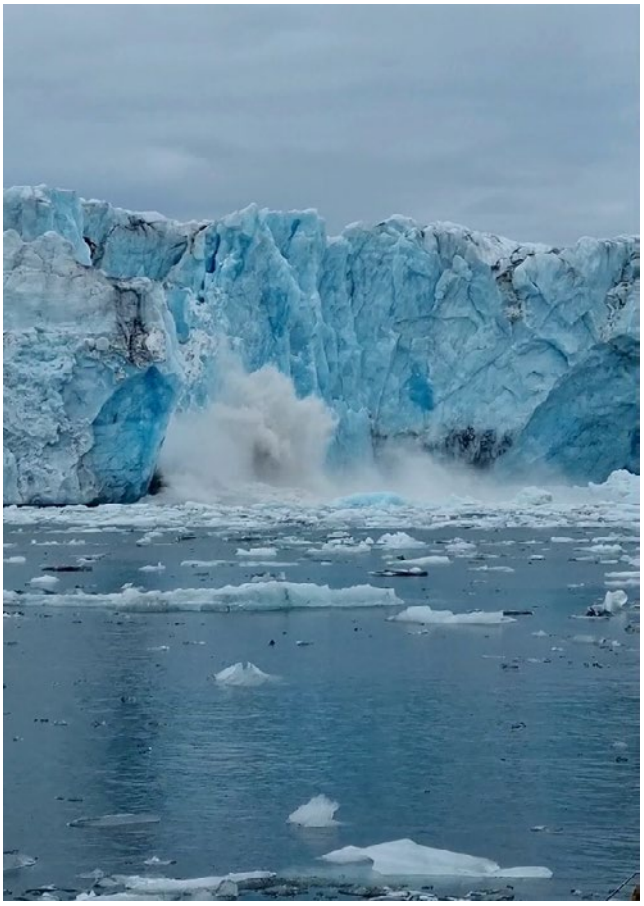
Svalbard's ecosystems are vulnerable to climate change and pollution, and monitoring systems in this region are crucial. Although microorganisms are major drivers of biogeochemical cycles in Arctic ecosystems, microbiological variables are not yet comprehensively monitored. Microbial communities are sensitive to change and could therefore serve as environmental sentinels. Moreover, development of pathogenic bacteria and antibiotic resistance could threaten both ecosystems and human health, especially in sensitive areas such as the high Arctic. A more uniform and efficient monitoring and data collection system is needed to understand the microbial ecosystems of the present and detect changes in a future warming Arctic.

This chapter gives an overview of current knowledge about Svalbard's diverse microbial communities, their connections with climate

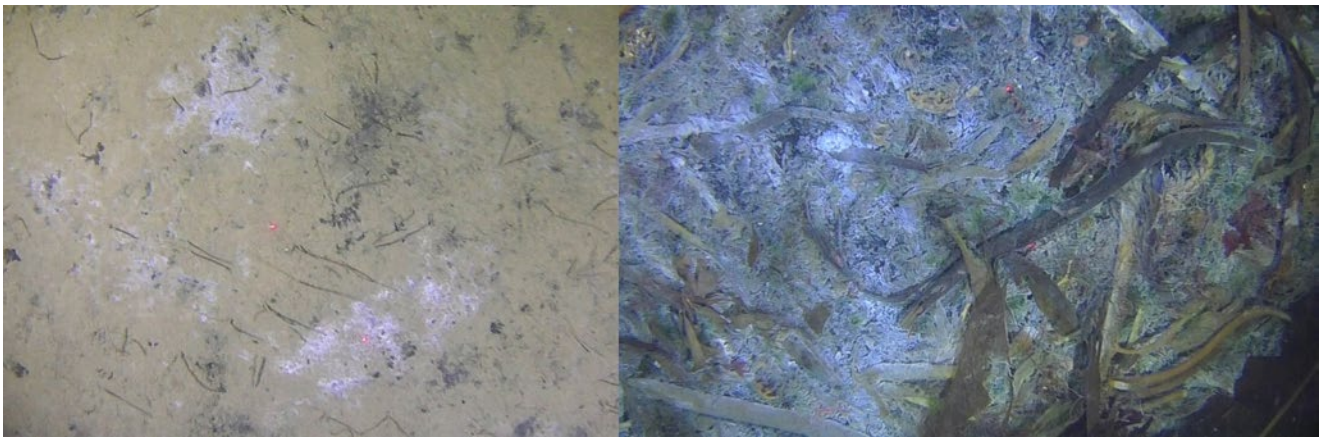
change, chemical pollution, antibiotic resistance, and the potential spread of pathogenic species. We also suggest guidelines for future microbial community monitoring and use of microorganisms as environmental sentinels.



Calving of the retreating and intensively melting Storbreen glacier, Hornsund. (Photo: Agata Zaborska, IOPAN)

RECOMMENDATIONS

- MICROBIAL PROXIES – Define a clear set of microbial variables to test microbes for suitability as potential sentinels of environmental changes in Svalbard.
- LONG-TERM MONITORING PROGRAMMES – Encourage supplementation of existing marine and terrestrial infrastructure with technological systems that would enable collection of long-term data time series on microbial ecology in key areas of Svalbard and in seasons that are poorly covered at present.
- IMPLEMENTATION – Promote a spatially well distributed long-term microbial survey, prioritising studies in eastern Svalbard. Identify regional hotspots of climate change.
- INTERDISCIPLINARITY – Integrate analysis of environmental and microbial community variables to relate microbial communities to other disciplines. Include microbial variables in climate models.
- HARMONISATION AND STANDARDISATION – Draft a handbook of standardised procedures and harmonised management of data on microbial abundance/structure/function. Define antibiotic resistance breakpoints for the Arctic.



Microbial mats at the bottom of Yoldiabukta and Hornsund. (Photo: Kajetan Deja, IOPAN)

CHAPTER 7

Dagger fly covered with pollen sitting in a flower, demonstrating the importance of these insects in pollination in regions like Svalbard where specialised pollinators such as bees do not occur. (Photo S.J. Coulson)

Terrestrial and freshwater invertebrate science in Svalbard in a changing world: from regional to pan-Arctic scales (STAFIEN - Svalbard Terrestrial and Freshwater Invertebrate Ecology Network)

Click here for full chapter

HIGHLIGHTS

Invertebrates are an integral part of all terrestrial and freshwater ecosystems yet their ecology is poorly understood in the Arctic. Svalbard provides a unique location for strengthening multidisciplinary knowledge of these organisms and understanding their role and resilience in a changing world.

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Invertebrates are ubiquitous. Diverse in form and function, they play crucial roles in ecosystems: for example as food for other organisms, as pollinators, and as decomposers. Invertebrate species vastly outnumber vascular plants, birds and mammals combined, but we know little about them and their roles due to challenges in identification, sampling, access, and funding.

One of the world's fastest changing environments, Svalbard is also a hotspot for multidisciplinary environmental research, ideal for studying responses to change. Nonetheless, comprehensive

biodiversity surveys across Svalbard are still needed, to better inform governance actions aimed at protecting this unique environment.

Research on Svalbard's terrestrial and freshwater invertebrate community is key to understanding resilience and vulnerability to environmental change. Upscaling results from Svalbard will help us assess threats and consequences across the whole Arctic.

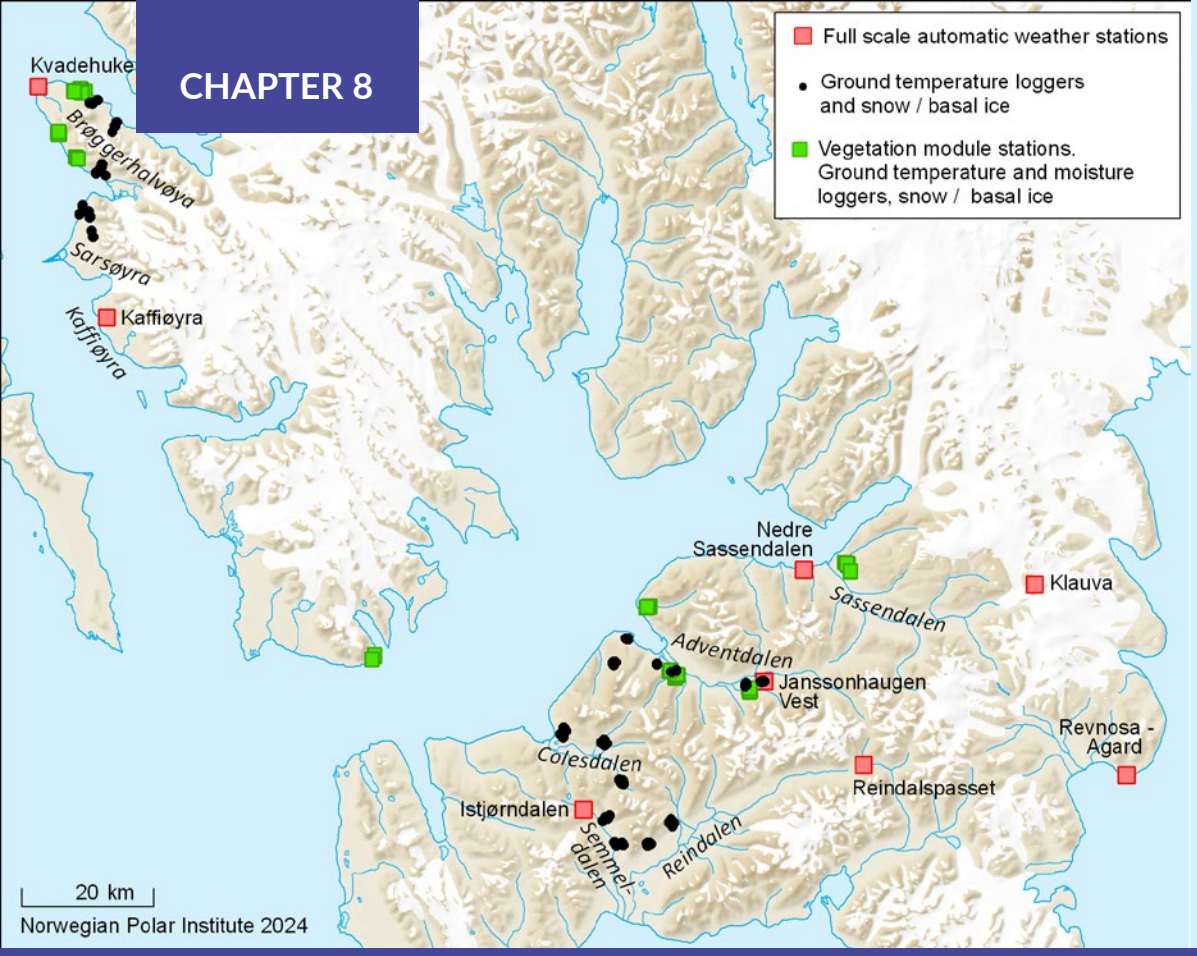
RECOMMENDATIONS

- *Document biodiversity and drivers of change over time.* Knowledge of the current invertebrate fauna is key to documenting change. However, a serious lack of baseline and long-term data prevents even basic analyses.
- *Secure logistical and infrastructural support for sustained invertebrate research in Svalbard.* Many invertebrate populations vary in size greatly from year to year. Documenting a response to environmental change requires multi-year data collection to distinguish long-term responses from year-to-year fluctuations.
- *Collaborate more.* The logistics Arctic research require that disciplines collaborate and exploit science opportunities judiciously. There are clear opportunities for broader collaboration, for example the tourist industry, the Governor's office, or institutions doing environmental monitoring of Svalbard, to gain access to less accessible regions.
- *Create online collaboration tools to enhance data collection.* Each discipline has methods and protocols that must be followed to obtain reliable data. Tools such as a protocol handbook enable closer collaboration with other players in Svalbard.
- *Leverage SIOS to unlock new research opportunities.* With its broad scientific network, SIOS can promote invertebrate science in Svalbard and for interdisciplinary collaboration on sample collection during fieldwork and other research activities.

The endemic (i.e. only known from Svalbard) aphid *Acyrthosiphon svalbardicum* on *Dryas* flower. The local distribution of this species is limited by summer temperatures, and it only occurs on *D. octapetala* in warm and sunny locations where the ground is released from winter snow cover early in the spring. (Photo S.J. Coulson)

Example of the diversity of microarthropods recovered from a soil and vegetation extraction, including springtails, mites, spiders and beetles. (Photo S.J. Coulson)

CHAPTER 8



Map of the COAT Svalbard climate monitoring network, including eight full-scale automatic weather stations and > 300 ground surface temperature loggers (2 cm below ground), and the vegetation monitoring stations (N=57) where a suite of climate-related variables is collected. Note that symbols group sites for both loggers and vegetation monitoring stations. Map: Anders Skoglund / Norwegian Polar Institute

Operationalisation of COAT in SIOS – an example of adaptive ecosystem-based monitoring in practice (COAT)

Click here for full chapter

HIGHLIGHTS

The Climate Ecological Observatory for Arctic Tundra (COAT):

- Is an adaptive, ecosystem-based, long-term monitoring programme for Norwegian low and high Arctic tundra ecosystems.
- Implements five biotic monitoring modules, focusing on climate sensitive, key components of the terrestrial food web, and a climate monitoring network.
- Is in a long-term, operational phase of the monitoring.

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COAT is a long-term observation system for real-time detection, documentation, understanding and prediction of climate impacts on Norwegian Arctic tundra ecosystems. During 2016–2023, COAT set up research infrastructure for data collection, field logistics and data management across five food web monitoring modules, covering key components (predators, herbivores, vegetation) and a climate monitoring network. Since 2024, COAT receives state funding for the operational phase.

The long-term monitoring utilises automated (e.g., camera traps, sound stations, telemetric devices), and semi-automated (e.g., drones and satellites) infrastructures and manual field measurements (e.g., censuses of abundance, demography and vital rates, herbivore

exclosures). The study designs and measurements capture climate gradients and contrasting management regimes.

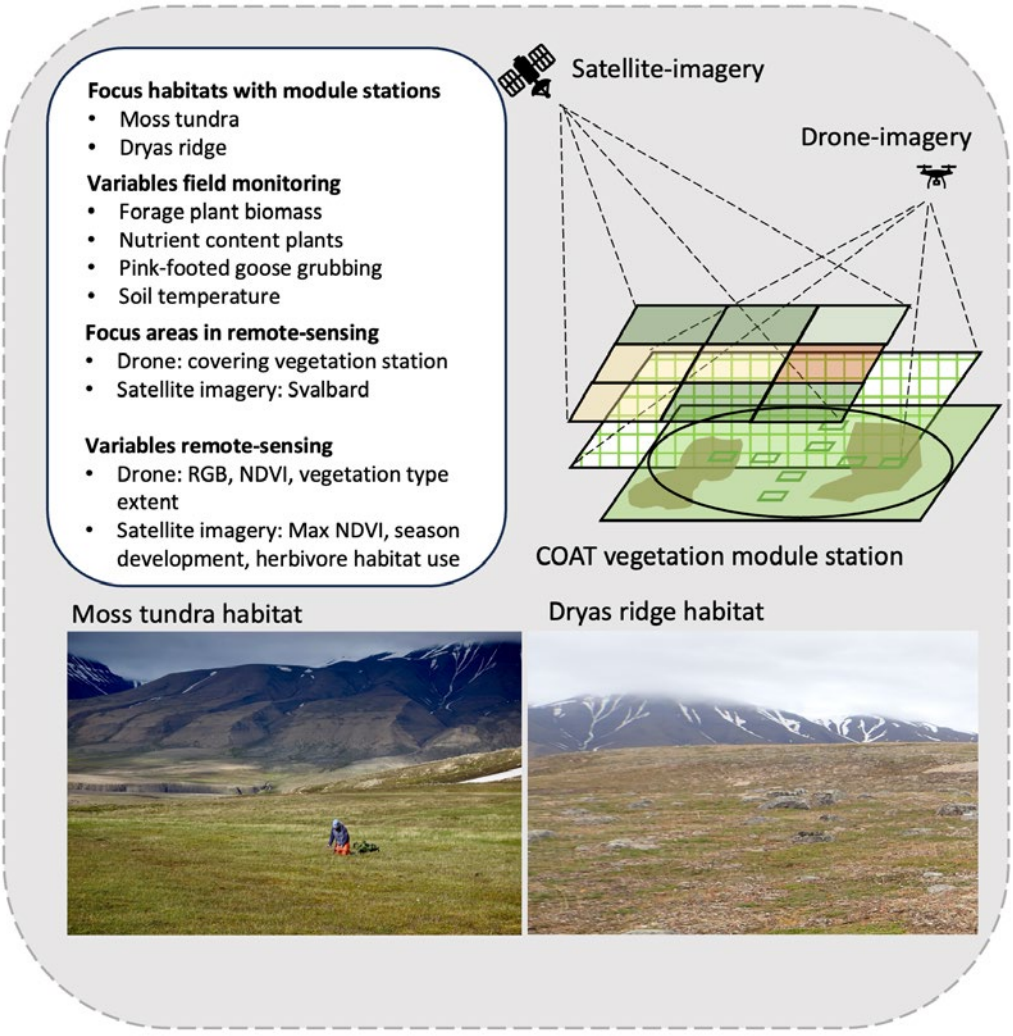
Eight full-scale automatic weather stations and over 300 ground surface temperature loggers form the core of COAT's climate monitoring network. The stations provide hourly real-time data on central climatic variables (e.g., air, soil and permafrost temperatures, precipitation, and snow depth), all likely drivers of ecosystem components, and essential for monitoring basal ice cover, snowmelt timing, permafrost thawing and season start.

Svalbard has had three consecutive record-breaking summers (2022–2024). The rapid and substantial changes in climatic conditions, particularly rising surface and permafrost temperatures, longer, warmer growing seasons, and shorter snow-covered season, are impacting the terrestrial ecosystem. Herbivore abundances are increasing in response to the prolonged snow-free season, greening and warmer winters, which increase forage availability and thus survival and reproduction. COAT does extensive field-based monitoring of vegetation, producing data to improve understanding of bottom-up processes in the terrestrial food web.

RECOMMENDATIONS

We suggest COAT should:

- Quantify the conceptual models, including multi-driver analyses with climate and management as the main impact pathways, for the biotic modules not yet quantified.
- Develop short-term, iterative predictive models for key components of the terrestrial food web, based on quantified causal relations, to provide management recommendations.



Overview of the study designs, focal habitats and variables collected at the 57 vegetation monitoring module stations in the two COAT Svalbard regions – Brøgger Peninsula in the northeast, and Nordenskiöld Land in central Spitsbergen. (Photos: Jakob Assmann, NPI (left), Virve Ravolainen, NPI (right))

CHAPTER 9

Water pool formation near the NCU Polar Station on Kaffiøyra after the April 2019 RoS event. (Photo: Ireneusz Sobota, NCU)

Understanding and analysing recurrent warm events in Svalbard: a comprehensive review on land cryosphere (AWARE)

Click here for full chapter

HIGHLIGHTS

- Increased frequency of extreme events in the Svalbard archipelago during winter
- Direct consequences of extreme events on the annual coastal snowpack and hydrological system
- Direct impact of extreme events on the ecosystem and local fauna
- Improved definition of metrics for the identification of extreme events

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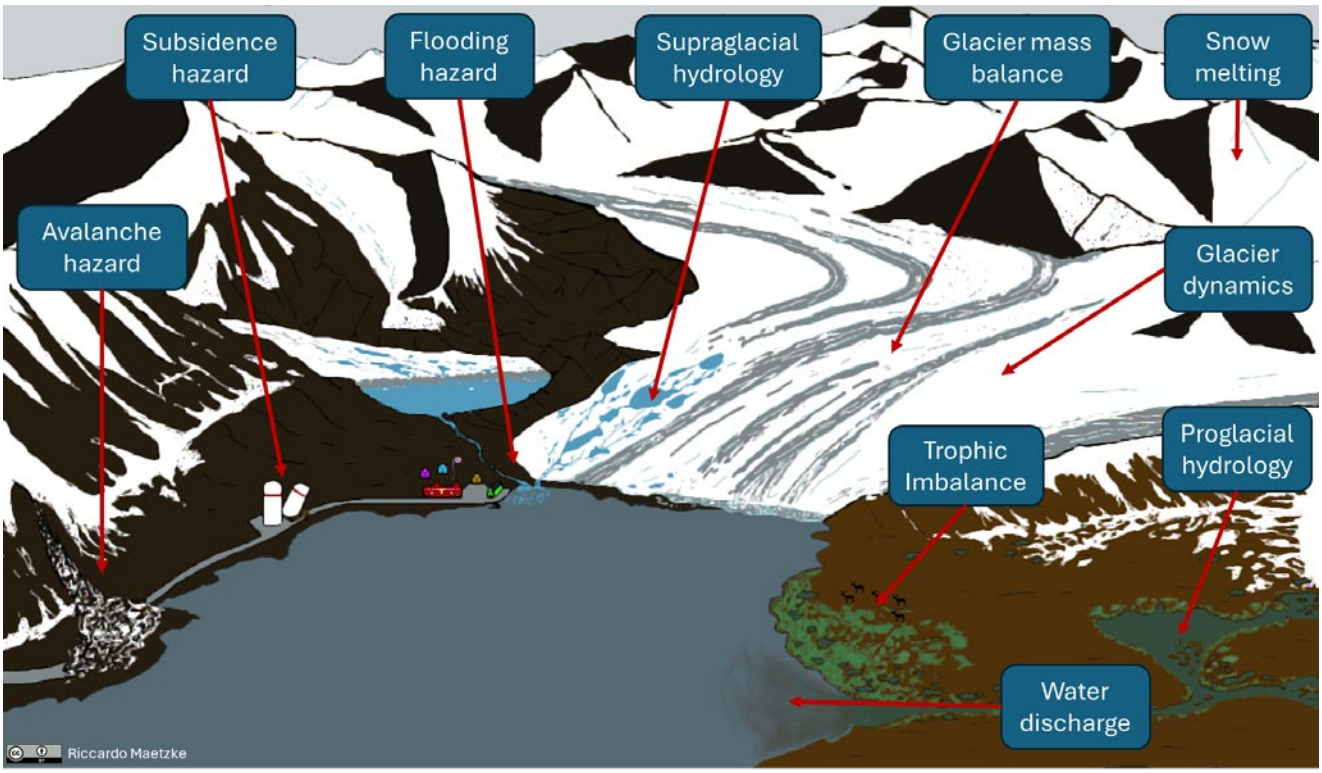
The Svalbard archipelago is experiencing rapid climate-driven transformations, characterised by increasingly frequent and intense anomalous weather conditions, known as “winter warm spells” or “heatwaves”. Such phenomena are often associated with “rain-on-snow” (RoS) events (i.e., occurrence of rain falling on snow during winter or early spring), triggering a series of impacts on environmental, ecological, and socioeconomic spheres. Winter warm spells, with their persistent inflows of warm, moist air, lead to prolonged periods of abnormally high temperatures, frequently coinciding with RoS

events. Winter warm spells also contribute to accelerate snow and ice melt, increase permafrost thaw, and destabilise the ground, thus releasing greenhouse gases and altering hydrological flow patterns. Combined, changes in snow cover, formation of internal ice layers, and exposure of darker, less reflective surfaces contribute to faster melting and raise avalanche risk. Warm spells also affect microbial activity, potentially reshaping biogeochemical cycles that are crucial to Arctic ecosystems. Warm events influence the mobility and fate of pollutants and nutrients by enhancing transport from mid-latitudes to the Arctic. They can hasten release of contaminants and nutrients, especially when warm spells coincide with RoS events. Satellite remote sensing and atmospheric analyses have proven effective in detecting RoS events, but comprehensive interdisciplinary research is also essential for full knowledge of their impact on Svalbard's environment, economy and communities.

RECOMMENDATIONS

- Develop consistent definitions and metrics for heatwaves and warm spells to enhance data analysis across the Arctic in collaboration with WMO.
- Install sensors to measure snow height, snow water equivalent, temperature, and liquid water content to enhance knowledge about snow dynamics. Additionally, create long-term research sites in Ny-Ålesund, Longyearbyen, and Hornsund to study the impact of heatwaves and warm spells.
- Include impact assessment studies on the marine environment, permafrost, and biology, for a comprehensive view of environmental changes.
- Assess societal consequences and support the development of adaptive strategies to mitigate impacts on Svalbard's economy.



Sketch illustrating potential impacts generated by warm spells and heatwaves in the terrestrial cryosphere of Svalbard. (Graphic: Riccardo Maetzke, CNR-ISP)

CHAPTER 10

Assessing anthropogenic and natural aerosol sources in the Arctic: A baseline to detect changes due to climate change (AAA-Source)

Click here for full chapter

HIGHLIGHTS

- Arctic aerosol sources are changing with global warming.
- Local natural aerosol currently dominates, followed by anthropogenic long-range transported.
- Metal aerosols come from anthropogenic long-range and Arctic soil sources.
- Aerosols from wildfires and local anthropogenic sources need to be monitored.

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The natural and anthropogenic sources of aerosol in the Arctic are changing with global warming. At present, natural, locally produced aerosol dominates. Besides, as sea ice and land snow cover retreat, biogenic and crustal aerosol is expected to increase. These natural aerosols influence climate through effects on solar radiation, cloud properties, and nutrient and metal cycling. Anthropogenic aerosols transported from far away dominate in winter–spring seasons, when they cause "Arctic haze". Their impact depends on both sustainable development policies in mid-latitude countries and hemispheric circulation patterns. In addition to non-sea salt sulphate and black carbon, Arctic haze contains metals that can negatively affect human health. Aerosols from local anthropogenic sources and wildfires have so far only been studied during specific events, but they are expected to increase and need to be quantified and monitored.

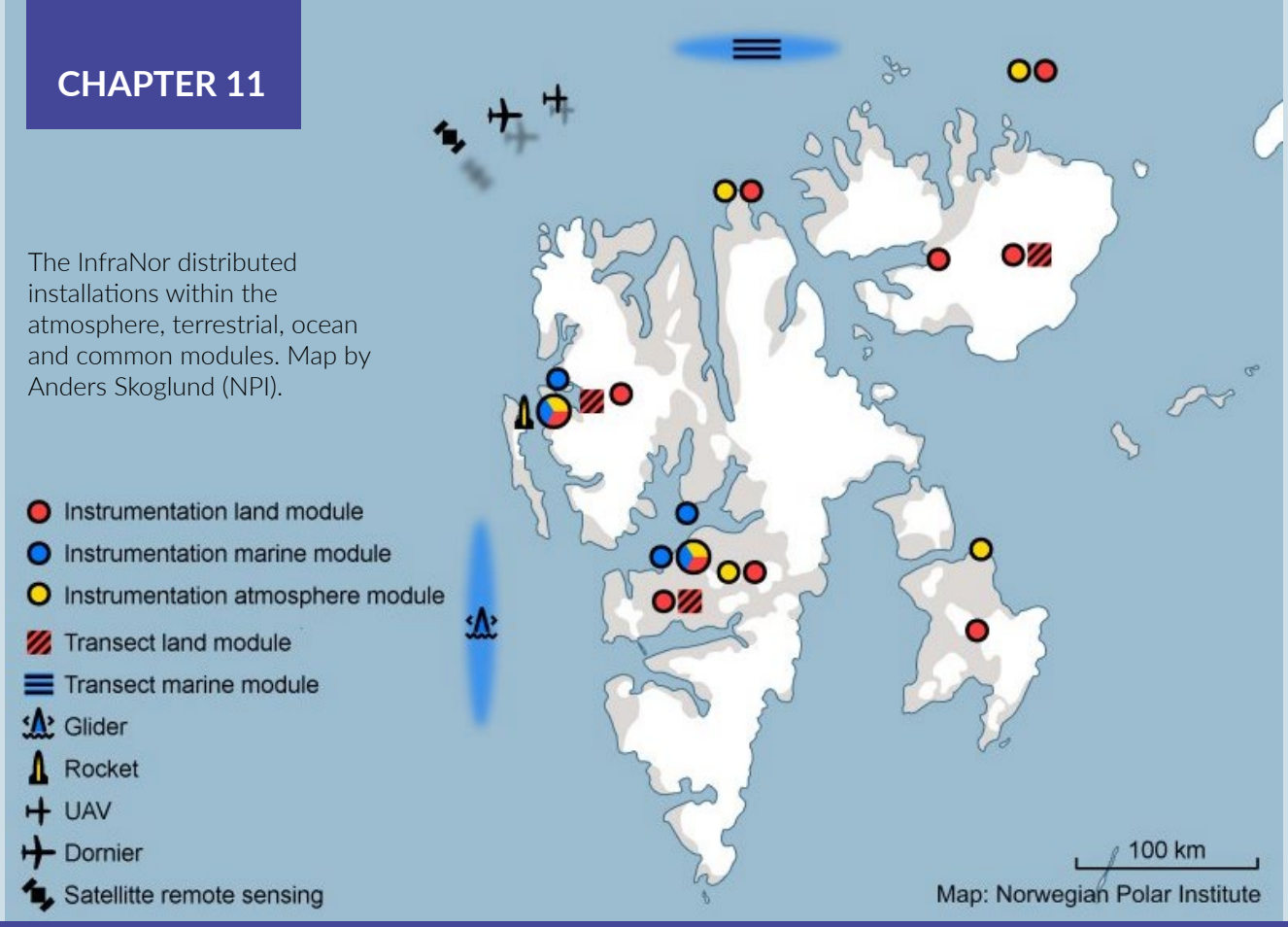
The chemical composition and source of aerosols are relevant for studying air quality and public health in densely populated regions but also in the clean, sparsely populated Arctic. This chapter presents current Arctic aerosol composition and sources and warns that atmospheric aerosol load and toxicity could increase in the future. The aims are: 1) to give experimental input to modellers to predict the future state of atmospheric aerosol; 2) to inform citizens about air quality; 3) to stimulate policymakers to promote sustainable development; and 4) to provide a baseline against which future data can be compared, to evaluate changes in the atmospheric composition.

RECOMMENDATIONS

- Increase the quality and quantity of observations in the Arctic using long-term monitoring and intensive field studies, applying innovative techniques. Several metals and compounds need to be monitored continuously because they are toxic or serve as tracers for aerosol sources. Measuring methanesulphonate and levoglucosan is desirable to quantify biogenic aerosol and biomass burning aerosols, respectively.
- Foster a new generation of scientists by periodical schools for atmospheric research in the Arctic.
- Develop trans-disciplinary approaches. This can be done by organising workshops involving social and economic researchers alongside atmospheric scientists.

Aerosol sampling stations in the Arctic. For each site, the flag of the country hosting the station is shown.

CHAPTER 11



The InfraNor distributed installations within the atmosphere, terrestrial, ocean and common modules. Map by Anders Skoglund (NPI).

Towards an integrated data-driven infrastructure (InfraNor)

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HIGHLIGHTS

SIOS-InfraNor:

- has established and operates a multidisciplinary, state-of-the-art observational system in Svalbard for marine, terrestrial and atmospheric research,
- has developed, upgraded and renewed the Norwegian infrastructure node of SIOS, making the information available in a standardised manner to the international scientific community,
- maintains long-term monitoring to deliver consistent time series data, crucial for evaluating environmental changes in a high Arctic region facing the most severe climate change.

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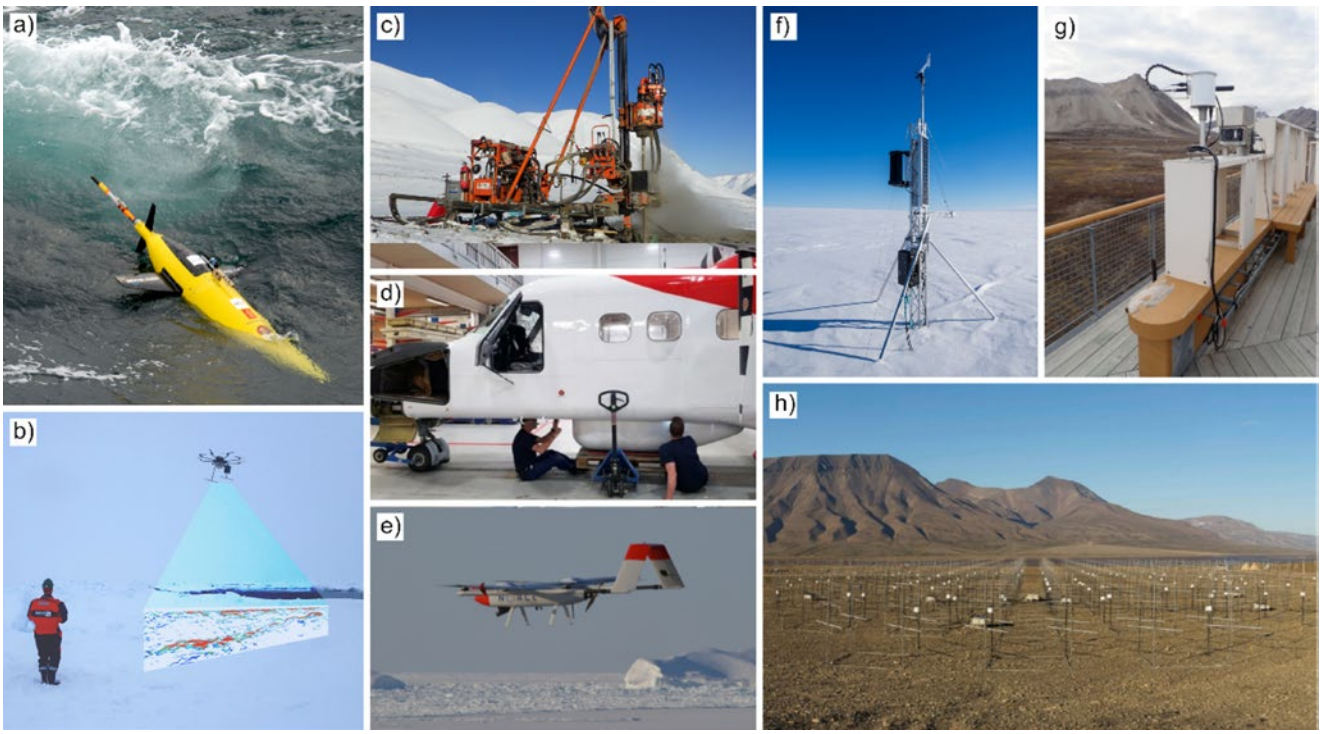
The InfraNor project illustrates the importance of the national investments in research infrastructure, in Svalbard and its surrounding oceans, including a coherent data management system. It constitutes the Norwegian contribution to SIOS for the benefit of its members and their communities.

It tallies 42 items (infrastructures and space-related research activities/products) already implemented or soon to be fully implemented under the responsibility of 14 Norwegian research institutions. Emphasis is on upgrading existing and establishing new infrastructure to produce a more coherent dataset among sites with similar instruments to help to address Earth System Science questions related to Global Change.

InfraNor focuses also on developing new technology that will reduce the footprint of future scientific activities in Svalbard, e.g., by deploying instrument pods aboard commercial airliners in regular traffic to map ocean characteristics.

RECOMMENDATIONS

- To monitor rapid climate shifts and their impacts in the Arctic, it is vital to secure long-term funding for Svalbard's observatories and ensure open, accessible, and well-documented data to foster collaboration and wider research use.
- Enhanced use of different levels of remote sensing (e.g., satellites, aircraft, drones) could be supported by various funding tools, e.g., transnational access support from EU, SIOS access programme. Higher-level product development and user training workshops would lower user barriers.
- The data produced by SIOS and supported by projects like SIOS-InfraNor should be evaluated against Copernicus service requirements in cross-disciplinary working group meetings. The recently published Copernicus Polar Roadmap 2024 highlights the evolution of these services.
- In reference to the updated Copernicus Roadmap and its recommendations, a re-analysis of observation gaps is strongly recommended.
- Further synergies should be sought by integrating SIOS InfraNor data (e.g., vegetation and snow data) as drivers of ecosystem change, particularly related to the long-term ecosystem-based monitoring done by COAT and other SIOS-related projects.



Selected InfraNor Infrastructure: a) ocean glider (Photo: Rudi Caeyers), b) multirotor radar drone (Photo: Rolf Ole), c) permafrost borehole drilling (Photo: Ullrich Neumann), d) Dornier DO228 aircraft instrument pod (Photo: Agnar Sivertsen, e) SOUSY radar VTOL drone (Photo: William Copeland), f) Etonbreen automatic weather station (Photo: Thorben Dunse), g) Pandora spectrometer (Photo: NP/NILU), h) SOUSY radar (Photo: Njål Gulbrandsen).

CHAPTER 12

An all-sky image of the red-dominant dayside aurora. (Image credit: The Kjell Henriksen Observatory)

SIOS' contribution to the ICARP IV process (SICAR)

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HIGHLIGHTS

The SESS reports and the recommendations contained therein create a solid foundation for SIOS's contribution to the ICARP IV process. A workshop held in Longyearbyen in January 2024 provided additional multidisciplinary contributions. The workshop participants represented various Earth System Science fields and career stages.

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This chapter presents the contribution of the Svalbard Integrated Arctic Earth Observing System (SIOS) to the IV International Conference on Arctic Research Priorities (ICARP IV[1]).

ICARP IV is a process for Arctic Research Planning for the next decade. The process is ongoing, spanning from 2022 to 2026. It will discuss the state of Arctic science, as well as the Arctic's role in global affairs and systems, to:

- consider the most urgent knowledge gaps, Arctic research priorities and needs for the next decade
- explore avenues to address these research needs

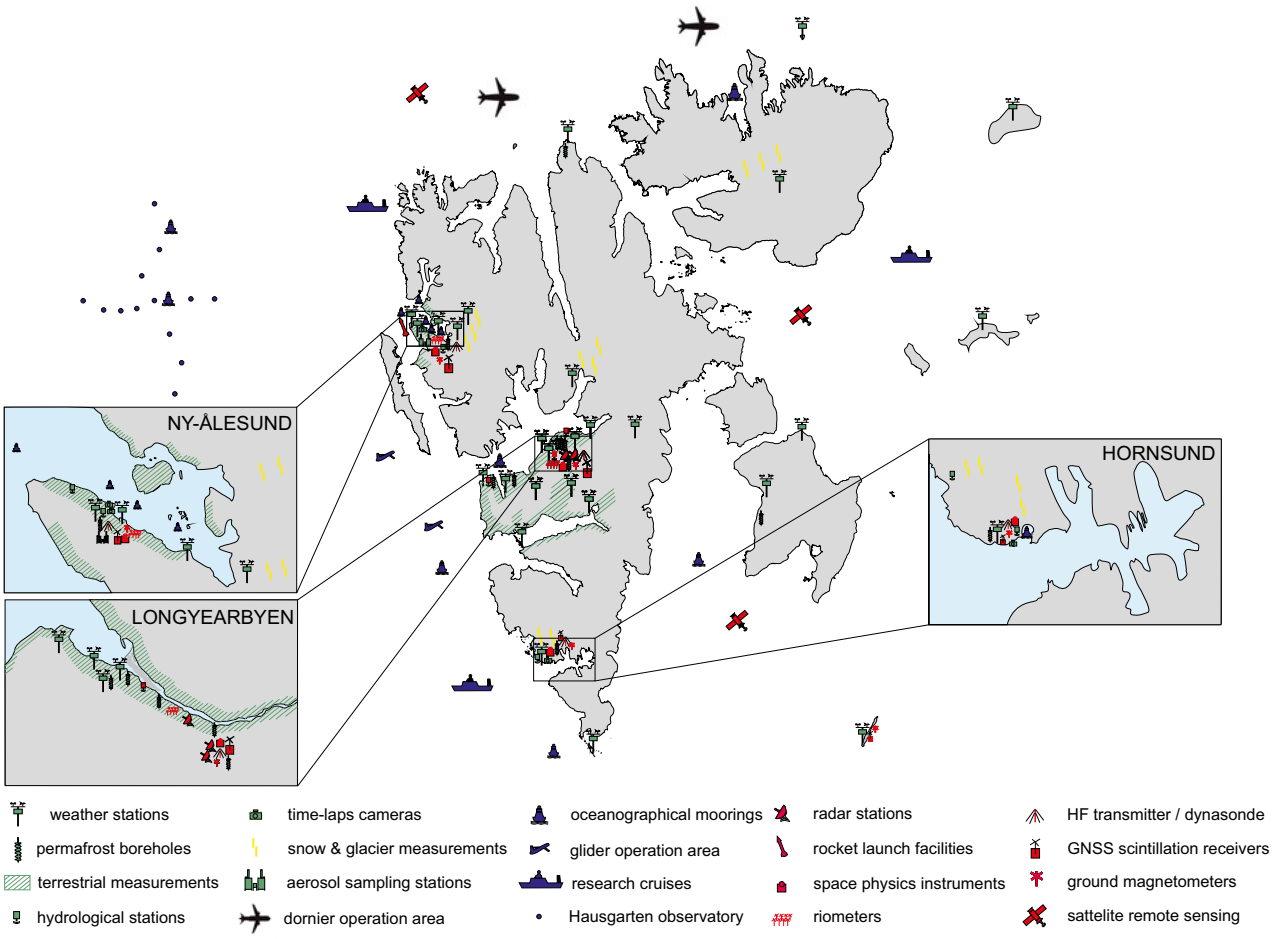
1 https://icarp.iasc.info/

SIOS organised a workshop as a part of the SIOS Polar Night Week 2024, seeking community input and including a panel discussion with keynote speakers. SIOS' contribution to the ICARP IV process is based on the workshop discussions, recommendations from the six SESS reports published so far, and a synthesis report compiled from the first four SESS report recommendations. The recommendations were selected based on their pan-Arctic relevance.

SIOS recommends that ICARP IV be ambitious. It should favour long-term observations in multidisciplinary contexts. SIOS also recommends co-location of observations as this has multiple benefits, one being a huge potential to decrease the environmental footprint of science.

RECOMMENDATIONS

- Ask bold questions. What do we need to do to make sure the world remains liveable for future generations? Finding answers to such questions requires broad collaborative networks like SIOS.
- Improve multidomain integration of science, ideally based on long-term, continuous time series supplemented by implementation of new technology.
- Encourage co-location of observations to focal sites for researchers from multiple disciplines. This will also encourage cross-disciplinary cooperation and new joint scientific initiatives.
- Minimise duplication of observations and datasets through cooperation and coordinated use of infrastructure and logistics, thus also minimising the environmental impact of research.
- Leverage interest in the Arctic by bringing together researchers from around the world to share data and infrastructure (e.g., within SIOS), build common understanding, and ultimately shape environmental policy in a geopolitically strategic and resource-rich region.



SIOS observation infrastructure in Svalbard, with insets of the three main science hubs – Longyearbyen, Hornsund and Ny-Ålesund – to present the various types of observations in greater detail. (Christiansen et al. 2024, republished with permission from Copernicus Publications under licence[1])

1 https://publications.copernicus.org/for_authors/licence_and_copyright.html

Secular shift of the magnetic dip pole and its consequences for auroral boundaries (PoleMotion)

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1. Introduction

The magnetic dip pole is the location on Earth's surface where the observed geomagnetic field is vertical. During the last 30 years, the position of Earth's northern magnetic dip pole has shifted almost 1500 km, and continues to move several tens of kilometres every year (Yizengaw 2020). This motion, illustrated in Figure 1, reflects the large scale changes in the flow of metal alloys in Earth's outer core (Metman et al. 2020; Landeau et al. 2022).

Geomagnetic field models can also be used to define geomagnetic poles. The geomagnetic poles are usually computed from the first few coefficients of a magnetic field model, such the International Geomagnetic Reference Field (IGRF) (Alken et al. 2021). The IGRF representation of the magnetic field includes a magnetic dipole at the centre of Earth, and the geomagnetic poles are where this dipole axis intersects Earth's surface. The model-based magnetic poles are not identical to the dip poles, and show a less dramatic shift over the last decades. Many popular space weather applications, e.g., the Aurora Forecast 3D App (Sigernes et al. 2011) illustrated in Figure 1 use this geomagnetic pole as origin.

Aurora is generated by electrons travelling along the magnetic field and eventually hitting atoms and molecules in the upper atmosphere (Paschmann et al. 2002). The location of the auroral oval is thus largely governed by the configuration of the geomagnetic field. A valid question is therefore whether the location of the aurora shifts in response to the moving magnetic pole. Earlier attempts to address this question, e.g., Tsyganenko (2019) used models of the magnetic field to assess displacement of the aurora due to secular magnetic changes. They concluded that any changes in aurora would be miniscule, and that the location of the auroral oval was determined almost entirely by space weather effects. More recently, Zossi et al. (2020, 2021) used both model data and satellite observations to study secular changes due to the dip pole motion. They found indication of a shrinking polar cap area, i.e., a poleward motion of the auroral oval during a 30 year period.

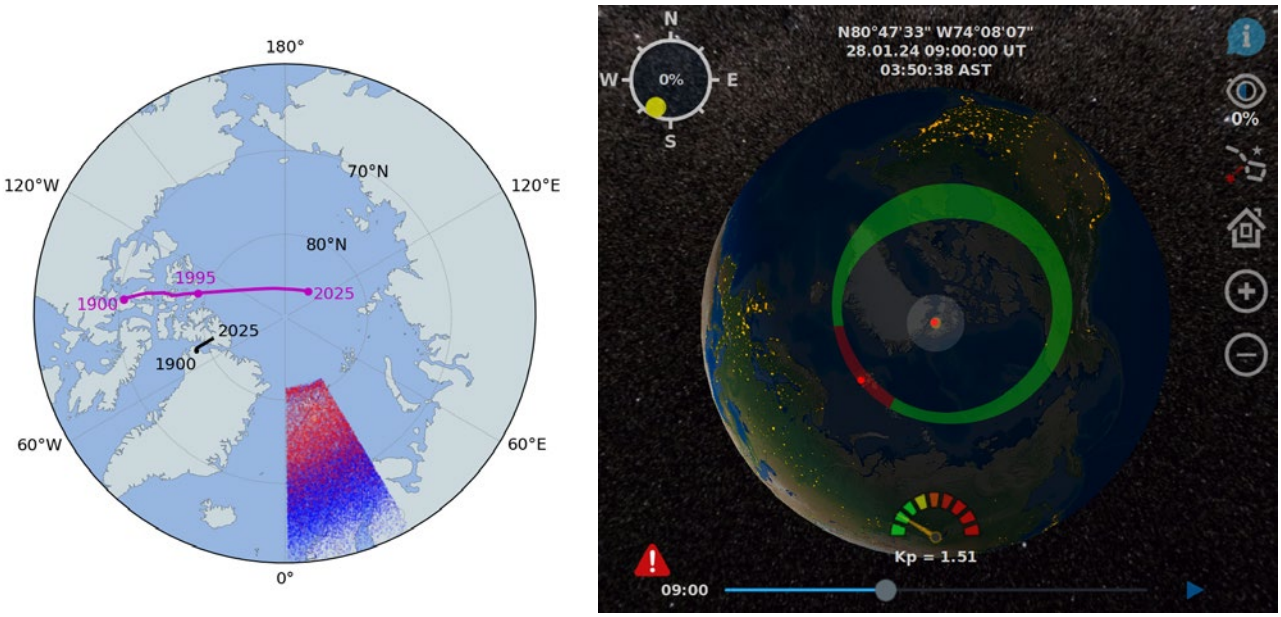

Figure 1: Left: Map illustrating the shift of the magnetic dip pole (magenta) and dipole model pole (black) since 1900 (Alken et al. 2021). Right: A model of the quiet auroral oval as used in Aurora Forecast 3D, a popular App for smartphones. The red segment of the auroral oval indicates the magnetospheric cusp, a region of space magnetically directly connected to the solar wind.

The present report tries to address consequences of long term variations in the geomagnetic field by utilising decades of magnetic field observations from Svalbard, as well as observations of auroral boundaries. In particular, we try to investigate whether secular changes in the geomagnetic field have any impact on the auroral oval as observed over Svalbard. We also document the long term changes of the local magnetic field in Svalbard, and address some of the impacts on navigation and infrastructure.

2. Consequences of magnetic field changes

2.1. Observed secular changes in the magnetic field in Svalbard

Absolute measurements of the magnetic field are conducted regularly at the Hornsund geomagnetic observatory, Svalbard. Figure 2 shows the evolution of the magnetic field at this station over the last decades. From the horizontal components of the magnetic field (Bx, By), we can infer an approximately 10-degree eastward rotation of the magnetic field direction over the last decades, consistent with the motion of the dip pole. We also note that the dominant vertical component (Bz), and consequently the total magnetic field, increases over time. In contrast, the Earth's dipole moment (a global feature) has decreased over the last decades (Alken et al. 2021; Koochak and Fraser-Smith 2017).

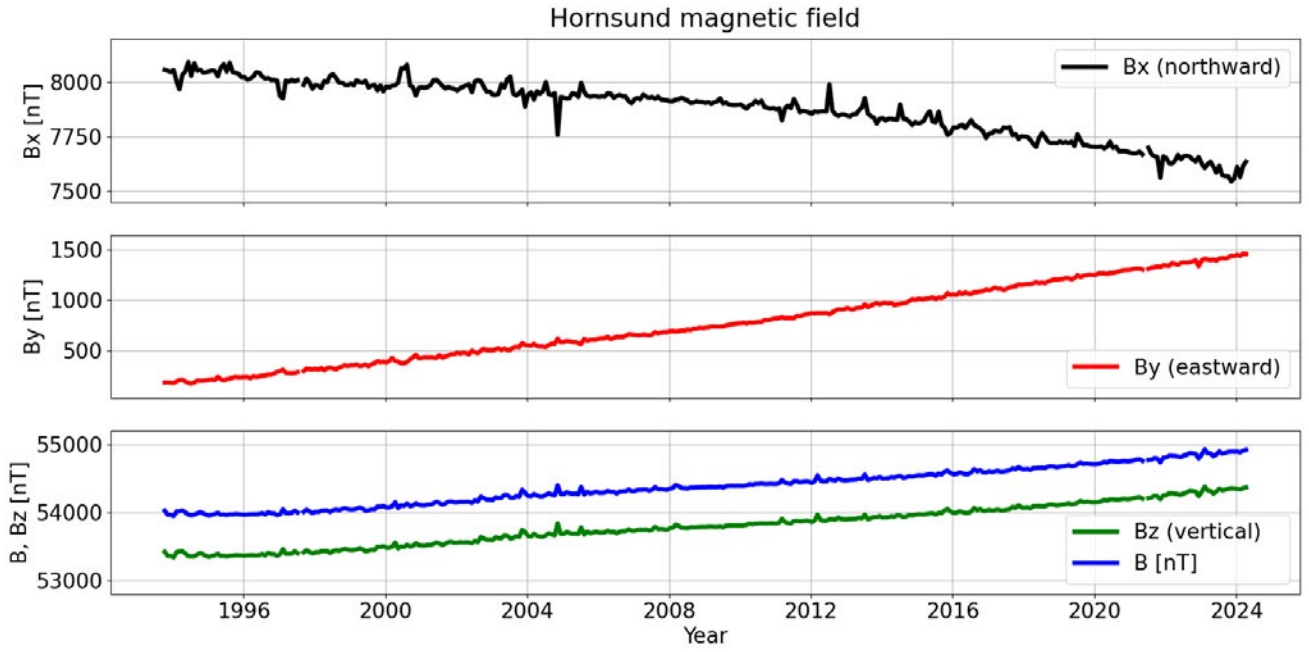

Figure 2: Evolution of the magnetic field in Hornsund over the last few decades. Top panel: Bx (north-south component); Middle panel: By (eastward component); Bottom panel: Total field (blue line) and the Bz (vertical component, green line). We note that the vertical component and total field intensity have been increasing. Also the vertical component is larger than the horizontal components (Bx and By), meaning that the geomagnetic field is almost vertical. Short-time variations in the plot should be ignored; they are the result of random space weather effects observed on the monthly sampling day.

2.2. Remote sensing of auroral boundaries

Aurora is generated when electrons accelerated along the magnetic field lines interact with atoms and molecules in the upper atmosphere. Consequently, when low orbit satellites in polar orbits traverse the auroral oval, they will typically detect an increase in the flux of field-aligned electrons as they encounter the auroral oval. A corresponding drop in flux is observed when they exit the auroral zone. This change in flux is often sharp and takes place within a short time (which, for low orbit satellites corresponds to a small spatial distance), and can thus be used as a proxy for an auroral boundary.

Based on experience from Breedveld (2020), we used measurements of field-aligned electron fluxes from the Medium Energy Proton and Electron Detector (MEPED) on board the Polar Operational Environmental Satellites (POES) and Meteorological Operational Satellites (METOPS) (Evans and Greer 2002) to automatically detect such boundaries. The left panel of Figure 3 shows an example of auroral boundaries detected by the POES N15 satellite on 1 Jan 2017. More details about the detection algorithm can be found in Appendix 1.

For this study, we used a total of 8 different NOAA and METOPS satellites in operation between 1998 and 2024, covering different magnetic local times (MLT). Each satellite crosses the Northern Hemisphere auroral oval at approximately 850 km altitude twice per orbit (in, out). Each orbit takes approximately 110 minutes, resulting in approximately 14 orbits every day. The time resolution of the measurements is 2 seconds, corresponding to approximately 150 km spatial resolution.

Automatic boundary detection does not always work, but there are typically, between 10 and 20 detected boundaries from each satellite each day, and a total of more than 700,000 boundaries over the period 1998–2024. The right part of Figure 3 shows all polar (red dots) and equatorward (blue dots) boundaries, organised into a MLAT vs MLT coordinate system. The origin of this plot at 90° magnetic latitude (MLAT) is the modelled geomagnetic pole (which moves slightly over time, see Figure 1), and the longitudes are given in terms of magnetic local time; 12 always points towards the Sun, 06 towards dawn.

We note a significant spread of the detected boundaries. This can primarily be attributed to space weather effects with time scales ranging from less than a minute to several days. During periods with strong solar wind driving, magnetic flux is eroded on the dayside magnetopause, leading to a equatorward shift of the dayside auroral oval.

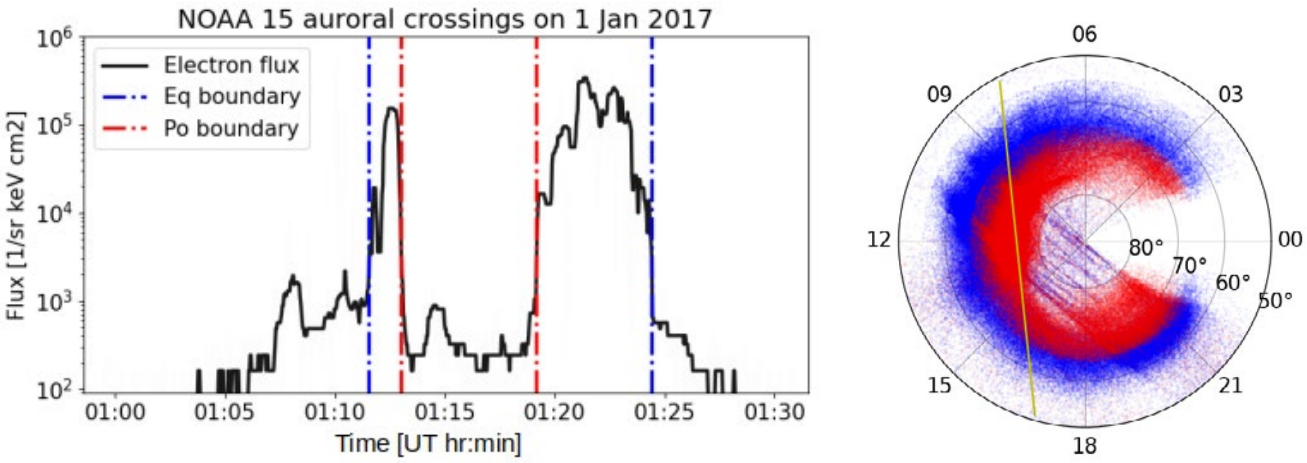

Figure 3: Left: Example of measured electron flux (black line) during a typical NOAA 15 passage through the auroral oval. Automatically detected boundaries are indicated by red and blue vertical lines for poleward and equatorward boundaries, respectively. Right: Collection of all boundaries detected by 8 different METOPS and NOAA satellites between 1998 and 2024. Some of the individual satellite tracks can be discerned, as well as some obvious erroneous boundary detections. The yellow line indicates the trajectory of the NOAA 15 satellite during the passage illustrated in the left panel.

Correspondingly, the build-up of magnetic energy in the Earth's nightside magnetosphere leads to a stretched magnetotail and associated equatorward shift of the nightside auroral oval. Likewise, during very quiet solar wind conditions, the auroral oval tends to contract and move poleward, resulting in a smaller polar cap area. These variations are often referred to as the expanding–contracting polar cap scenario (Milan et al. 2012).

2.3. Secular variations in location of the auroral oval

To investigate the secular changes in the auroral oval over Svalbard, we selected all valid boundaries detected within a sector spanning 1-31° geographic longitude as indicated in the left panel of Figure 1. To minimise space weather effects, we also discarded boundaries detected during disturbed conditions (i.e., any boundaries detected when the Kp index was above 2+). This filtering will also remove most of the space weather effects due to the 11-year solar cycle and 27-day solar rotation period (Chapman and Dudok de Wit 2024).

Figure 4 shows the 26-year trends in average locations of the poleward and equatorward auroral boundaries. A yearly average and linear regression were applied to capture the long term trends. A significant, albeit small shift towards lower latitudes can be noted for both the poleward and equatorward auroral boundaries in the Svalbard sector.

We also checked the trend for other longitude sectors. From the dip pole shift shown in Figure 1, one would intuitively expect a corresponding shift of the auroral oval away from Canada toward Siberia. That would mean an equatorward shift of the auroral oval over the Siberian sector (60-120° east longitude) and poleward shift over the Canadian sector (60-120° west). Table 1

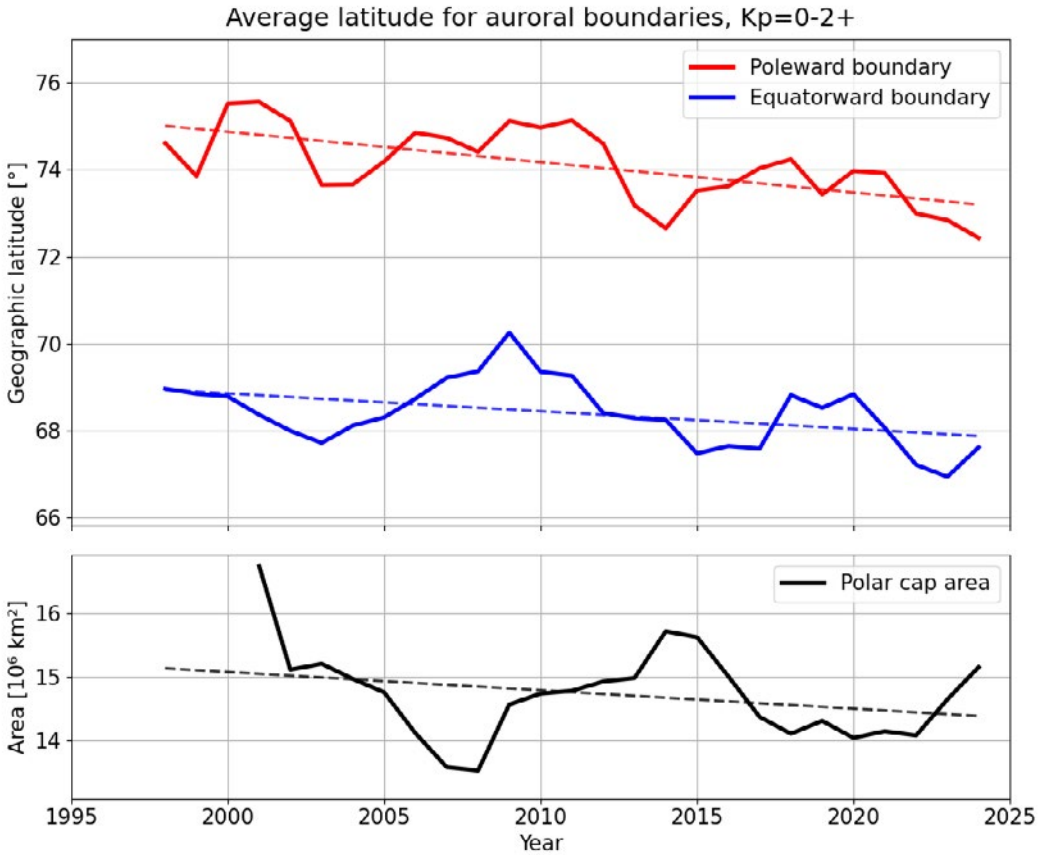

Figure 4: Top panel: change in median latitude of polar (red) and equatorward (blue) boundary in the Svalbard sector over the last 26 years. Bottom panel: corresponding change in polar cap area over the same interval. Solar cycle variations are notable. Dashed lines show linear fits to the observed changes (for the polar cap area, the fit is based on data from 2001-2024).

Sector / longitude range (see Figure 1)	Annual latitudinal change of boundary over 26 years	
	Poleward boundary	Equatorward boundary
Svalbard (1–31° East)	-0.069°	-0.041°
Siberian (60–120° East)	-0.066°	-0.071°
Bering (150° East–30° West)	-0.008°	-0.023°
Canadian (60–120° West)	0.056°	0.066°

Table 1: Annual change in median latitude of polar and equatorward boundaries in various geographic sectors based on linear regression over a 26-year period. Positive values indicate poleward motion, negative values indicate equatorward motion of the auroral boundaries. These results indicate a shift of the entire auroral oval over time.

summarises the results from our study. Overall, the secular shifts of the boundaries are consistent with this hypothesis, and also consistent with model based results reported by, e.g., Kataoka and Nakano (2021).

As in Breedveld (2020), we also tested elliptical and circular fits to the entire auroral oval. This is possible for the years 2001–2024, when there are enough satellites to provide a sufficient MLT coverage. This enables us to calculate the area of the polar cap (i.e., the area with open magnetic flux poleward of the auroral oval). Consistent with Zossi et al. (2021), these fits reveal a small decrease of the polar cap area over the last decades. However, as shown in the lower part of Figure 4, variations due to space weather effects and solar cycle are more prominent than the secular variation.

2.4. Detecting auroral boundaries using radar observations

Given that Svalbard is located around 77–80° geographic latitude, i.e., poleward of the typical auroral oval, one would expect that an equatorward retreat of the auroral oval would imply a lower chance of observing aurora. Fortunately, Svalbard is well equipped with ground-based instrumentation for auroral research, so we had the opportunity to test this hypothesis using the EISCAT (European Incoherent Scatter) radar located in Svalbard.

The EISCAT radar is part of a network in northern Fennoscandia (Rishbeth and Williams 1985). These radars study the Earth's upper atmosphere and ionosphere and their interactions with the solar wind. By transmitting powerful radio waves into the atmosphere and analysing the resulting scattered signals, it is possible to obtain height profiles of electron density, temperature, and velocity in the ionosphere.

In order to automatically detect auroral boundaries from radar measurements, we tested two methods: The Canny algorithm (Canny 1986; see in Appendix 1) is inspired by image processing, and uses EISCAT height profiles of electron density to detect sharp edges which could indicate sharp boundaries in electron density. This method shows promising results, and is well suited for automatic processing and feature extraction, but still needs some refinement.

The second method, which we eventually employed, is more conventional. We make a slice in the height profiles at a radar range corresponding to ca. 110 km altitude to obtain a time line of electron densities. These time lines are then checked for sharp boundaries analogous to the satellite-detected boundaries. Additional methodological details, including an illustration of the detected boundaries, can be found in Appendix 1.

By normalising the detected boundaries to the total observation time, we obtain a frequency of boundary detection. Figure 5 shows the evolution of detection frequency over 26 years of EISCAT Svalbard data. We note a declining detection probability over time. While this trend is consistent with the remote sensing data, and can be interpreted as an indication of an auroral zone moving away from Svalbard, the results are subject to uncertainties and possibly bias which need to be further investigated. There are very few observations in 2011, which might explain the outlier for this year.

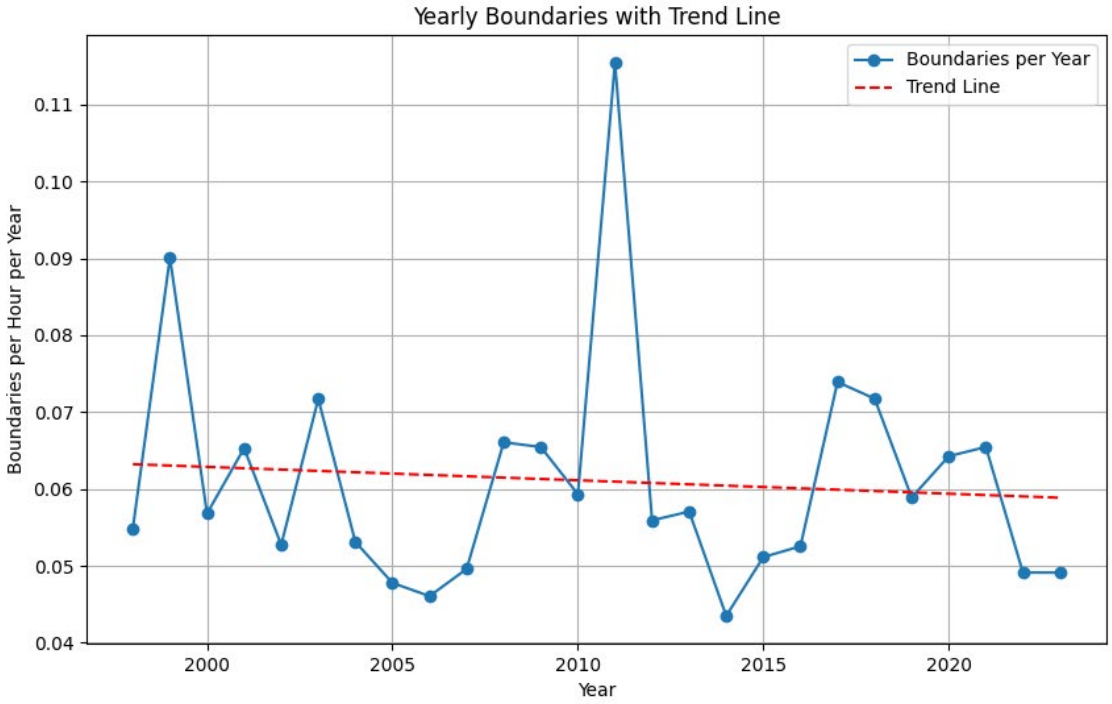

Figure 5: Frequency of auroral boundaries detected in the Svalbard radar over the last 26 years. The dashed line shows a linear fit to the observations.

2.5. Synthesis of observations

In summary, long-term measurements show a rapid motion of the northern dip pole. Observations of the magnetic field at Hornsund, Svalbard, show a rotation of the field consistent with this motion. In contrast to the IGRF model, which suggests a weakening of Earth's dipole moment, the magnetic field strength in Hornsund increases. Remote sensing of auroral boundaries using satellites over a 26-year period show a consistent, albeit slow equatorward motion of the auroral oval over Svalbard.

Observations of auroral boundaries by the EISCAT Svalbard radar indicate a decrease in probability, consistent with an auroral boundary moving further away. However, there may be alternative explanations for the EISCAT observations, so further investigations are required before drawing any firm conclusions.

3. Contribution to interdisciplinarity and societal impact

A study of auroral boundaries and changes in the local magnetic field may at first glimpse be seen as a purely academic exercise of interest for space physicists and geologists. However, the results reported here can have profound effects on society. In particular, a changing magnetic field has a direct impact on navigation and infrastructure in Svalbard.

Despite the widespread use of global satellite navigation systems (GNSS), the magnetic field is still of vital importance for navigation and orientation. Magnetic coordinates are usually provided on maps, and the changing magnetic field direction requires regular revisions of maps. Another example: airport runways are designated by their magnetic orientation, and approach procedures to airfields are typically published in a magnetic reference frame. Figure 6 shows the runway signage at Longyearbyen airport being changed on 23 Sep 2023. Prior to this date, the runway orientation was close to 100° or 280° (depending on whether the approach is from east or west) magnetic orientation.

Figure 6: Runway signage at Longyearbyen airport being revised due to changes in the magnetic field. In September 2023, the old runway sign 28-10 (i.e., close to magnetic orientations 280° and 100°, respectively) had to be replaced by 27-09 (270° and 90° magnetic orientation) due to the moving magnetic pole. (Photo: Ine Therese Pedersen)

Consequently, the runways were designated 10 and 28. Today Longyearbyen airport designated its runways 09 and 27. Approach procedures and aviation charts will have to be revised accordingly.

Even if we disregard navigation by magnetic compass and only rely on GNSS, we may be in for trouble. Over longer time scales (several solar cycles), a reduced magnetic field will imply greater impacts of space weather effects, and consequently more disturbance in signals used for satellite navigation and communication. A reduced terrestrial field will shrink geospace (Russell et al. 2017) and imply that, e.g., geostationary satellites spend more time outside this protective shield.

4. Unanswered questions

On a short time perspective, an obvious question is "*What will happen to the dip pole and the aurora over the next decades?*" The model estimations by Livermore et al. (2020) suggest a further shift of the dip pole in the coming decades, but these predictions are uncertain. On an even longer timescale, the rapid shift in dip position also evokes speculations about a complete flip of the geomagnetic field.

The terrestrial magnetic field is also important for planetary habitability. A magnetic field shields the planetary atmosphere from the direct impact of the solar wind and radiation from space. It has been argued that without this shield, no life at all would have been possible on Earth. This claim is debated though (see discussion in, e.g., Gunell et al. (2018)). Still, the declining magnetic dipole moment and subsequent reduction in magnetic shielding obviously raise some questions about habitability of Earth on a geological timescale.

5. Recommendations for the future

A challenge when conducting a study utilising long time series is the availability and format of data. For this particular study, we encountered this issue with the magnetic field measurements from Hornsund. These measurements are presently not available from a single source and are not part of SIOS core data sets. As noted in Section 6, magnetic field data for later years were downloaded as binary files (HDF-5 format) from Intermagnet, whereas data from earlier years were downloaded from a different source and in a different, non standard, binary format.

Remote sensing using satellites (and other space- and airborne observation platforms) will be even more important in the future. In this study we used data from eight different satellites. Although the instrumentation is identical for all satellites over the entire period studied, three different data formats were used and had to be processed. Some of the older data sets are poorly documented, and the recommended software to unpack the various formats – some of them intended to handle sequential data tapes – are outdated and will not run on modern computers without significant modifications. For future studies, we would also obviously benefit from additional satellite data and better local time coverage.

The situation is even more challenging for ground-based instrumentation like radars and optical instruments, since long-time measurement series are not always feasible. In particular, the EISCAT radars in Svalbard and Tromsø are usually run only during campaigns, often during specific geomagnetic conditions, thus introducing a bias into the observations. Their characteristics are different, and required different treatments in our study. Improvements are underway, though: the next generation of incoherent scatter radar systems such as the EISCAT 3D (Baddeley et al. 2023) will have greatly improved capabilities, with lower power consumption, enabling longer runs. However, the parameters will probably not be directly comparable to the existing radars.

Consequently, our immediate recommendations based on this study are:

- Harmonise the data format and integrate magnetic field measurements from Svalbard into the SIOS Core Data set (SCD).
- Make POES/METOPS satellite data available in a single file format with proper metadata and documentation.

6. Data availability

All data used for this study are available from public archives. Links to data sources are shown in Table 2.

Data set	Period	Data provider	URL
Space weather	1994–2024	NASA CDAWeb, USA	https://spdf.gsfc.nasa.gov/pub/data/omni/low_res_omni/
Magnetic field	1994–2001	IMAGE, Finland	https://space.fmi.fi/image/www/
Magnetic field	2002–2024	Intermagnet, UK	https://imag-data.bgs.ac.uk/GIN V1/
EISCAT	1997–2024	Madrigal, Sweden	https://madrigal.eiscat.se/madrigal/
METOPS and POES satellite data	1998–2024	NOAA, USA	https://www.ncei.noaa.gov/data/poes-metop-space-environment-monitor

Table 2: Overview of data sources. NOAA = National Oceanic and Atmospheric Administration; IMAGE = International Monitor for Auroral Geomagnetic Effects; NASA = National Aeronautics and Space Administration; CDAWeb = Coordinated Data Analysis Web.

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8. References

Alken P, Thébault E, Beggan CD, Amit H, Aubert J, Baerenzung J et al (2021) International Geomagnetic Reference Field: the thirteenth generation. Earth, Planets and Space 73(1):49. https://doi.org/10.1186/s40623-020-01288-x

Baddeley L, Lorentzen D, Haaland S, Heino E, Mann I, Miloch W, Oksavik K, Partamies N, Spicher A, Vierinen J (2023). Space and atmospheric physics on Svalbard: a case for continued incoherent scatter radar measurements under the cusp and in the polar cap boundary region. Progress in Earth and Planetary Science 10(1):53. https://doi.org/10.1186/s40645-023-00585-9

Breedveld M (2020) Predicting the auroral oval boundaries by means of the polar operational environmental satellite (POES) particle precipitation data (Master's thesis). UiT – The Arctic University of Norway. https://hdl.handle.net/10037/19283

Canny J (1986). A computational approach to edge detection. IEEE Transactions on Pattern Analysis and Machine Intelligence, PAMI-8(6):679–698. https://doi.org/10.1109/TPAMI.1986.4767851

Chapman SC, Dudok de Wit T (2024) A solar cycle clock for extreme space weather. Scientific Reports 14:8249. https://doi.org/10.1038/s41598-024-58960-5

Evans D, Greer M (2002) Polar orbiting environmental satellite space environment monitor 2: Instrument descriptions and archive data documentation (Technical memorandum). NOAA Space Environment Center, Boulder, Colorado, USA.

Gunell H, Maggiolo R, Nilsson H, Stenberg Wieser G, Slapak R, Lindkvist J, Hamrin M, De Keyser J (2018) Why an intrinsic magnetic field does not protect a planet against atmospheric escape. Astronomy and Astrophysics 614:L3. https://doi.org/10.1051/0004-6361/201832934

Gussenhoven MS, Hardy DA, Burke WJ (1981) DMSP/F2 electron observations of equatorward auroral boundaries and their relationship to magnetospheric electric fields. Journal of Geophysical Research 86(A2):768–778. https://doi.org/10.1029/JA086iA02p00768

Kataoka R Nakano S (2021) Auroral zone over the last 3000 years. Journal of Space Weather and Space Climate 11:46. https://doi.org/10.1051/swsc/2021030

Kilcommons LM, Redmon RJ, Knipp DJ (2017) A new DMSP magnetometer and auroral boundary data set and estimates of field-aligned currents in dynamic auroral boundary coordinates. Journal of Geophysical Research 122(8):9068–9079. https://doi.org/10.1002/2016JA023342

Koochak Z, Fraser-Smith AC (2017) An Update on the Centered and Eccentric Geomagnetic Dipoles and Their Poles for the Years 1980-2015. Earth and Space Science 4(10):626–636. https://doi.org/10.1002/2017EA000280

Landeau M, Fournier A, Nataf H-C, Cébron D, Schaeffer N (2022) Sustaining Earth's magnetic dynamo. Nature Reviews Earth and Environment 3 4):255–269. https://doi.org/10.1038/s43017-022-00264-1

Livermore PW, Finlay CC, Bayliff M (2020) Recent north magnetic pole acceleration towards Siberia caused by flux lobe elongation. Nature Geoscience 13(5):387–391. https://doi.org/10.1038/s41561-020-0570-9

Metman MC, Beggan CD, Livermore PW, Mound JE (2020) Forecasting yearly geomagnetic variation through sequential estimation of core flow and magnetic diffusion. Earth, Planets and Space 72(1):149. https://doi.org/10.1186/s40623-020-01193-3

Milan SE, Gosling JS, Hubert B (2012) Relationship between interplanetary parameters and the magnetopause reconnection rate quantified from observations of the expanding polar cap. Journal of Geophysical Research 117(A3):A03226. https://doi.org/10.1029/2011JA017082

Paschmann G, Haaland S, Treumann R (2002) Auroral Plasma Physics. Space Science Reviews 103(1). https://doi.org/10.1007/978-94-007-1086-3

Rishbeth H, Williams P (1985) The EISCAT ionospheric radar: The system and its early results. Royal Astronomical Society, Quarterly Journal 26:478–512.

Russell CT, Strangeway RJ, Zhao C, Anderson BJ, Baumjohann W, Bromund KR et al (2017) Structure, force balance, and topology of Earth's magnetopause. Science 356(6341):960-963. https://doi.org/10.1126/science.aag3112

Sigernes F, Dyrland M, Brekke P, Chernouss S, Lorentzen DA, Oksavik K, Sterling Deehr C (2011) Two methods to forecast auroral displays. Journal of Space Weather and Space Climate 1(1):A03. https://doi.org/10.1051/swsc/2011003

Tsyganenko NA (2019) Secular Drift of the Auroral Ovals: How Fast Do They Actually Move? Geophysical Research Letters 46(6):3017–3023. https://doi.org/10.1029/2019GL082159

Yizengaw E (2020) The Potential Impacts of the Erratic Motion of Dip Equator and Magnetic Poles. Journal of Geophysical Research 125(8):e28129. https://doi.org/10.1029/2020JA028129

Zossi B, Amit H, Fagre M, Elias AG (2021) Observed Auroral Ovals Secular Variation Inferred from Auroral Boundary Data. Geosciences 11(8):351. https://doi.org/10.3390/geosciences11080351

Zossi B, Fagre M, Amit H, Elias AG (2020) Geomagnetic Field Model Indicates Shrinking Northern Auroral Oval. JGR Space Physics 125(8):e27434. https://doi.org/10.1029/2019JA027434

Appendix 1: Boundary detection using radar and satellite

A1 Auroral boundaries from ESCAT radar measurements

The Canny edge detection algorithm (Canny 1986) is a multi-step method for identifying image edges by detecting areas of rapid intensity change. It consists of five key steps: noise reduction using a Gaussian filter, gradient calculation to detect intensity changes, non-maximum suppression to refine the edges, double thresholding to classify edges based on gradient strength, and edge tracking by hysteresis to finalise the detection. In our study, we apply the Canny algorithm to a combined mask derived from specific colour ranges in an HSV-generated image (the colour coded EISCAT height profiles). These colour masks isolate relevant features within the image, and the Canny algorithm detects edges within these masked regions. In our application we consider profiles below 150 km altitude, as boundaries are most pronounced below this threshold. The results for one example can be seen in Figure A1.

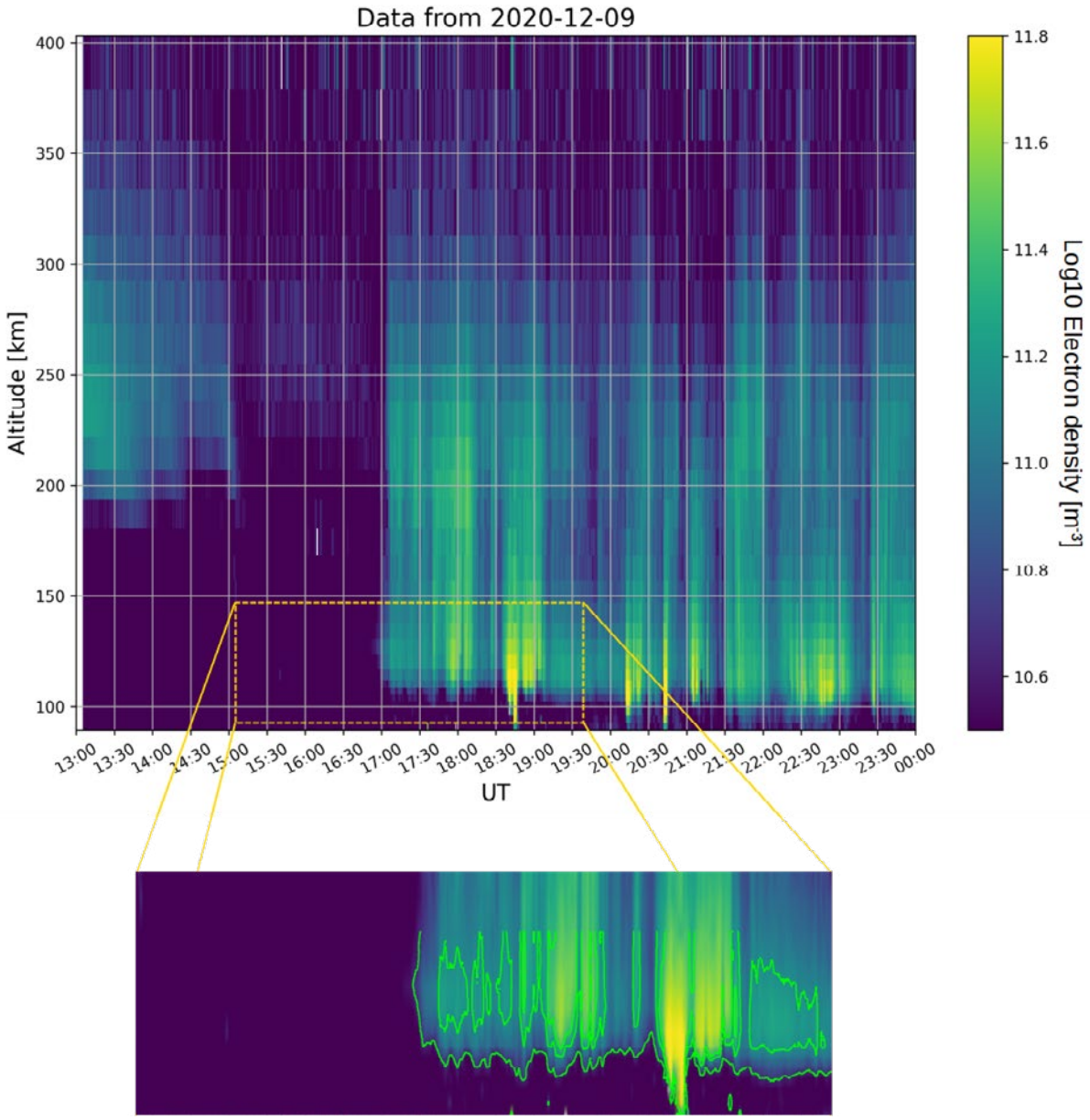

Figure A1: EISCAT Ne intensities interpolated for a range of altitudes on 9 Dec 2020, on the Tromsø radar (UHF experiment). Aurora can be seen throughout the experiment. The bottom part shows a zoomed-in image of the 100-150 km altitude with the automatically detected vertical and horizontal boundaries in fluorescent green

The Canny algorithm is highly accurate and effective at detecting clear, noise-reduced edges, making it ideal for images with simple, well-defined edges. However, it is computationally intensive and requires careful parameter tuning, which can limit its performance on complex or textured images such as the colour coded EISCAT height profiles. In this specific case, the Canny algorithm works well on the profiles obtained during night-time aurora. The main drawback is the need for defining parameters that are not entirely globally defined.

To obtain annual statistics of boundary detection and ensure a fail-safe procedure for our methods, we analysed the electron density (Ne) profiles of all the available experiments. We analysed each experiment's Ne data, focusing on altitudes around 110 km. We calculated a rolling average of Ne to smooth the data and identified significant peaks using a dynamic height threshold. Valid peaks are filtered based on several criteria, including the time of occurrence, proximity to other peaks, and pre- and post-peak conditions. We then detect a proxy for a potential start boundary peak where Ne does not drop below a specified threshold. The results can be seen in Figure A2.

We analysed the total peaks and boundary peaks detected during the dark season (October to March) and the light season (April to September) for Tromsø and Svalbard radars. As anticipated, the number of detected peaks and boundaries was higher during the dark season. Specifically, Tromsø detected 2773 peaks and 390 boundaries from October to March, compared to 726 peaks and 145 boundaries from April to September. Similarly, Svalbard recorded 6663 peaks and 518 boundaries in the dark season, while 2319 peaks and 307 boundaries were detected in the light season.

A2 Auroral boundaries from Polar Operational Environmental Satellites

The procedure to detect boundary based on observations of field aligned electrons from the NOAA-POES satellites is largely based on the study by Breedveld (2020) as well as earlier work by Gussenhoven et al. (1981) and Kilcommons et al. (2017). We use 30-2500 keV precipitation electrons from the last generation Medium Energy Proton and Electron Detector (MEPED). Our data set contains observations from 1998 onwards, and the instrumentation

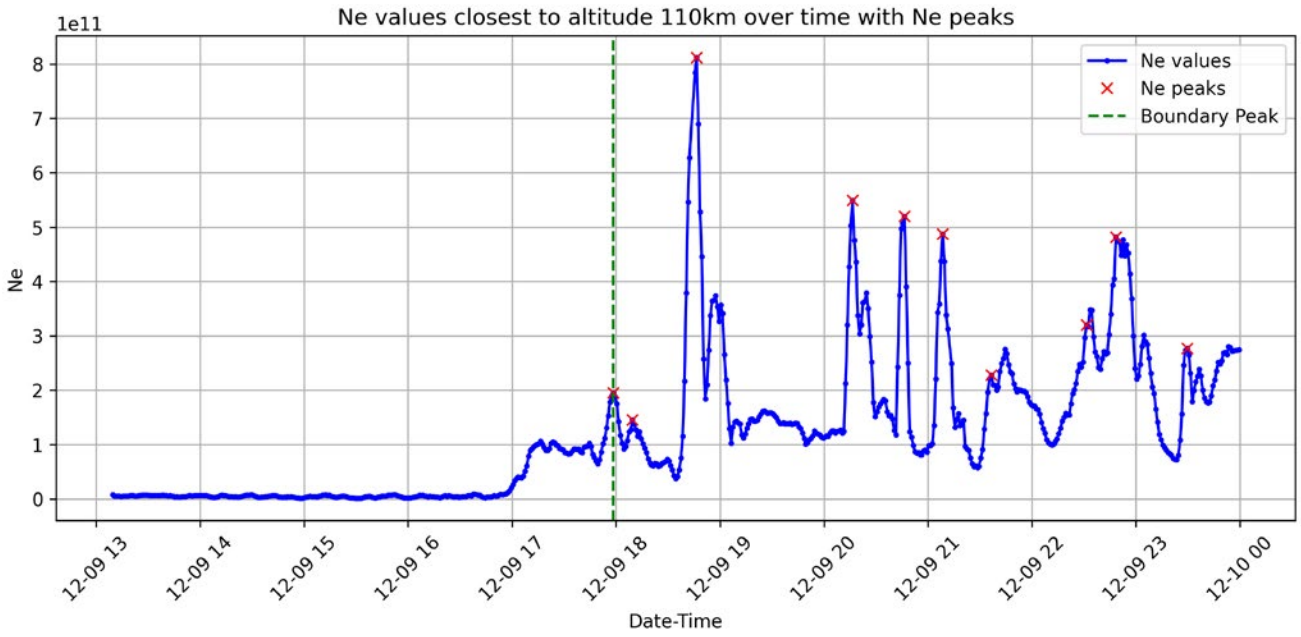

Figure A2: EISCAT Radar Ne intensities around an altitude of 110 km on 9 Dec 2020, on the Tromsø radar (UHF experiment). The green dotted line represents our boundary start proxy and the red crosses represent high intensity throughout the aurora

is identical on all METOPS and NOAA satellites used here. Basically, the procedure is as follows:

1. Calculate average fluxes of field aligned electrons with energies above 30 keV for the polar cap region and a region well equatorward of the auroral oval as a reference background flux.
2. Apply a rolling median over 15 samples (30 seconds) to remove any outliers in the measurements.
3. Slide a step function across the data interval to detect sharp increases in the flux of field-aligned electrons. If the increase is above a certain threshold, and the flux level is well above the background flux, tag it as a boundary.
4. When a boundary is detected, use flux change (increase, decrease) to classify the boundary as an equatorward or poleward boundary. Record time and geographic latitude and magnetic local time (MLT).
5. Calculate and store a quality factor based on how sharp (flux gradient) the boundary is, and how well it is defined (change in flux).
6. Define a threshold in the quality value to classify the boundary as valid or invalid, and use this for filtering of data.

Note that the above fluxes of field-aligned electrons do not necessary coincide with the visible aurora, which is mainly generated by electrons of lower energies. Nor do the detected boundaries necessarily coincide with EISCAT-derived boundaries, since both technique and measurement altitude are different. However, we are primarily interested in secular changes in boundaries, not the exact location or intensity of visible aurora.

Geology of Svalbard: Deep-time and Deep-Earth (SVALGEOL)

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1. Introduction

Geology is the science that deals with the solid Earth's physical structure and substance, its development from distant past to the present and future, and the processes that act on and within it. Sometimes referred to more broadly as "Earth science" or "geoscience", geology includes diverse professions (Figure AF4 in Senger et al. 2024a). Geoscientific work covers a broad range of spatial (from microscopic to global) and temporal (from milliseconds to millions and even billions of years) scales. A multidisciplinary framework is crucial to decipher the past evolution of the Earth System, understand and mitigate geohazards, identify drivers and quantify changes in palaeoclimate, and provide authorities and industry with an understanding of the subsurface, as well as the landscape surrounding us. This understanding is crucial for many applications, including mineral and hydrocarbon extraction, groundwater management, and energy transition/decarbonisation.

The geosphere is the solid portion of the Earth, ranging from the surface of our planet down to the deep interior. It encompasses minerals, rocks, soil, fluids, landforms, and the processes shaping them. Many important processes link the geosphere to the Earth's four other spheres (cryo-, bio-, atmo- and hydro-spheres). SIOS's objectives include "focusing on processes and their interactions between these different spheres". By literally underlying all of these spheres, the geosphere, and by extension geology, is central to deciphering the broader Earth System at present, but also in deep-time at timescales spanning millions to billions of years, dating back to the very beginning of our planet. Finally, and probably most importantly in today's anthropogenically enhanced climate-change, understanding the Earth's past climate history through the study of the ancient rock record and its many palaeoclimate proxies, including fossils, strengthens the predictive power and accuracy of future climate models.

Carbon is the chemical backbone of life on Earth and its cycle is one example of multiscale processes that is rooted in the geosphere but affects all other spheres. Figure 1 illustrates sources, reservoirs, fluxes and sinks within the global carbon cycle and the related rock cycle. Marine sediments and sedimentary rocks are the most voluminous sinks of carbon globally. However, the common misconception is that the processes acting on moving carbon (e.g., as CO_2) to and from this main geosphere sink are too slow to be of relevance, except humans' use of fossil fuels (coal, oil and gas) and volcanic activity.

1.1. Geology in Svalbard: societal relevance

The well exposed geology in Svalbard provides a natural laboratory for geoscientists. It offers world-class outcrops of Archean to Quaternary aged rock successions and exhibits a range of rock types (i.e., lithologies, which together represent all stages of the rock cycle; Figure 1), which in turn reflect a wide variety of tectonic styles, volcanic and magmatic events, and sedimentary basin development. Scientific and industrial boreholes (e.g., coal and petroleum exploration) offer valuable insights into the subsurface, facilitating outcrop–borehole correlations and deciphering past plate tectonic reconstructions and climate change. Integration of geophysical data with systematic surface geological mapping provides a strong foundation for deciphering the 3D architecture and 4D evolution of Svalbard in the context of the Earth System.

Geology is omnipresent in Svalbard. All the former and present permanent settlements (except for the Hornsund research station) are strategically placed near coal seams that were previously mined (Pyramiden, Ny-Ålesund, Sveagruva, Bjørnøya) or are still actively mined (Barentsburg and Longyearbyen). Year-round coal mining in Longyearbyen since 1906 provided a foundation upon which other activities, including research and education, tourism and governance, build. Less well-known is the fact that Svalbard was central

to the start of the Norwegian oil adventure, with 18 boreholes drilled from 1961 to 1994 by a mix of international companies, resulting only in economically unfeasible discoveries (Senger et al. 2019). Svalbard, and in particular the upper Palaeozoic and Mesozoic (~400-66 Ma (Ma = millions of years ago)) basin fill, provides an excellent analogue for enhancing the knowledge of the petroleum systems in the Norwegian continental shelf (e.g., Nøttvedt et al. 1993; Henriksen et al. 2011b; Olaussen et al. 2025).

More recently, geologists have contributed to begin lowering Svalbard's atmospheric CO_2 emissions by investigating the feasibility of subsurface storage of the CO_2 emitted from the Longyearbyen coal power plant (Braathen et al. 2012; Olaussen et al. 2019). The project generated a wealth of data, including eight fully cored research boreholes, seismic data, outcrop studies, and water injection tests (Senger et al. 2024b). The solid understanding of the deep subsurface near Longyearbyen has also proven to be crucial when considering the potential role that geothermal energy (Senger et al. 2023b) or local natural gas (Ohm et al. 2019) could play in Longyearbyen's future energy mix. In addition, the drill cores provide an opportunity to study how the local–regional–global Earth System has evolved in the geological past (i.e., deep-time palaeoclimate covered in section 2.3), the influence of climate change on infrastructure in Longyearbyen, and links to geohazards such as earthquakes and landslides.

1.2. Aim and objective of this chapter

In this chapter, we share a summarised and holistic understanding of Svalbard's geology. Specifically, we: 1) Provide an overview of Svalbard's pre-Quaternary (i.e., older than 2.58 million years) geology for the entire SIOS community, focussing on the role of geology in understanding the Earth System, societal relevance and interlinkages of the geosphere to the cryosphere, hydrosphere, biosphere and atmosphere; 2) Provide a synthesis of

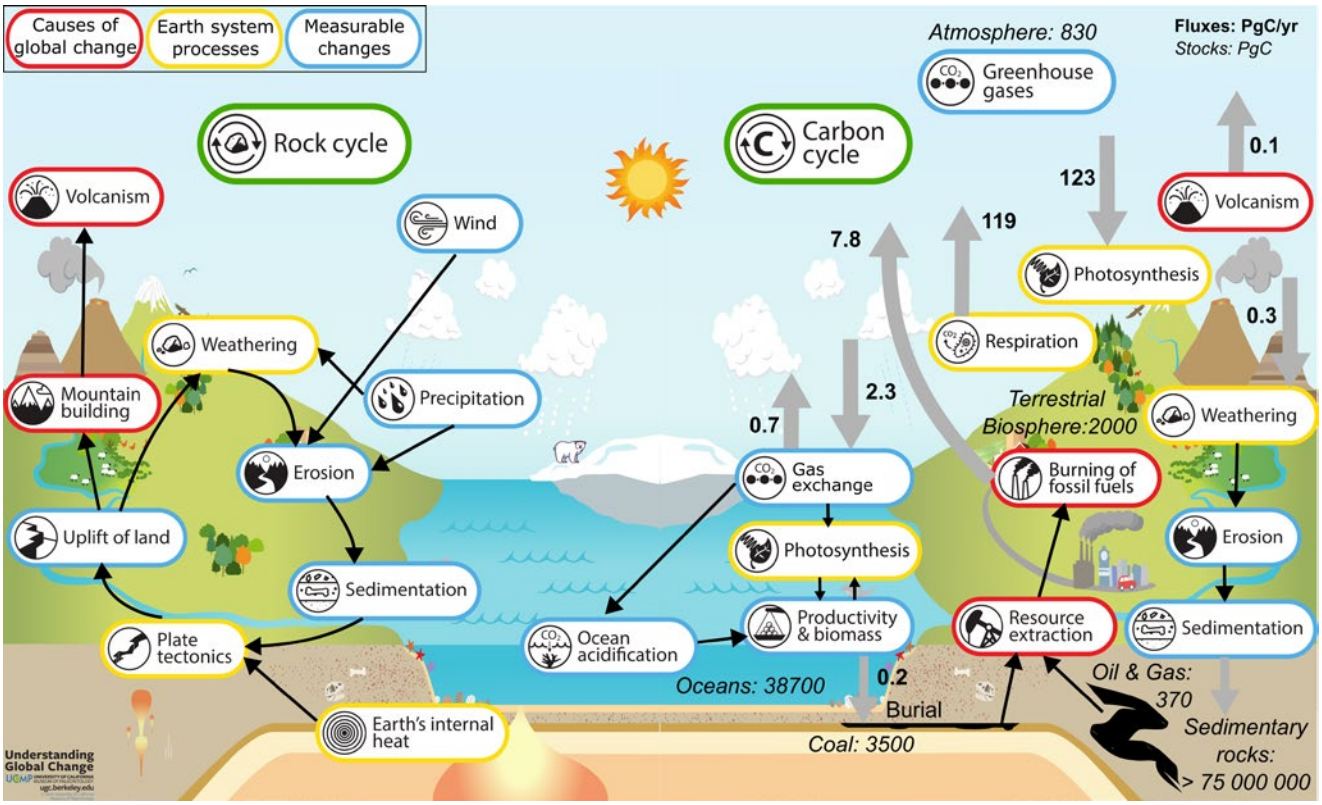

Figure 1: Overview of the rock cycle and carbon cycle showing the importance of geology within the global system. Numbers show carbon reservoirs in PgC (P = peta; 1 PgC = 10^{15} gC = 1 Gigaton of Carbon) and fluxes indicate PgC/yr. Flux and stock input from Ciais et al. (2014) and Falkowski et al. (2000). Figure adapted from Understanding Global Change Berkeley, University of California (2024).

the heterogeneous types of data that geoscientists are working with, including provision of key data sets from Svalbard (largely in the digital appendix (Senger et al. 2024a), appendix figures (AF) and tables (AT) are referred to here); 3) Recommend concrete ways geology can be integrated into SIOS and how diverse geological data should be stored FAIRly.

2. Overview of existing knowledge

2.1. Geological scientific exploration of Svalbard: a brief history and status of geological mapping

The first geologist to visit Svalbard was the Norwegian geology professor Baltazar Keilhau (University in Christiania, now Oslo) in 1827 (Keilhau 1829, 1831; Dallmann 2015). Between 1850 and 1920, geoscientific exploration increased in Svalbard, and 114 expeditions conducted geological mapping, palaeontological studies, and mineral and coal exploration (Harland 1997). These expeditions were dominated by European scientists (Jones 2008) resulting in the first geological maps of Svalbard embedded in the expansive geology compilation "Sketch of the geology of Spitsbergen" (Nordenskiöld 1867) and a broad geological summary (Nathorst 1910).

From the turn of the 20th century Norway was a key player in Arctic geoscientific research, as manifested by Fritjof Nansen's *Fram* expeditions to the central Arctic Ocean from 1893 to 1896, and the state-funded Spitsbergen Expeditions of Gunnar Isachsen (1909) and Adolf Hoel (from 1910). The Svalbard Treaty (granting Norway full sovereignty over Svalbard) was signed at Versailles in 1920 and ratified in 1925. Norway's Svalbard and Arctic Ocean Research survey (NSIU) was formally founded in 1928, and reorganised to the current Norwegian Polar Institute (NPI) in 1948. Orvin (1947) provides a full bibliography up to this time. After 1945, the United Kingdom (Harland 1997), the Soviet Union (Krasil'ščikov 1996), and Poland (Birkenmajer 1980) also conducted systematic geoscientific exploration of Svalbard.

Geology-related research accounts for >35% of scientific research conducted in Svalbard (Figure 2A). Between 1960 and 1990, 40-50% of the published peer-reviewed articles were geology-related (Figure 2), coinciding with the peak period of onshore petroleum exploration (Senger et al. 2019) and the initiation of a systematic geological mapping programme at NPI under the leadership of Tore Gjelsvik (NPI Director, 1960–1983). Analysis of data from the Research in Svalbard Portal (RiS[1]) reveals the international background of the research institutions, with approximately half (49.4%) being Norwegian and 27 different countries represented (Figure 2B). Most research (73%) is fieldwork-related, with a significant (11,2%, Figure 2C) education component, largely driven by the University Centre in Svalbard (UNIS) established in Longyearbyen in 1993.

Elvevold (2015) provides an excellent overview of the history of resource extraction in Svalbard, including coal, petroleum, industrial materials, and ore minerals. Until the ratification of the Svalbard Treaty (and the Svalbard Mining Code) in 1925, prospecting and claiming often caused conflicts. Since 1925, the Svalbard Mining Code (described in Senger et al. 2019) stipulates how land is claimed for resource extraction. Thanks to the Svalbard Treaty, companies from all signatory nations have equal access to the natural resources as Norwegian companies, provided they adhere to Norwegian regulations. As of 2017, 6% of Svalbard's land area was claimed for resource exploration, divided over 349 individual claims (Senger et al. 2019). Most of the claims are for coal production by the Norwegian state-owned company Store Norske Spitsbergen Kulkompani AS (SNSK) and the Russian company Trust Arktikugol.

1 https://www.researchinsvalbard.no/

Both commercial and research expeditions contributed to deciphering the main elements of Svalbard's geological history, as summarised in the Geoscience Atlas of Svalbard (Dallmann 2015). Svalbard offers examples of rift basins formed in extensional settings (e.g., Billefjorden Trough; Steel and Worsley 1984) and foreland basins formed in compressional settings (e.g., Central Spitsbergen Basin; Helland-Hansen and Grundvåg 2021). In addition, volcanism occurred at several time intervals, including during the Early Cretaceous (Senger et al. 2014b), Miocene (Prestvik 1978) and Quaternary (Skjelkvåle et al. 1989; Smelror et al. 2024).

Geological mapping of Svalbard is conducted by NPI and is complete at the regional scale (Dallmann 2015; Figure 2D). Ongoing research by various groups in specific areas continues to fine-tune and improve the geological mapping at the local scale (Jochmann et al. 2020). From the late 1970s the Universities of Bergen (Ron Steel) and Oslo (David Worsley) organised extensive expeditions (sponsored by oil companies and the Norwegian authorities) including international specialist geologists from the industry to reveal, in particular, the upper Palaeozoic to Cenozoic basin fill in Svalbard (e.g., Steel and Worsley 1984).

With its rich history of multidisciplinary geoscientific research, Svalbard offers unique insights into data integration, deep-time palaeoenvironments and "from depth to surface" 3D/4D processes covered in sections 2.2 to 2.4.

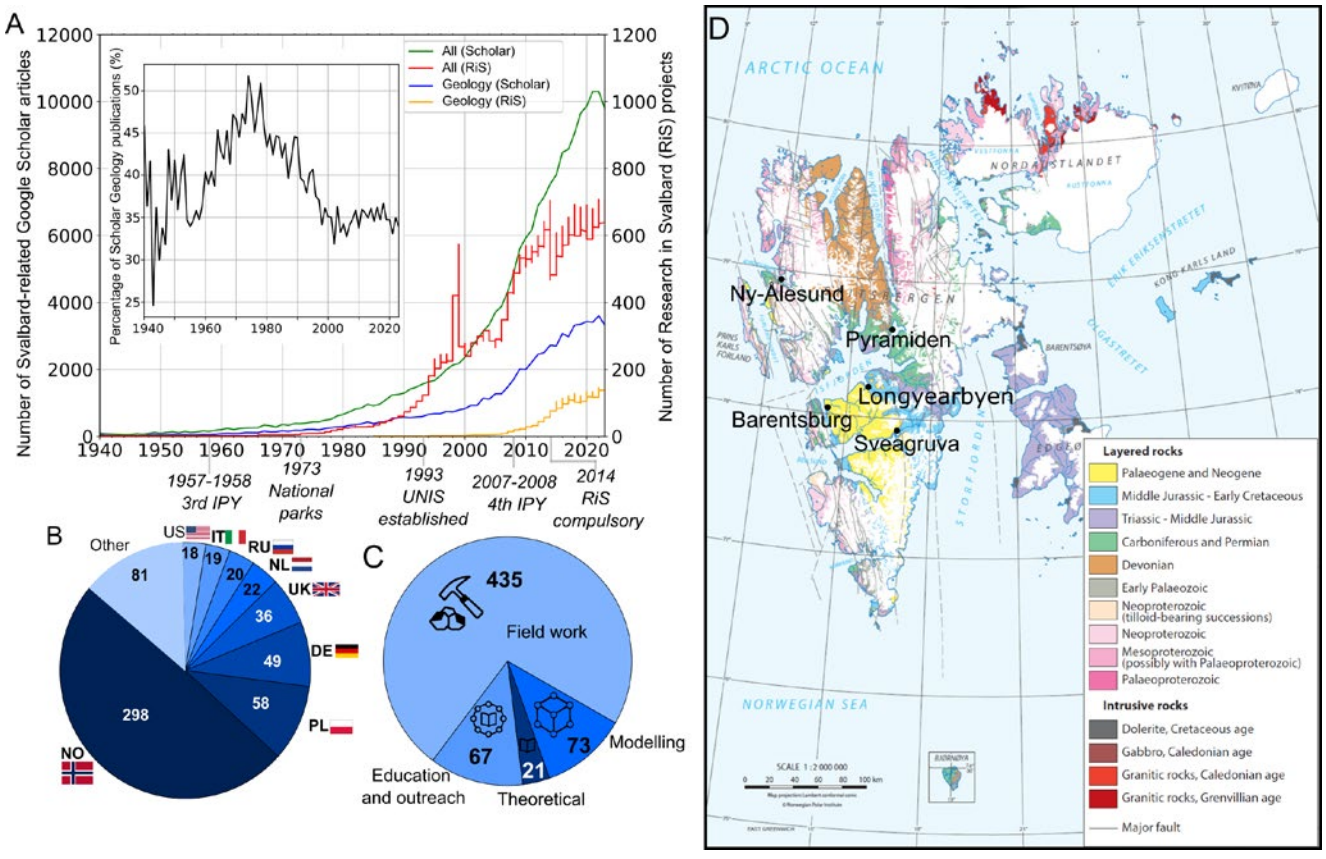

Figure 2: Synthesis of geological research in Svalbard through time. A) Active and complete projects recorded in the official Research in Svalbard Portal (RiS) and publications on Google Scholar. Total number of Google Scholar articles mentioning Spitsbergen OR Svalbard (green) compared to the articles also including the term "geology" (blue). Inset shows the percentage of articles including the word geology over time. B) Norway is the institution responsible for just under half the projects in the RiS Portal (601 active or completed projects in total). Other: South Korea 11, Czech Republic 10, Sweden 9, China 9, India 9, France 6, Denmark 5, Finland 3, Iceland 3, Israel 3, Austria 2, Belgium 2, Switzerland 2, Japan 2, Slovenia 1, Brazil 1, Ireland 1, Hong Kong 1, Canada 1. C) Fieldwork is the main category of research conducted. D) Modern geological map of Svalbard with main settlements. Source: Dallmann (2015).

2.2. Digital geological revolution and integration of data sets – data acquisition, integration and joint interpretation

Whether working with a view of a rocky outcrop, a hand-sample taken to a lab and analysed, or a numerical model run on supercomputers, geologists employ a wide range of datasets and techniques. Geoscientists are able to tackle grand questions with non-linear interactions and increasing complexity, but this has not evolved without some major breakthroughs in understanding. During the past century, the broad field of geosciences has undergone several revolutions including continental drift (Wegener 1912), seafloor spreading (Isacks et al. 1968), and plate tectonics (Wilson 1966). Furthermore, we are now considered to be in a modern revolution where planetary-scale changes, including the evolution of Earth's interior and surface, are connected and palaeoclimate can be modelled at geological time scales.

Geologists employ sedimentology (e.g., Cutbill and Challinor 1965; Steel and Worsley 1984; Grundvåg et al. 2019), structural geology (e.g., Dallmann 1992; Bergh et al. 1997; Piepjohn et al. 2016), biostratigraphy (e.g., Manum 1960; Bjærke and Thusu 1976; Feyling-Hanssen and Ulleberg 1984; Århus 1991; Śliwińska et al. 2020), magnetostratigraphy (e.g., Hounslow et al. 2007; Zhang et al. 2021), geochronology (e.g., Corfu et al. 2013), thermochronology (e.g., Dörr et al. 2012; Barnes and Schneider 2019; Meier et al. 2024), detrital-zircon provenance studies (e.g., Pettersson et al. 2009; Petersen et al. 2016; Anfinson et al. 2022), palaeontology (e.g., Tozer 1973; Hurum et al. 2018), seismic geophysics (e.g., Eiken 1985, 1994), electromagnetic geophysics (e.g., Beka et al. 2017; Selway et al. 2020), potential field geophysics (e.g., Dumais et al. 2022), and remote sensing (e.g., Zagórski et al. 2020) to interpret a region's geological evolution, as illustrated by the Svalbard examples listed here and in Table AT6 in Senger et al. (2024a). Numerical modelling of crustal (e.g., Klitzke et al. 2016; Minakov et al. 2018) or mantle (e.g., Heyn et al. 2024) processes, 2D or 3D structural restorations (e.g., Bergh et al. 1997; Gac et al. 2020), analogue modelling (e.g., Leever et al. 2011), deciphering vertical motions (e.g., Medvedev et al. 2023), or plate tectonic reconstructions (e.g., Torsvik et al. 1985) add the time component to the process understanding. In addition, the compilation and quantification of all important geological processes and physical/chemical parameters impacting deposition, preservation, and deformation of sedimentary strata, can serve as inputs used in forward modelling of sedimentary systems. This can furthermore be a useful tool to reconstruct the complete history of sedimentary basins in the context of tectonic-climatic drivers.

Seismic acquisition along profiles (2D), grids (3D; also called the "geological Hubble" by Cartwright and Huuse (2005)) and in repeated surveys (4D) allows geologists to map out the subsurface and show how fluids (water, oil, natural gas or injected CO_2) move in the subsurface. An extensive onshore and offshore 2D seismic grid is available in Svalbard (Eiken 1994; Bælum et al. 2012; Blinova et al. 2013; Figure in Appendix 4). Seismic modelling of outcrops allows directly linking geometries from outcrops to modelled seismic profiles and was pioneered early on in Svalbard (Helland-Hansen et al. 1994; Johansen et al. 1994, 2007).

At present, field geology is undergoing a digital revolution. 3D digitisation through Light Detection and Ranging (LiDAR) scanning and structure-from-motion (SfM) photogrammetry enables high-resolution georeferenced representations of geological outcrops (Buckley et al. 2008; Westoby et al. 2012), drill cores and hand samples (Betlem et al. 2020). The increased availability of affordable unmanned aerial vehicles (UAVs, i.e., drones; Hann et al. 2021) with high-quality cameras provides an optimal angle for photographing outcrops for SfM modelling and acquiring aerial photospheres (i.e., 360° images) that provide a bird's eye overview of Svalbard geo-landscapes (www.vrsvalbard.com; Horota et al. 2024). Digital outcrop models facilitate quantitative analyses, such as seismic modelling (Anell et al. 2016; Johansen et al. 2023), fracture characterisation (Rizzo et al. 2024) and systematic mapping of sand injectites (Ogata et al. 2023), even on otherwise inaccessible parts of outcrops. The

UNIS-led Svalbox database (map.svalbox.no; Senger et al. 2021; Betlem et al. 2023, 2024) openly shares a growing collection of digital outcrop models in the context of regional geoscientific data. These new digital options can be easily linked to other field data (e.g., sedimentary logs, sample locations), subsurface data and the regional geology.

The digital revolution is also transforming geoscience education, promoting a more integrated and quantitative approach compared to traditional field geology alone. In Svalbard, examples include the use of integrated digital outcrops in bachelor-level courses at UNIS (Senger et al. 2021) and thematic educational data packages compiled for both the West Spitsbergen Fold-and-Thrust Belt (WSFTB; Horota et al. 2023) and regional Arctic tectonics (Senger et al. 2024d). Furthermore, the digitisation of landscapes and fossils enhances the outreach potential, as demonstrated locally in Longyearbyen by the life-sized reptile-themed playground and an interactive geology display at the Svalbard Museum. These advancements make geoscience more accessible and more engaging for both students and the public.

Geologists should ideally have a solid understanding of all the available multidisciplinary data sets and be able to integrate field, subsurface, microscopic, geochemical, remote sensing and digital geological data (Table AT6 in Senger et al. 2024a). Modern geoscientists work across multiple scales with respect to time and space, considering past processes shaping the geosphere to understand the Earth System's evolution. Svalbard is, undeniably, an excellent natural laboratory for this purpose.

2.3. Deep-time – palaeoclimatic significance and main influences on past to present climates in Svalbard

The geological archives on Svalbard cover much of the Phanerozoic (Figure 3). These rocks record both regional and global climatic and tectonic changes. The effects of tectonic processes on the climatic evolution in Svalbard have been profound, and can be broadly grouped into long-term plate tectonic, tectono-magmatic and tectono-topographic effects. The sedimentary record of Svalbard was influenced by:

i) Global climate: Key climatic events preserved in Svalbard's sedimentary archives include: glacial deposits and interglacial carbonates of the Cryogenian and Ediacaran ice ages (e.g., Halverson et al. 2004, 2018; Hoffman et al. 2012; Millikin et al. 2022), which demonstrate climate fluctuations comparable to those observed in the Neogene; mixed siliciclastic-carbonate and evaporite successions which formed in response to severe glacio-eustatic sea-level variations related to the climate fluctuations during the late Palaeozoic Ice Age (e.g., Ahlborn and Stemmerik 2015; Sorento et al. 2020); carbonate and siliciclastic succession deposited near the Permian–Triassic boundary (251.9 Ma) recorded the end of the Permian mass extinction (EPME; ca. 252 Ma) and the subsequent ecosystem recovery (e.g., Zuchuat et al. 2020; Foster et al. 2023); coal deposits from three past greenhouse climate periods: the late Palaeozoic (ca. 370–350 Ma; e.g., Abdullah et al. 1988; Janocha et al. 2024), the Early Cretaceous (ca. 125 Ma; e.g., Nemec 1992), and the early Palaeogene (ca. 61 Ma; e.g., Marshall et al. 2015; Golovneva et al. 2023), providing a record of past vegetation from these intervals.

However, several past climatic events remain understudied in Svalbard, as sediment drill cores primarily targeted intervals of interest to mining and petroleum industries (Olaussen et al. 2019; Senger et al. 2019). Therefore, high-resolution drilling campaigns targeting key climate change events could reveal causal relationships between events such as hyperthermals (short-term phases of geologically rapid global warming occurring over tens of thousands of years) and mass extinctions (Senger et al. 2023a). As a consequence of climate change, high latitudes are presently experiencing polar amplification (i.e., higher magnitude change at higher latitudes) of global warming. They are also projected to experience this in all future climate scenarios provided by the Intergovernmental Panel on Climate Change (IPCC). The IPCC report is extensively using deep-time climate records,

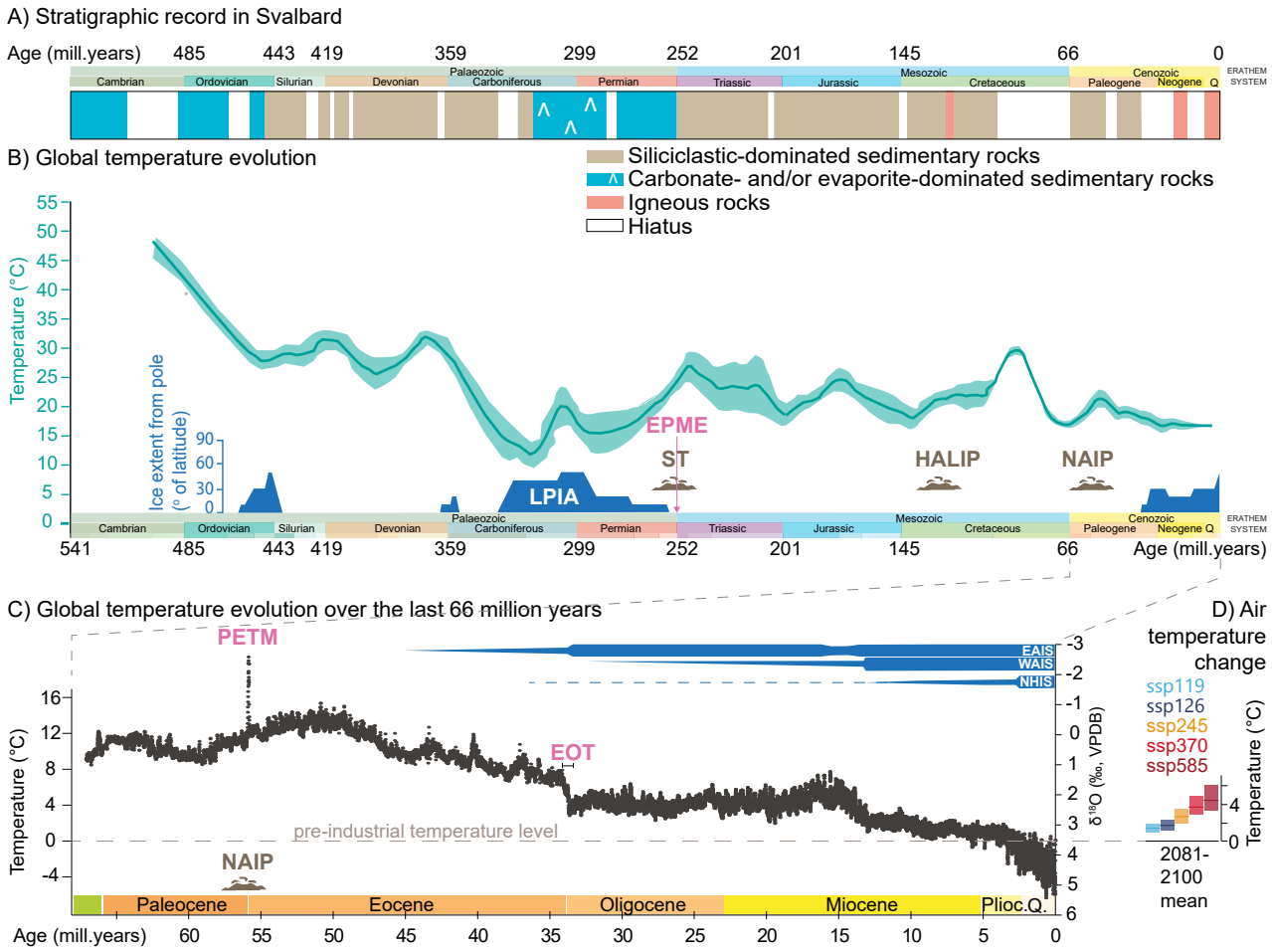

Figure 3: **A)** Deep-time stratigraphic record in Svalbard and **B)** Global mean values of tropical sea surface temperatures over the last 540 Ma from Scotese et al. (2021; green curve, with shaded area 95% confidence intervals, based on oxygen isotopes from phosphatic and carbonate fossils), glaciations from Macdonald (2020); major LIPs recorded in Svalbard: ST–Siberian Traps, HALIP–High Arctic Large Igneous Province, NAIP–North Atlantic Igneous Province. **C)** Global temperature over the last 60 Ma (modified from Westerhold et al. 2020); **D)** and global surface air temperature projections (mean for years 2081-2100) relative to 1850–1900 according to the Shared Socioeconomic Pathways (SSP; modified from Figure 4.35 in IPCC (2021)). Other abbreviations LPIA: Late Palaeozoic Ice Age, EPME: End-Permian Mass Extinction, PETM: Palaeocene–Eocene Thermal Maximum, EOT: Eocene–Oligocene Transition, EAIS: East Antarctic Ice Sheet, WAIS: West Antarctic Ice Sheet, and NHIS: Northern Hemisphere Ice Sheet.

such as from the Palaeocene–Eocene Thermal Maximum (PETM; 55.9–55.7 Ma), to improve our understanding of warmer-than-present climate (IPCC 2021).

ii) Long-term global tectonic influence: Overall, Svalbard has migrated from equatorial latitudes at 400 Ma to its current position between 76°N and 80°N (e.g., Harland 1997). Consequently, the geological record of Svalbard has been affected by this northward motion due to long-term global plate tectonic evolution. For example, between 320 and 270 Ma, when Svalbard was in a subtropical climate, deposition was typified by evaporite rocks. Thick coal seams formed from accumulations of organic material, revealing the presence of humid tropical forests when Svalbard was located near the equator (ca. 350 Ma). In contrast, coal deposits that formed at ca. 61 Ma when Svalbard was located within the Arctic Circle suggest a humid and temperate climate at that time (e.g., Golovneva et al. 2023).

Oceanic gateways play an important role in oceanic circulation, biota exchange, heat and nutrient distribution, and hence the global climate (e.g. Berggren 1982; Bahr et al. 2021; Straume et al. 2022). A key element of the modern icehouse climate is the deep-water exchange between the Arctic and the Atlantic oceans via the Fram Strait (e.g., von Appen et al. 2015). The opening of the Fram Strait has been postulated as one of the initial

drivers towards the modern icehouse climate (e.g., Hossain et al. 2021). Water exchange across the Fram Strait may have occurred between 24 and 21 Ma, or at 17 Ma (Jakobsson et al. 2007; Jokat et al. 2016), or as early as ca. 34 Ma (Hutchinson et al. 2021; Śliwińska et al. 2023). Further study of the Svalbard margins may better constrain this key tectonic event.

iii) Tectono-magmatic influences: The present-day Arctic holds evidence of several large-scale magmatic and volcanic events since the Palaeozoic Era (~540 Ma; Figure 3B). These episodic events, referred to as Large Igneous Provinces (LIPs; e.g., Ernst and Youbi 2017), are characterised by outpourings of large volumes of molten rock (magma) over ~1-5 million years (Bryan and Ernst 2008; Svensen et al. 2012, 2019; Ernst et al. 2021).

LIPs inject massive volumes of volatile gases, including CO_2, CH_4 and SO_2, into the atmosphere, either from direct magmatic and volcanic degassing or from contact metamorphism of host rocks (Jones et al. 2016). Greenhouse gases perturb the global carbon cycle, negatively impact the environment, and lead to rapid global warming (e.g., hyperthermals). LIPs also seem to be linked with most mass-extinction events (Green et al. 2022). Evidence of several LIP events are recorded in Svalbard, such as:

1) The Siberian Traps, LIP in present-day Russia, began forming at ca. 252 Ma, when the volcanic and thermogenic gases released led to Earth's most severe extinction event, the end-Permian mass extinction (Svensen et al. 2009; Burgess and Bowring 2015). Ash layers from Svalbard are hypothesised to be derived from the Siberian Traps (Zuchuat et al. 2020), and can constrain the timing and the cause of the extinction.

2) In the Early Cretaceous, the emplacement of the High Arctic Large Igneous Province (HALIP, ~130-80 Ma old) is coincident with periodic oxygen-deficient conditions in the deep oceans, known as Oceanic Anoxic Events, and may have influenced global ocean circulation patterns (Polteau et al. 2016; Midtkandal et al. 2016). In Svalbard, the HALIP-related magmatic rocks (Dallmann 1999; Senger et al. 2014b) generated metamorphic aureoles, particularly in Triassic organic-rich shales (Brekke et al. 2014; Senger et al. 2014a; Senger and Galland 2022). The contact of the hot magma with the sedimentary rocks led to a release of up to 20 000 Gt of carbon in Svalbard–Barents Shelf (Polteau et al. 2016).

3) Opening of the Northeast Atlantic Ocean, starting ~56 Ma, was associated with the North Atlantic Igneous Province (NAIP) and the release of large volumes of carbon (Svensen et al. 2004; Gutjahr et al. 2017). Together with shallow-water hydrothermal venting, these processes are suggested as the trigger for the PETM (Berndt et al. 2023) which led to a transient 4–6°C global warming on already hothouse climate conditions (e.g., Inglis et al. 2020). In Svalbard, the PETM has been documented in several locations (e.g., Dypvik et al. 2011; Jones et al. 2019).

iv) Tectono-morphological influences: High topography can impact the local precipitation patterns, and lead to the nucleation of glaciers if climatic conditions are favourable. In Svalbard during the Cenozoic, topography was produced in these ways:

1) Plate motions resulted in the formation of the WSFTB, which took place largely under a greenhouse climate (at ca. 59–33 Ma). Some studies argue for the presence of ephemeral ice caps or small ice sheets in the northern hemisphere by ca. 37 Ma (Tripati and Darby 2018). Nucleation and growth of these ice caps might have been possible only because of the presence of topography.

2) The topographic response to rifting and oceanic spreading coincided with climatic deterioration in the late Neogene following the opening of the Arctic–Atlantic gateway (e.g., Haaland et al. 2024). As climate warms up, deglaciation leads to loss of mass (ice plus eroded sediments) and thus to enhanced uplift (e.g., Medvedev et al. 2018). This appears to be the situation in Svalbard at present (Kierulf et al. 2022).

All these processes have had cumulative effects on the type and amount of weathering, erosion rate, runoff, depositional settings, and landscape evolution, thus affecting both habitable and uninhabitable environments of the Svalbard archipelago.

2.4. Deep-Earth – linking deep with shallow processes

The surface and interior of the Earth are inextricably linked due to the long-term cooling of the Earth and mantle convection. The slow and broad-scale evolution of the interior provides a long-term and deep-Earth trend on which shorter-term near-surface processes, such as the elastic lithospheric response to erosion and deglaciation or local changes in sea level, are superimposed. Understanding surface observations and processes deeper into the Earth and consideration of timescales from the present day to millions of years ago is essential to tie these together.

Internally, the Earth can be divided into several layers, depending on the physical, chemical, thermal and/or structural differentiations (Figure 4B, and appendix 3). These divisions determine the location, type and nature of geological processes at the Earth's surface, for example volcanism, seismicity, and surface deformation (including uplift, subsidence and horizontal motions). Appendix 3 provides an overview of the various methods geophysicists employ to study the different layers of the Earth, with examples and observations from Svalbard. Below we expand upon selected Earth-to-surface links relevant for Svalbard.

i) Current plate tectonic configuration – Svalbard is located on the NW corner of the Eurasian lithosphere plate, and is also near two presently active segments of a divergent plate boundary, the Gakkel Ridge to the north, and the Knipovich Ridge to the west. Motion in these spreading systems began around 55 million years ago, before which Svalbard was much closer to Greenland. Whilst these boundaries accommodate the creation of new seafloor (at a rate of around 1 cm/yr in the Svalbard region, decreasing to zero towards the Laptev Sea), stresses related to these processes can also be transferred into the plate interior.

ii) Past tectonic motion – Svalbard experienced several deformation episodes related to past shifts in tectonic plates throughout the Phanerozoic times. These include compressional events (i.e., mountain building events) and extensional episodes (i.e., rifting episodes) throughout Phanerozoic times. Large-scale surface or near-surface structures, including faults, sedimentary basins, fold and thrust belts, are caused by these tectonic deformations.

iii) Orogenies – The most recent mountain-building event in Svalbard was the Eurekan deformation (alternatively, Orogeny) at ~ 60-35 Ma (e.g., Piepjohn et al. 2016; Schneider et al. 2019). It occurred as Greenland slid past Svalbard causing, (1) uplift and deformation of the WSFTB, (2) motion along long, steeply dipping N-S to NNW-SSE trending faults such as the Hornsund tectonic zone and Billefjorden Fault Zone, (3) metamorphism at mid-crustal levels (Kośmińska et al. 2020), (4) a depression east of the WSFTB, known as the Central Spitsbergen Basin, and (5) an ocean connection between the North Atlantic and the Arctic. Several earlier deformation events also affected Svalbard, including Ellesmerian, Caledonian and Timanian events.

iv) Seismicity – Svalbard's seismicity is a function of its long-lived tectonic and recent glacial history. Most earthquakes occur offshore, along the Knipovich and Molloy ridges, and associated transform faults (Schweitzer et al. 2021). Many smaller (magnitude Mw < 3) earthquakes occur across continental Svalbard, including near Nordaustlandet (Figure 4A), and are likely related to ongoing regional uplift and far-field tectonic stress propagation. Strong intraplate earthquakes occur, including a 2008 Mw 6.1 event in Storfjorden (Figure 4A) which featured year-long complex aftershocks (Pirli et al. 2013, 2021).

v) Large-scale volcanism – As mentioned in section 2.3, several Large Igneous Provinces (LIP) affected Svalbard (including the 124.5 Ma HALIP event that also included lava flows on Kong Karls Land;

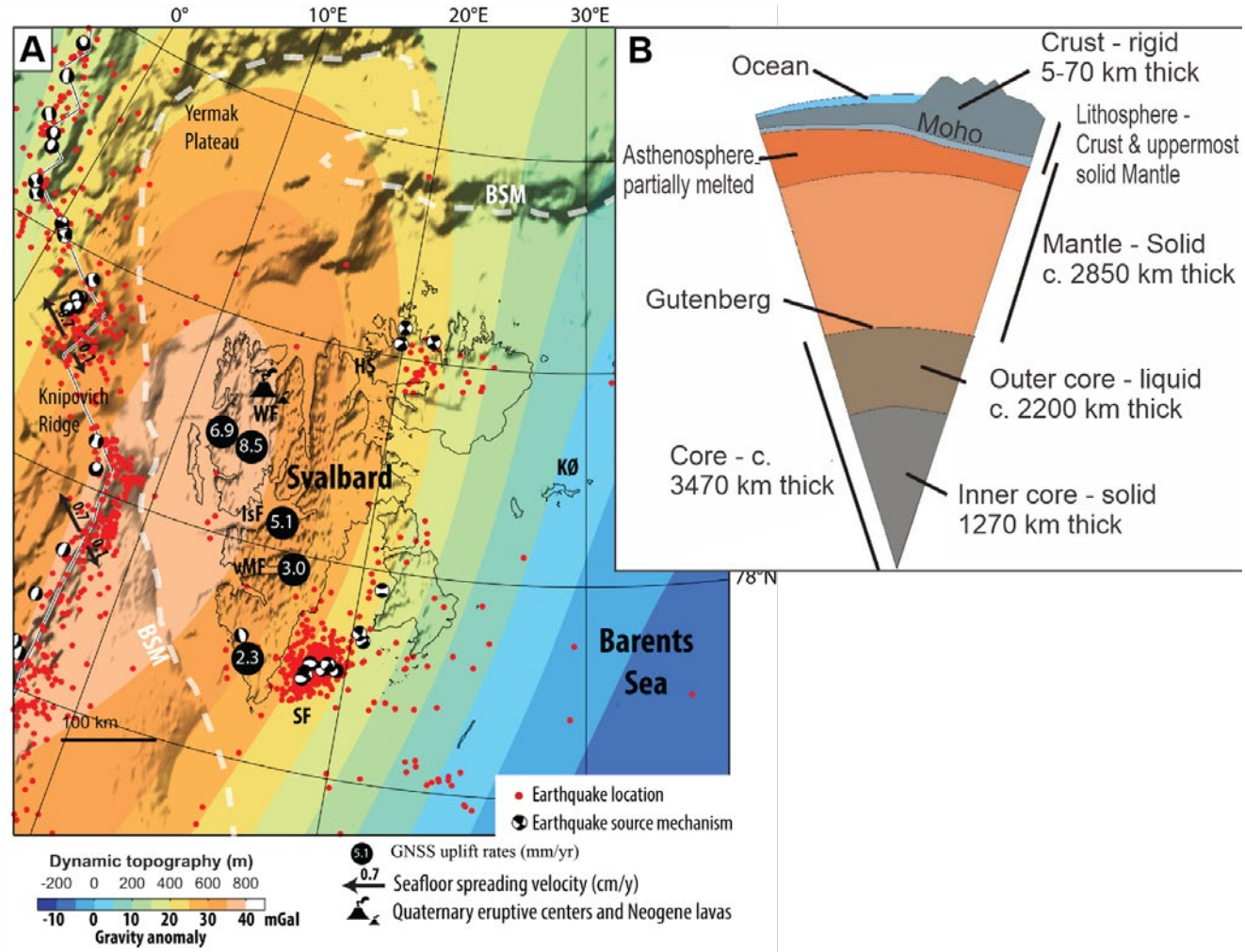

Figure 4: A) Example of deep and shallow coupling for Svalbard, modified from Minakov (2018). Dynamic topography inferred from long-wavelength gravity anomalies whereby maximum topography (~ 800 m) corresponds to the location of Quaternary and Miocene aged volcanism (WF) in Svalbard. Abbreviations: HS – Hinlopenstredet, IsF – Isfjorden, vMF – van Mijenfjorden, SF – Storfjorden. WF – Woodfjorden, KØ – Kongsøya (Kong Karls Land), BSM – Barents Sea continental margin (based on crustal thickness, see Klitzke et al. 2015). Earthquake focal mechanisms from the global CMT catalogue (Dziewonski et al. 1981; Ekström et al. 2012) with additional moment tensor solutions (Mitchell et al. 1990; Pirli et al. 2013). Plate boundary configuration (Argus et al. 2011) with black arrows showing spreading direction. Uplift rates obtained by subtracting predicted effect of present-day ice melting from observed Global Navigation Satellite System (GNSS) velocities (Kierulf et al. 2022). **B)** Layering of the Earth (Geological Survey of Ireland 2024).

Olaussen et al. 2018; Smelror et al. 2018). This type of volcanism is caused by a mantle plume, a hot buoyant conduit of molten rock which rises from the core–mantle boundary. Strongly upwelling mantle regions, such as around plumes, are typically associated with long-wavelength gravity highs (and density deficit), known as dynamic topography. Their thermal imprint may have a lasting effect on the thermal structure of the upper mantle.

vi) Regional volcanism – NW Svalbard, including Sverrefjellet and the Bockfjorden Volcanic Complex, experienced regional volcanism during Miocene to Quaternary times (e.g., Skjelkvåle et al. 1989; Ionov et al. 2002a, b; Senger et al. 2024c). Volcanism of this nature reflects deeper sub-crustal thermo-chemical structures. Volcanic rocks with deeply derived xenoliths (solid rock fragments transported by magma) provide insights into the composition of the mantle and lower crust. A positive upper mantle temperature anomaly beneath western Svalbard coincides spatially with the Quaternary volcanic eruptive centres (Minakov 2018).

vii) Thermal springs – Locally, Spitsbergen has several mineral springs, e.g., such as in the

Bockfjorden area (Jamtveit et al. 2006). These springs are typically related to either deep crustal circulation of hydrothermal fluids or to mixing of sub-permafrost hot brines with glacial or sea water infiltration (e.g., Olichwer and Tarka 2018). The occurrence and characteristics of the springs, such as the mineral composition and temperature, are often associated with the geology, e.g., occurrence of sedimentary rocks, marbles, as well as the distribution of faults.

viii) Heat flow – Heat flow is a measure of the amount of heat escaping from the Earth's interior, related to the thermal properties of the underlying crust and mantle. Svalbard has a higher geothermal gradient (the increase in temperature with depth) than mainland Norway, which is why geothermal energy is advocated as a possible source of renewable energy for Longyearbyen (Senger et al. 2023b). Onshore surface heat flow data are sparse and heterogeneous (e.g., Klitzke et al. 2016; Grad and Majorowicz 2020; Senger et al. 2023b). Offshore heat flow values range from 80 to > 300 mW/m^2 from offshore continental slopes to mid-ocean spreading zones (e.g., Crane et al. 1991; Okay and Crane 1993; Geissler et al. 2014; Dumke et al. 2016; Klitzke et al. 2016) and 40 to 80 mW/m^2 onshore in mainland Norway and continental Europe.

ix) Current and recent uplift – Svalbard is presently undergoing uplift as measured using the Global Navigation Satellite System (GNSS; Figure 4A). Uplift is driven by the elastic response of ice mass changes and viscoelastic response on glacial changes in the past. The latter includes a signal from the glacial retreat after the little ice age, made possible by a low viscosity asthenosphere layer (e.g., Mémin et al. 2014; Nield et al. 2014; Weerdesteijn et al. 2022). The first permanent GNSS station (NYAL; Ny-Ålesund in 1993) recorded uplift rates of 6 mm/year in 2000, increasing to 12 mm/yr in 2020 (Kierulf et al. 2022). Other stations including Longyearbyen (LYRS) and Hornsund (HORN/WUTH) showed uplift of around 10 mm/year in 2020. GNSS data indicate systematic large annual variations with a rapid uplift in the short Arctic summer, and slow subsidence during winter. The extent of pre-glacial uplift in Svalbard correlates with gravity anomalies, seismic velocity structure, and the high rates of glacial isostatic adjustment (Minakov 2018; Sættem et al. 1994; Dimakis et al. 1998). We identify the following sources of uplift at various spatial-temporal scales: a) regional pre-glacial/Neogene uplift, as indicated by an erosional unconformity and the progradation of glacial sediments at the Barents Sea continental margins. It was suggested that this Neogene uplift has preconditioned the onset of glaciations (e.g., Dimakis et al. 1995). The nature of the Neogene uplift has been explained by a thin lithosphere/hot mantle formed during the propagation of seafloor spreading through the Fram Strait at ca. 20–10 Ma (Engen et al. 2008; Dörr et al. 2012; Minakov 2018); b) postglacial rebound which probably equilibrated faster and was smaller in amplitude in the northwest because of the smaller ice thickness and weak mantle; c) viscoelastic response to the glacial retreat after the little ice age; and d) spatially varying uplift in response on present day ice melting.

x) Hydrocarbon formation – Hydrocarbons form when thick organic-rich units are buried to depths of ~2–3 km and exposed to temperatures of 60–120°C over time. The burial history of a basin, including source rock volume and quality, sediment thickness, and thermal history, controls the maturation rates, which in Svalbard shows strong east–west gradients (Olaussen et al. 2025). Svalbard's uplift rates affect petroleum systems (Henriksen et al. 2011a) notably through ongoing active thermogenic gas generation and hydrocarbon re-migration. Natural gas, while an energy source, is also a greenhouse gas. Permafrost onshore temporarily caps migrating gas (Birchall et al. 2023; Birchall 2023) but uplift affects pore fluid pressures, leading to near-surface gas migration (Hornum et al. 2020) including via pingos and glacial forefields (Hodson et al. 2020; Kleber et al. 2023; Hodson et al. 2025). In Svalbard's relatively shallow fjords, natural gas seepage is strongly controlled by the subsurface architecture (source rocks, fault zones; Rodes et al. 2023). Natural gas hydrates likely exist onshore and offshore (Betlem et al. 2019, 2021). Gas hydrates hold more gas per unit rock volume

than conventional shallow gas reservoirs and can have rapid and considerable short-term climate feedbacks via rapid losses of thermodynamic stability (e.g., Portnov et al. 2016).

3. Contributions to interdisciplinarity

Geoscientists have a diverse toolbox, working across a broad range of scales (both temporal and spatial) and utilising a variety of data sets and methodologies (see Senger et al. 2024a). Whilst research typically has focussed on basic and applied topics of the geosphere, there is increasing attention and value being placed on interdisciplinary research that ties geosciences to the other spheres. Figure AF3 in Senger et al. (2024a) takes a global view of this, and summarises changes that traverse scales and spheres, as well as the human and non-human contributions. The cryosphere is not included but is crucial when considering Svalbard or other Arctic and polar regions (Figure 5).

There are ample studies linking the solid Earth to processes occurring on or above the Earth's surface. One example is the link between topography and atmospheric conditions (e.g., wind patterns, temperature, precipitation, snow depth; Skeie and Grønås 2000; Reeve and Kolstad 2011; Kilpeläinen et al. 2011). Similarly, sub-sea topography (i.e., bathymetry) influences oceanic circulation and water mass exchange, thereby establishing direct geosphere–hydrosphere linkage. Over geological times, the landscapes change due to tectonic and geomorphic processes, including uplift, subsidence, deformation, sea-level changes, deposition, and erosion. Studies show how tectonic events influence regional–global climate (e.g., Andes, Himalayas; Armijo et al. 2015; Clift 2017), but also how climate influences the tectonic evolution of mountain belts (e.g., Whipple 2009). Such tectonic–climatic couplings have been largely overlooked in Svalbard to date, even though land uplift inevitably facilitated the initiation of glaciations. Conversely, the globally important opening of the Fram Strait with implications on oceanographic exchange to the Arctic Ocean has been covered through oceanography, geophysics (Dumais et al. 2022), plate tectonic and palaeoceanographic reconstructions (Engen et al. 2008; Straume et al. 2020), dating onshore fault movements (Haaland et al. 2024), and thermal evolution (Meier et al. 2024).

The deep-time palaeoclimatic signal recorded in the geosphere (see section 2.3) is paramount to understanding how the different spheres interact in the absence of human influence (Figure AF3 and AF4 in Senger et al. 2024a). Considering global mass extinctions, for instance the end-Permian mass extinction, the geological record allows geoscientists to decipher its causes, how this event affected the atmosphere, hydrosphere, biosphere and geosphere 252 million years ago, and how the planet responded in its aftermath (Hurum et al. 2018; Zuchuat et al. 2020). Deep-time geological records also inform us about the evolution of life, linking the geosphere and biosphere. Svalbard's rock record includes globally significant fossil finds that determined our understanding of life evolution, including Ordovician fish fossils (Bockelie and Fortey 1976), one of the oldest reconstructed fossil fish brains (Stensiö 1927), one of the world's oldest forests in the Devonian (Berry and Marshall 2015), the world's oldest ichthyosaur from the Early Triassic (Kear et al. 2023), marine reptiles from the Jurassic to Cretaceous transition (Delsett et al. 2016), Cretaceous dinosaur footprints at northern latitudes (Lapparent 1962), the migration of pantodonts from North America to Europe in the Palaeocene (Lüthje et al. 2010) and the lush vegetation, including deciduous forests, growing throughout the polar night (Clifton 2012).

Considering the Earth System in three dimensions is important in understanding how processes at depth manifest at the surface. The 3D architecture of faults, for instance, controls fluid migration (e.g., natural gas, groundwater), methane seeps (SIOS Core Data 1.17; Rodes et al. 2023; Hodson et al. 2025) and springs of natural waters.

Multidisciplinary data integration (as discussed in section 2.2) facilitates building multi-scale 3D models of the Earth. Adding the deep-time (section 2.3) and deep-Earth (section 2.4) dimensions expands this to 4D and allows the appreciation of how processes from depth to the surface influence each other through time.

The cryosphere has direct interaction with all other spheres. Onshore, permafrost caps natural gas and prevents it (for the time being) from being released to the atmosphere (Birchall et al. 2023). In the same geological conditions in Svalbard's fjords, the same natural gas is vented to the shallow ocean (Rodes et al. 2023). Gas hydrates may be locally present both onshore (Betlem et al. 2019) and in Svalbard's fjords (Betlem et al. 2021), potentially hosting larger volumes of greenhouse gases that could get destabilised as climate change continues (Hanssen-Bauer et al. 2019). The permafrost thickness is in general poorly constrained, but is fundamentally controlled by topography, meteorology, geothermal heat flux and the presence and style of glaciers.

In summary, geoscientists study (1) the interactions between the geosphere and geofluids, and (2) how the geosphere interacts with the entire Earth System (Figure 5). The research is undertaken at two very different scales: 1) "Anthropocene"; i.e., how these interactions have and will influence human development, and 2) deep-time; i.e., how these interactions are recorded in the geological past.

The aim of this contribution is to outline the broad field of geosciences. In the future, we would like to see targeted interdisciplinary projects that address the interactions between the geosphere and other spheres. We foresee that geospatial data analytics may be an excellent foundation to discover relationships between various elements (e.g., bedrock geology, topography, atmospheric parameters, glacier properties, vegetation, uplift).

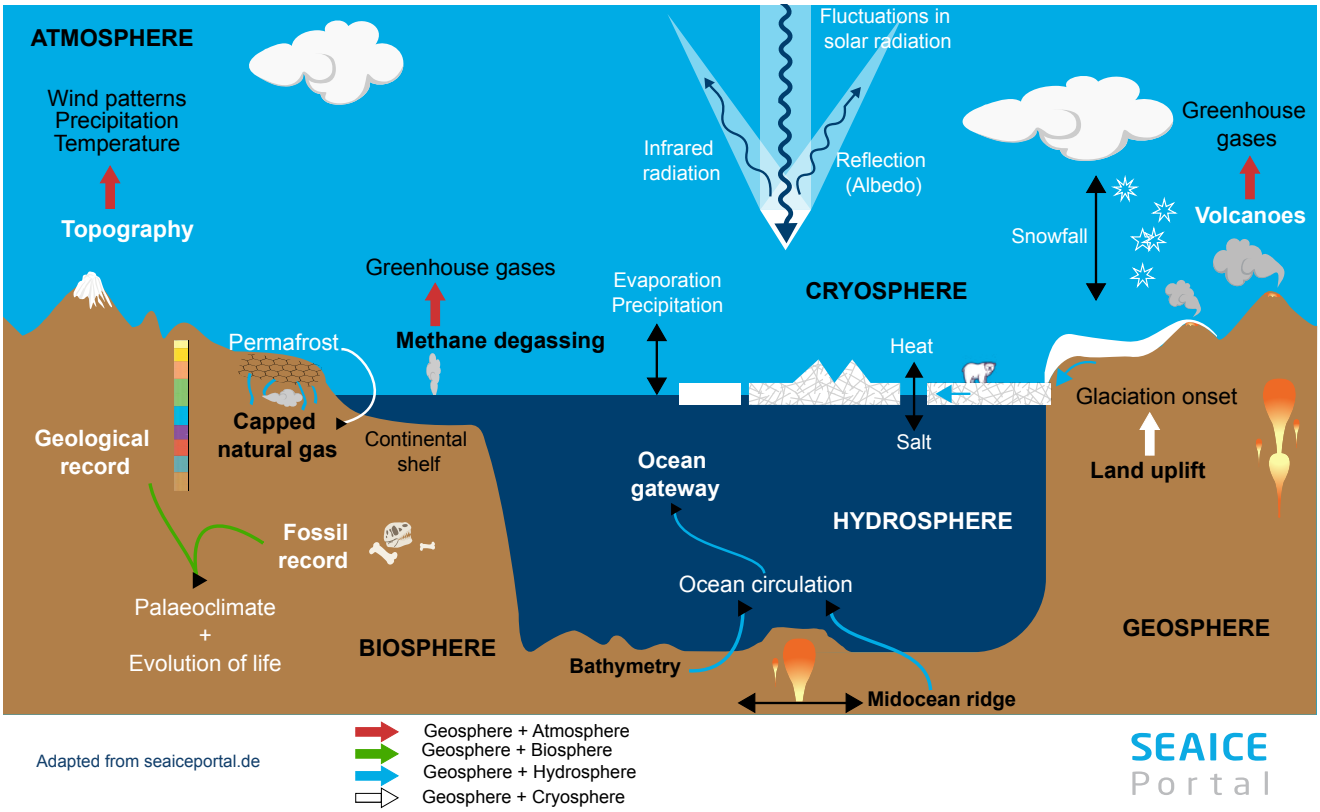

Figure 5: Interaction of the geosphere with the atmosphere, biosphere, hydrosphere and cryosphere. Colours of the arrows indicate main sphere interaction described by the processes. Figure adapted from the SEAICE Portal, Alfred Wegener Institute (2024).

4. Unanswered questions

We consider overarching themes that multi-disciplinary geoscientific teams should prioritise within the next decade (i.e., towards the next International Polar Year, IPY, in 2032/33):

1. Data integration and joint interpretation (section 2.2)
   a. How can heterogeneous, multi-scale, multi-physical, multi-temporal, multi-disciplinary geoscientific data sets be consolidated and harmonised to facilitate joint interpretation by geoscientists?
   b. What data formats, software, and workflows are desired to facilitate the enhanced usage of data analytics (including machine learning/AI) in geosciences?
   c. What is the spatial coverage of key geological data sets and where should the community focus when planning new acquisition campaigns?
   d. How can this heterogeneous data be made freely available to the scientific community and the general public?
   e. How can the scientific findings be efficiently translated and shared with local communities and decision makers?

2. Deep-time palaeoclimate, palaeoenvironment and tectonic evolution (section 2.3)
   a. When did the Fram Strait open as a deep-water oceanic gateway? How did this influence the global oceanic circulation patterns?
   b. How does the stratigraphy of the Cenozoic sediments reflect the climatic and tectonic influences? How can processes related to tectonic–climatic coupling be better understood?
   c. How systematic or heterogeneous is the Earth's System and the response of sedimentary basins to hyperthermal events?
   d. Which parts of Svalbard's stratigraphy are well dated (radiometrically and otherwise), what are the uncertainties of the age models, and where are the key data gaps warranting further research?
   e. How can Svalbard's rock record improve global marine and terrestrial biodiversity curves, especially for high-resolution intervals?

3. Deep-Earth and coupling of deep and shallow processes (section 2.4)
   a. How and why does present-day uplift vary laterally? What are the underlying processes controlling it and how does the crustal structure influence their surface expression? What models, in addition to ice mass loss, can be used to explain the geodetic trends from GNSS stations?
   b. How did the landscape evolve in the past, including spatially varying exhumation rates, and links to tectono-climatic processes (link 2b)?
   c. Why do large earthquakes occur in Svalbard, particularly in Storfjorden, and can the seismicity pattern be predicted/understood?
   d. Why does the present-day (and past) heat flow vary laterally across Svalbard and where are the geothermal hot spots?
   e. What is the extent and thickness of onshore and near-shore permafrost?

5. Recommendations for the future

We have provided 28 concrete recommendations within 5 main categories in Appendix 1. In summary, we recommend that SIOS:

- Promotes the geosphere as a central and important element within the SIOS community by actively seeking geosphere-themed sessions at key conferences, SIOS-led infrastructure calls, future SESS report chapters and outreach activity.
- Utilises SIOS' data management expertise to support the geoscientific community in Svalbard

to make the heterogeneous geoscientific data FAIRly available. This can be achieved through providing transformation tools, recommendations on data repositories, soliciting geosphere-focussed data papers and considering how more static regional geoscientific data can complement the more traditional time-series focussed SIOS core data.
- Takes an active role in adequate documentation, long-term storage and active re-use of physical material (i.e., rock samples, drill cores) by re-vitalising the Svalbard Rock Vault concept and enhancing the possibility of registering physical location of samples through the RiS Portal.
- Strives to transform "data" (geosphere-related and otherwise) into "products", with societal or scientific relevance by conducting questionnaires with key stakeholders on what geoscientific data are crucial, regularly providing geospatial data packages and organising geosphere-focussed hackathons.
- Serves as a platform connecting the geosphere community with other scientific communities through co-ordinating boat-based multidisciplinary expeditions and supports the development of large-scale geoscience projects leading up to the International Polar Year in 2032/33.

6. Data availability

Geoscientists work with heterogeneous data sets spanning across both depth and temporal scales. Not all data sets are curated, and none are presently available in the SIOS data portal. However, many data sets are important to put SIOS data (SIOS Core Data and other data) into a regional context. To facilitate this, and set the scene for including more geoscientific data in SIOS in the future, we have categorised all geoscientific data in five main categories (Table AT6 in Senger et al. 2024a). Furthermore, we provide a list of well-documented data sets with corresponding data papers (Table 1) and useful online geoscientific resources and online data portals (Appendix 2). Finally, we list both generic and thematic data repositories suitable for the various data sets (Appendix 3).

Not all heterogeneous geoscientific data (Table AT6 in Senger et al. 2024a) facilitate FAIR data management, partly due to lack of recognised data standards and "digitisation" of essentially non-digitisable data (e.g., unstructured data in thousands of publications on Svalbard geology). However, as the data revolution also reaches the geosciences, offering new opportunities with data analytics/AI, the Svalbard geoscientific community should embrace this challenge and make data as much as possible FAIRly available.

Table 1: Well-documented geological data sets with their corresponding data paper. Geoscientists use a lot more data sets, many of which are not properly curated as required by SIOS. These are summarised in Table AT6 in Senger et al. (2024a).

Dataset	Parameter	Period	Location	Metadata access (URL)	Dataset provider
Longyearbyen CO_2 lab data package	Various	2006–2024	Adventdalen	Senger et al. (2024b)	Kim Senger (ORCID 0000-0001-5379-465)
Digital outcrop model	DOM/DTM	2020	Konusdalen	Betlem et al. (2024)	Peter Betlem (ORCID 0000-0002-6017-9415)
Fossils from Arctic collection	Physical samples		Arctic	Nakrem et al. (2023)	Hans Arne Nakrem (ORCID 0000-0002-8024-9281

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8. References

Abdullah WH, Murchison D, Jones JM et al (1988) Lower Carboniferous coal deposition environments on Spitsbergen, Svalbard. Org Geochem 13:953–964. https://doi.org/10.1016/0146-6380(88)90277-X

Ahlborn M, Stemmerik L (2015) Depositional evolution of the Upper Carboniferous – Lower Permian Wordiekammen carbonate platform, Nordfjorden High, central Spitsbergen, Arctic Norway. Nor J Geol 95:91–126. https://doi.org/10.17850/njg95-1-03

Anell I, Lecomte I, Braathen A, Buckley SJ (2016) Synthetic seismic illumination of small-scale growth faults, paralic deposits and low-angle clinoforms: A case study of the Triassic successions on Edgeøya, NW Barents Shelf. Mar Pet Geol 77:625–639. https://doi.org/10.1016/j.marpetgeo.2016.07.005

Anfinson OA, Odlum ML, Piepjohn K et al (2022) Provenance Analysis of the Andrée Land Basin and Implications for the Paleogeography of Svalbard in the Devonian. Tectonics 41:e2021TC007103. https://doi.org/10.1029/2021TC007103

Argus DF, Gordon RG, DeMets C (2011) Geologically current motion of 56 plates relative to the no-net-rotation reference frame. Geochem Geophys Geosystems 12:. https://doi.org/10.1029/2011GC003751

Århus N (1991) Dinoflagellate cyst stratigraphy of some Aptian and Albian sections from North Greenland, southeastern Spitsbergen and the Barents Sea. Cretac Res 12:209–225. https://doi.org/10.1016/0195-6671(91)90035-B

Armijo R, Lacassin R, Coudurier-Curveur A, Carrizo D (2015) Coupled tectonic evolution of Andean orogeny and global climate. Earth-Sci Rev 143:1–35. https://doi.org/10.1016/j.earscirev.2015.01.005

Bælum K, Johansen TA, Johnsen H et al (2012) Subsurface structures of the Longyearbyen CO 2 Lab study area in Central Spitsbergen (Arctic Norway), as mapped by reflection seismic data. Nor J Geol 92:377–389

Bahr A, Kaboth-Bahr S, Karas C (2023) The opening and closure of oceanic seaways during the Cenozoic: pacemaker of global climate change? Geol Soc Lond Spec Publ 523:141–171. https://doi.org/10.1144/SP523-2021-54

Barnes CJ, Schneider DA (2019) Late Cretaceous–Paleogene burial and exhumation history of the Southwestern Basement Province, Svalbard, revealed by zircon (U-Th)/He thermochronology. In: Piepjohn K, Strauss JV, Reinhardt L, McClelland WC (eds) Circum-Arctic Structural Events: Tectonic Evolution of the Arctic Margins and Trans-Arctic Links with Adjacent Orogens. Geological Society of America

Beka TI, Bergh SG, Smirnov M, Birkelund Y (2017) Magnetotelluric signatures of the complex tertiary fold–thrust belt and extensional fault architecture beneath Brøggerhalvøya, Svalbard. Polar Res 36:. https://doi.org/10.1080/17518369.2017.1409586

Berggren WA (1982) Role of ocean gateways in climatic change. In: Climate in Earth History: Studies in Geophysics. National Academy Press, Washington D.C., pp 118–125

Bergh SG, Braathen A, Andresen A (1997) Interaction of Basement-Involved and Thin-Skinned Tectonism in the Tertiary Fold-Thrust Belt of Central Spitsbergen, Svalbard. AAPG Bull 81:637–661. https://doi.org/10.1306/522B43F7-1727-11D7-8645000102C1865D

Berndt C, Planke S, Alvarez Zarikian CA et al (2023) Shallow-water hydrothermal venting linked to the Palaeocene–Eocene Thermal Maximum. Nat Geosci 16:803–809. https://doi.org/10.1038/s41561-023-01246-8

Berry CM, Marshall JEA (2015) Lycopsid forests in the early Late Devonian paleoequatorial zone of Svalbard. Geology 43:1043–1046. https://doi.org/10.1130/G37000.1

Betlem P, Birchall T, Lord G et al (2024) High-resolution digital outcrop model of the faults, fractures, and stratigraphy of the Agardhfjellet Formation cap rock shales at Konusdalen West, central Spitsbergen. Earth Syst Sci Data 16:985–1006. https://doi.org/10.5194/essd-16-985-2024

Betlem P, Rodés N, Birchall T et al (2023) Svalbox Digital Model Database: A geoscientific window into the High Arctic. Geosphere 19:1640–1666. https://doi.org/10.1130/GES02606.1

Betlem P, Roy S, Birchall T et al (2021) Modelling of the

gas hydrate potential in Svalbard's fjords. J Nat Gas Sci Eng 94:104127. https://doi.org/10.1016/j.jngse.2021.104127

Betlem P, Senger K, Hodson A (2019) 3D thermobaric modelling of the gas hydrate stability zone onshore central Spitsbergen, Arctic Norway. Mar Pet Geol 100:246–262. https://doi.org/10.1016/j.marpetgeo.2018.10.050

Birchall, T. (2023). Permafrost trapped natural gas in Svalbard, Norway. Video. https://www.youtube.com/watch?v=lGIvGb-3vCU

Birchall T, Jochmann M, Betlem P et al (2023) Permafrost trapped natural gas in Svalbard, Norway. Front Earth Sci 11:1277027. https://doi.org/10.3389/feart.2023.1277027

Birkenmajer K (1980) Polish geological investigations of the Svalbard Archipelago 1934—1979 (an outline). Pol Polar Res 1:217–220

Bjærke T, Thusu B (1976) Cretaceous palynomorphs from Spitsbergenbanken, NW Barents Shelf. Nor Polarinst Årb 258–262

Blinova M, Faleide JI, Gabrielsen RH, Mjelde R (2013) Analysis of structural trends of sub-sea-floor strata in the Isfjorden area of the West Spitsbergen Fold-and-Thrust Belt based on multichannel seismic data. J Geol Soc 170:657–668. https://doi.org/10.1144/jgs2012-109

Bockelie T, Fortey RA (1976) An early Ordovician vertebrate. Nature 260:36–38. https://doi.org/10.1038/260036a0

Braathen A, Bælum K, Christiansen HH et al (2012) The Longyearbyen CO2 Lab of Svalbard, Norway—initial assessment of the geological conditions for CO2 sequestration. Nor J Geol 353–376

Brekke T, Krajewski KP, Hubred JH (2014) Organic geochemistry and petrography of thermally altered sections of the Middle Triassic Botneheia Formation on south-western Edgeøya, Svalbard. Nor Pet Dir Bull 111–128

Bryan SE, Ernst RE (2008) Revised definition of Large Igneous Provinces (LIPs). Earth-Sci Rev 86:175–202. https://doi.org/10.1016/j.earscirev.2007.08.008

Buckley SJ, Howell JA, Enge HD, Kurz TH (2008) Terrestrial laser scanning in geology: data acquisition, processing and accuracy considerations. J Geol Soc 165:625–638. https://doi.org/10.1144/0016-76492007-100

Burgess SD, Bowring SA (2015) High-precision geochronology confirms voluminous magmatism before, during, and after Earth's most severe extinction. Sci Adv 1:e1500470. https://doi.org/10.1126/sciadv.1500470

Cartwright J, Huuse M (2005) 3D seismic technology: the geological 'Hubble.' Basin Res 17:1–20. https://doi.org/10.1111/j.1365-2117.2005.00252.x

Ciais P, Sabine C, Bala G et al (2014) Carbon and Other Biogeochemical Cycles. In: Edenhofer O, Pichs-Madruga R, Sokona Y et al. (eds) Climate Change 2013. Cambridge University Press, United Kingdom, pp 465–570

Clift PD (2017) Cenozoic sedimentary records of climate-tectonic coupling in the Western Himalaya. Prog Earth Planet Sci 4:39. https://doi.org/10.1186/s40645-017-0151-8

Clifton AJ (2012) The Eocene flora of Svalbard and its climatic significance. PhD Thesis, The University of Leeds

Corfu F, Polteau S, Planke S et al (2013) U–Pb geochronology of Cretaceous magmatism on Svalbard and Franz Josef Land, Barents Sea Large Igneous Province. Geol Mag 150:1127–1135. https://doi.org/10.1017/S0016756813000162

Crane K, Sundvor E, Buck R, Martinez F (1991) Rifting in the northern Norwegian-Greenland Sea: Thermal tests of asymmetric spreading. J Geophys Res Solid Earth 96:14529–14550. https://doi.org/10.1029/91JB01231

Cutbill JL, Challinor A (1965) Revision of the Stratigraphical Scheme for the Carboniferous and Permian Rocks of Spitsbergen and Bjørnøya. Geol Mag 102:418–439. https://doi.org/10.1017/S0016756800053693

Dallmann WK (1992) Multiphase tectonic evolution of the Sørkapp-Hornsund mobile zone (Devonian, Carboniferous, Tertiary), Svalbard. Nor Geol Tidsskr 72:49–66

Dallmann WK (1999) Lithostratigraphic Lexicon of Svalbard: Upper Palaeozoic to Quaternary bedrock. Norsk Polarinstitutt, Tromsø

Dallmann WK (2015) Geoscience Atlas of Svalbard. Norsk Polarinstitutt

Delsett LL, Novis LK, Roberts AJ et al (2016) The Slottsmøya marine reptile Lagerstätte: depositional environments, taphonomy and diagenesis. Geol Soc Lond Spec Publ 434:165–188. https://doi.org/10.1144/SP434.2

Dimakis P, Braathen BI, Faleide JI et al (1998) Cenozoic erosion and the preglacial uplift of the Svalbard–Barents Sea region. Tectonophysics 300:311–327. https://doi.org/10.1016/S0040-1951(98)00245-5

Dörr N, Lisker F, Clift PD et al (2012) Late Mesozoic–Cenozoic exhumation history of northern Svalbard and its regional significance: Constraints from apatite fission track analysis. Tectonophysics 514–517:81–92. https://doi.org/10.1016/j.tecto.2011.10.007

Dumais M-A, Gernigon L, Olesen O et al (2022) Crustal and Thermal Heterogeneities Across the Fram Strait and the Svalbard Margin. Tectonics 41:e2022TC007302. https://doi.org/10.1029/2022TC007302

Dumke I, Burwicz EB, Berndt C et al (2016) Gas hydrate distribution and hydrocarbon maturation north of the Knipovich Ridge, western Svalbard margin. J Geophys Res Solid Earth 121:1405–1424. https://doi.org/10.1002/2015JB012083

Dypvik H, Riber L, Burca F et al (2011) The Paleocene–Eocene thermal maximum (PETM) in Svalbard — clay mineral and geochemical signals. Palaeogeogr Palaeoclimatol Palaeoecol 302:156–169. https://doi.org/10.1016/j.palaeo.2010.12.025

Dziewonski AM, Chou T-A, Woodhouse JH (1981) Determination of earthquake source parameters from waveform data for studies of global and regional seismicity. J Geophys Res Solid Earth 86:2825–2852. https://doi.org/10.1029/JB086iB04p02825

Eiken O (1985) Seismic mapping of the post-Caledonian Svalbard. Polar Res 3:167–176. https://doi.org/10.3402/polar.v3i2.6950

Eiken O (1994) Seismic Atlas of Western Svalbard: A Selection of Regional Seismic Transects. Norsk Polarinstitutt, Oslo

Ekström G, Nettles M, Dziewoński AM (2012) The global CMT project 2004–2010: Centroid-moment tensors for 13,017 earthquakes. Phys Earth Planet Inter 200–201:1–9. https://doi.org/10.1016/j.pepi.2012.04.002

Elvevold S (2015) Georesources. In: Dallmann WK (ed) Geoscience Atlas of Svalbard. Norsk Polarinstitutt, pp 249–257

Engen Ø, Faleide JI, Dyreng TK (2008) Opening of the Fram Strait gateway: A review of plate tectonic constraints. Tectonophysics 450:51–69. https://doi.org/10.1016/j.tecto.2008.01.002

Ernst RE, Bond DPG, Zhang S-H et al (2021) Large Igneous Province Record Through Time and Implications for Secular Environmental Changes and Geological Time-Scale Boundaries. In: Ernst RE, Dickson AJ, Bekker A (eds) Large Igneous Provinces: A Driver of Global Environmental and Biotic Changes. American Geophysical Union, pp 1–26

Ernst RE, Youbi N (2017) How Large Igneous Provinces affect global climate, sometimes cause mass extinctions, and represent natural markers in the geological record. Palaeogeogr Palaeoclimatol Palaeoecol 478:30–52. https://doi.org/10.1016/j.palaeo.2017.03.014

Falkowski P, Scholes RJ, Boyle E et al (2000) The Global Carbon Cycle: A Test of Our Knowledge of Earth as a System. Science 290:291–296. https://doi.org/10.1126/science.290.5490.291

Feyling-Hanssen RW, Ulleberg K (1984) A Tertiary-Quaternary section at Sarsbukta, Spitsbergen, Svalbard, and its foraminifera. Polar Res 2:77–106. https://doi.org/10.1111/j.1751-8369.1984.tb00487.x

Foster WJ, Asatryan G, Rauzi S et al (2023) Response of Siliceous Marine Organisms to the Permian-Triassic Climate Crisis Based on New Findings From Central Spitsbergen, Svalbard. Paleoceanogr Paleoclimatology 38:e2023PA004766. https://doi.org/10.1029/2023PA004766

Gac S, Minakov A, Shephard GE et al (2020) Deformation Analysis in the Barents Sea in Relation to Paleogene Transpression Along the Greenland-Eurasia Plate Boundary. Tectonics 39:e2020TC006172. https://doi.org/10.1029/2020TC006172

Geissler WH, Pulm PV, Jokat W, Gebhardt AC (2014) Indications for the Occurrence of Gas Hydrates in the Fram Strait from Heat Flow and Multichannel Seismic Reflection Data. J Geol Res 2014:582424. https://doi.org/10.1155/2014/582424

Geological Survey of Ireland (2024) The Earth Structure. https://www.gsi.ie/en-ie/education/our-planet-earth/Pages/The-Earth-structure.aspx. Accessed 6 Sep 2024

Golovneva LB, Zolina AA, Spicer RA (2023) The early Paleocene (Danian) climate of Svalbard based on palaeobotanical data. Pap Palaeontol 9:e1533. https://doi.org/10.1002/spp2.1533

Goncharov AG, Nikitina LP, Borovkov NV et al (2015) Thermal and redox equilibrium conditions of the upper-mantle xenoliths from the Quaternary volcanoes of NW Spitsbergen, Svalbard Archipelago. Russ Geol Geophys 56:1578–1602. https://doi.org/10.1016/j.rgg.2015.10.006

Grad M, Majorowicz J (2020) Geophysical properties of the crust and upper mantle of the ocean-continent transition in Svalbard area. Pol Polar Res 41:1–22. https://doi.org/10.24425/ppr.2020.132567

Green T, Renne PR, Keller CB (2022) Continental flood basalts drive Phanerozoic extinctions. Proc Natl Acad Sci 119:e2120441119. https://doi.org/10.1073/pnas.2120441119

Griffin WL, Nikolic N, O'Reilly SY, Pearson NJ (2012) Coupling, decoupling and metasomatism: Evolution of crust–mantle relationships beneath NW Spitsbergen. Lithos 149:115–135. https://doi.org/10.1016/j.lithos.2012.03.003

Grundvåg S-A, Jelby ME, Śliwińska KK et al (2019) Sedimentology and palynology of the Lower Cretaceous succession of central Spitsbergen: integration of subsurface and outcrop data. Nor J Geol 99:. https://doi.org/10.17850/njg006

Gutjahr M, Ridgwell A, Sexton PF et al (2017) Very large release of mostly volcanic carbon during the Palaeocene–Eocene Thermal Maximum. Nature 548:573–577. https://doi.org/10.1038/nature23646

Haaland LC, Slagstad T, Osmundsen PT, Redfield T (2024) U-Pb calcite ages date oblique rifting of the Arctic–North Atlantic gateway. Geology 52:615–619. https://doi.org/10.1130/G52140.1

Halverson GP, Kunzmann M, Strauss JV, Maloof AC (2018) The Tonian-Cryogenian transition in Northeastern Svalbard. Precambrian Res 319:79–95. https://doi.org/10.1016/j.precamres.2017.12.010

Halverson GP, Maloof AC, Hoffman PF (2004) The Marinoan glaciation (Neoproterozoic) in northeast Svalbard. Basin Res 16:297–324. https://doi.org/10.1111/j.1365-2117.2004.00234.x

Hann R, Altstädter B, Betlem P, Deja K, Dragańska-Deja K, Ewertowski M, et al. (2021) Scientific Applications of Unmanned Vehicles in Svalbard. In: Moreno-Ibáñez et al (eds) SESS report 2020, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 78-103. https://doi.org/10.5281/zenodo.4293283

Hanssen-Bauer I, Førland EJ, Hisdal H et al (2019) Climate in Svalbard 2100 – A knowledge base for climate adaptation. The Norwegian Centre for Climate Services

Harland WB (1997) The Geology of Svalbard. Geological Society, London, Memoirs

Helland-Hansen W, Grundvåg S-A (2021) The Svalbard Eocene-Oligocene (?) Central Basin succession:

Sedimentation patterns and controls. Basin Res 33:729–753. https://doi.org/10.1111/bre.12492

Helland-Hansen W, Helle HB, Sunde K (1994) Seismic modeling of Tertiary sandstone clinothems, Spitsbergen. Basin Res 6:181–191. https://doi.org/10.1111/j.1365-2117.1994.tb00084.x

Henriksen E, Bjørnseth HM, Hals TK et al (2011a) Chapter 17 Uplift and erosion of the greater Barents Sea: impact on prospectivity and petroleum systems. Geol Soc Lond Mem 35:271–281. https://doi.org/10.1144/M35.17

Henriksen E, Ryseth AE, Larssen GB et al (2011b) Chapter 10 Tectonostratigraphy of the greater Barents Sea: implications for petroleum systems. Geol Soc Lond Mem 35:163–195. https://doi.org/10.1144/M35.10

Heyn BH, Shephard GE, Conrad CP (2024) Prolonged Multi-Phase Magmatism Due To Plume-Lithosphere Interaction as Applied to the High Arctic Large Igneous Province. Geochem Geophys Geosystems 25:e2023GC011380. https://doi.org/10.1029/2023GC011380

Hodson A, Kleber G, Platt S, Kalenitchenko D, Hensgens G, Fynn TI, Senger K, Tveit A, Øvreås L, ten Hietbrink S, Hollander J, Ammerlaan F, Damm E, Römer M, Fransson A, Chierici M, Delpech L-M, Pirk N, Sen A, Redeker K (2025) Methane in Svalbard. In: Runge et al (eds) SESS report 2024, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 106–137. https://doi.org/10.5281/zenodo.14425572

Hodson AJ, Nowak A, Hornum MT et al (2020) Sub-permafrost methane seepage from open-system pingos in Svalbard. The Cryosphere 14:3829–3842. https://doi.org/10.5194/tc-14-3829-2020

Hoffman PF, Halverson GP, Domack EW et al (2012) Cryogenian glaciations on the southern tropical paleomargin of Laurentia (NE Svalbard and East Greenland), and a primary origin for the upper Russøya (Islay) carbon isotope excursion. Precambrian Res 206–207:137–158. https://doi.org/10.1016/j.precamres.2012.02.018

Hopper JR, Funck T, Stoker MS et al (2022) Tectonostratigraphic Atlas of the North-East Atlantic Region. https://doi.org/10.22008/FK2/ZZQRQ1

Hornum MT, Hodson AJ, Jessen S et al (2020) Numerical modelling of permafrost spring discharge and open-system pingo formation induced by basal permafrost aggradation. The Cryosphere 14:4627–4651. https://doi.org/10.5194/tc-14-4627-2020

Horota RK, Senger K, Rodes N et al (2023) West Spitsbergen fold and thrust belt: A digital educational data package for teaching structural geology. J Struct Geol 167:104781. https://doi.org/10.1016/j.jsg.2022.104781

Horota RK, Senger K, Smyrak-Sikora A et al (2024) VRSvalbard – a Photosphere-Based Atlas of a High Arctic Geo-Landscape. First Break 42:35–42. https://doi.org/10.3997/1365-2397.fb2024029

Hossain A, Knorr G, Jokat W, Lohmann G (2021) Opening of the Fram Strait led to the establishment of a modern-like three-layer stratification in the Arctic Ocean during the Miocene. arktos 7:1–12. https://doi.org/10.1007/s41063-020-00079-8

Hounslow MW, Hu M, MØrk A et al (2007) Magneto-biostratigraphy of the Middle to Upper Triassic transition, central Spitsbergen, arctic Norway. J Geol Soc 164:581–597. https://doi.org/10.1144/0016-76492005-184

Hurum JH, Engelschiøn VS, Økland IH et al (2018) The history of exploration and stratigraphy of the Early to Middle Triassic vertebrate-bearing strata of Svalbard (Sassendalen Group, Spitsbergen). Nor J Geol 98:165–174. https://doi.org/10.17850/njg98-2-04

Hutchinson DK, Coxall HK, Lunt DJ et al (2021) The Eocene–Oligocene transition: a review of marine and terrestrial proxy data, models and model–data comparisons. Clim Past 17:269–315. https://doi.org/10.5194/cp-17-269-2021

Inglis GN, Bragg F, Burls NJ et al (2020) Global mean surface temperature and climate sensitivity of the early Eocene Climatic Optimum (EECO), Paleocene–Eocene Thermal Maximum (PETM), and latest Paleocene. Clim Past 16:1953–1968. https://doi.org/10.5194/cp-16-1953-2020

Ionov DA, Bodinier J-L, Mukasa SB, Zanetti A (2002a) Mechanisms and Sources of Mantle Metasomatism: Major and Trace Element Compositions of Peridotite Xenoliths from Spitsbergen in the Context of Numerical Modelling. J Petrol 43:2219–2259. https://doi.org/10.1093/petrology/43.12.2219

Ionov DA, Mukasa SB, Bodinier J-L (2002b) Sr–Nd–Pb Isotopic Compositions of Peridotite Xenoliths from Spitsbergen: Numerical Modelling Indicates Sr–Nd Decoupling in the Mantle by Melt Percolation Metasomatism. J Petrol 43:2261–2278. https://doi.org/10.1093/petrology/43.12.2261

IPCC (2021) Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. [Masson-Delmotte V, Zhai P, Pirani A et al. (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 2391 pp. https://doi.org/10.1017/9781009157896

Isacks B, Oliver J, Sykes LR (1968) Seismology and the new global tectonics. J Geophys Res 73:5855–5899. https://doi.org/10.1029/JB073i018p05855

Jakobsson M, Backman J, Rudels B et al (2007) The early Miocene onset of a ventilated circulation regime in the Arctic Ocean. Nature 447:986–990. https://doi.org/10.1038/nature05924

Jamtveit B, Hammer Ø, Andersson C et al (2006) Travertines from the Troll thermal springs, Svalbard. Nor J Geol 86:387–395

Janocha J, Wesenlund F, Thießen O et al (2024) Depositional environments and source rock potential of some Upper Palaeozoic (Devonian) coals on Bjørnøya, Western Barents shelf. Mar Pet Geol 163:106768. https://doi.org/10.1016/j.marpetgeo.2024.106768

Jochmann MM, Augland LE, Lenz O et al (2020) Sylfjellet: a new outcrop of the Paleogene Van Mijenfjorden Group in Svalbard. arktos 6:17–38. https://doi.org/10.1007/s41063-019-00072-w

Johansen S, Arntsen B, Raknes EB et al (2023) Seismic forward modelling of the Kvalhovden outcrop, Spitsbergen, Norway. Mar Pet Geol 147:106000. https://doi.org/10.1016/j.marpetgeo.2022.106000

Johansen S, Granberg E, Mellere D et al (2007) Decoupling of seismic reflectors and stratigraphic timelines: A modeling study of Tertiary strata from Svalbard. GEOPHYSICS 72:SM273–SM280. https://doi.org/10.1190/1.2759479

Johansen S, Kibsgaard S, Andresen A et al (1994) Seismic Modeling of a Strongly Emergent Thrust Front, West Spitsbergen Fold Belt, Svalbard. AAPG Bull 78:1018–1027. https://doi.org/10.1306/A25FE419-171B-11D7-8645000102C1865D

Jokat W, Lehmann P, Damaske D, Bradley Nelson J (2016) Magnetic signature of North-East Greenland, the Morris Jesup Rise, the Yermak Plateau, the central Fram Strait: Constraints for the rift/drift history between Greenland and Svalbard since the Eocene. Tectonophysics 691:98–109. https://doi.org/10.1016/j.tecto.2015.12.002

Jones MK (2008) Swedish Scientific Expeditions to Spitsbergen, 1758-1908. Tijdschr Voor Skand 29:

Jones MT, Jerram DA, Svensen HH, Grove C (2016) The effects of large igneous provinces on the global carbon and sulphur cycles. Palaeogeogr Palaeoclimatol Palaeoecol 441:4–21. https://doi.org/10.1016/j.palaeo.2015.06.042

Jones MT, Percival LME, Stokke EW et al (2019) Mercury anomalies across the Palaeocene–Eocene Thermal Maximum. Clim Past 15:217–236. https://doi.org/10.5194/cp-15-217-2019

Jull M, McKenzie D (1996) The effect of deglaciation on mantle melting beneath Iceland. J Geophys Res Solid Earth 101:21815–21828. https://doi.org/10.1029/96JB01308

Kear BP, Engelschiøn VS, Hammer Ø et al (2023) Earliest Triassic ichthyosaur fossils push back oceanic reptile origins. Curr Biol 33:R178–R179. https://doi.org/10.1016/j.cub.2022.12.053

Keilhau BM (1829) Über die geognostische Bildung der Insel Spitzbergen. Isis Von Oken 22:312–314

Keilhau BM (1831) Reise i Øst- og Vest-Finmarken samt til Beeren-Eiland og Spitsbergen, i Aarene 1827 og 1829. Johan Krohn, Christiania

Kierulf HP, Kohler J, Boy J-P et al (2022) Time-varying uplift in Svalbard—an effect of glacial changes. Geophys J Int 231:1518–1534. https://doi.org/10.1093/gji/ggac264

Kilpeläinen T, Vihma T, Ólafsson H (2011) Modelling of spatial variability and topographic effects over Arctic fjords in Svalbard. Tellus Dyn Meteorol Oceanogr 63:223–237. https://doi.org/10.1111/j.1600-0870.2010.00481.x

Kleber GE, Hodson AJ, Magerl L et al (2023) Groundwater springs formed during glacial retreat are a large source of methane in the high Arctic. Nat Geosci 16:597–604. https://doi.org/10.1038/s41561-023-01210-6

Klitzke P, Faleide JI, Scheck-Wenderoth M, Sippel J (2015) A lithosphere-scale structural model of the Barents Sea and Kara Sea region. Solid Earth 6:153–172. https://doi.org/10.5194/se-6-153-2015

Klitzke P, Sippel J, Faleide JI, Scheck-Wenderoth M (2016) A 3D gravity and thermal model for the Barents Sea and Kara Sea. Tectonophysics 684:131–147. https://doi.org/10.1016/j.tecto.2016.04.033

Kośmińska K, Spear FS, Majka J et al (2020) Deciphering late Devonian–early Carboniferous P–T–t path of mylonitized garnet-mica schists from Prins Karls Forland, Svalbard. J Metamorph Geol 38:471–493. https://doi.org/10.1111/jmg.12529

Krasil'ščikov AA (ed) (1996) Soviet geological research in Svalbard 1962-1992. Extended abstracts of unpublished reports. Norsk Polarinstitutt, Oslo

Lapparent A-F de (1962) Footprints of dinosaur in the Lower Cretaceous of Vestspitsbergen – Svalbard. Nor Polarinst Årb 1960:14–21

Leever KA, Gabrielsen RH, Faleide JI, Braathen A (2011) A transpressional origin for the West Spitsbergen fold-and-thrust belt: Insight from analog modeling. Tectonics 30:TC2014. https://doi.org/10.1029/2010TC002753

Lüthje CJ, Milàn J, Hurum JH (2010) Paleocene tracks of the mammal Pantodont genus Titanoides in coal-bearing strata, Svalbard, Arctic Norway. J Vertebr Paleontol 30:521–527. https://doi.org/10.1080/02724631003617449

Macdonald FA (2020) Deep-Time Paleoclimate Proxies. AGU Adv 1:e2020AV000244. https://doi.org/10.1029/2020AV000244

Manum S (1960) Some dinoflagellates and hystrichosphaerids from the lower Tertiary of Spitsbergen. Nytt Mag Bot 8:17–26

Marshall C, Large DJ, Meredith W et al (2015) Geochemistry and petrology of Palaeocene coals from Spitsbergen — Part 1: Oil potential and depositional environment. Int J Coal Geol 143:22–33. https://doi.org/10.1016/j.coal.2015.03.006

Medvedev S, Faleide JI, Hartz EH (2023) Cenozoic reshaping of the Barents-Kara Shelf: Influence of erosion, sedimentation, and glaciation. Geomorphology 420:108500. https://doi.org/10.1016/j.geomorph.2022.108500

Medvedev S, Hartz EH, Faleide JI (2018) Erosion-driven vertical motions of the circum Arctic: Comparative analysis of modern topography. J Geodyn 119:62–81. https://doi.org/10.1016/j.jog.2018.04.003

Meier K, O'Sullivan P, Jochmann MM et al (2024) Shallow Thermal Anomalies and Their Role in the Breakup Evolution Along the Conjugate Margins of the Fram Strait (Svalbard and Eastern North Greenland), Indicated by Low-Temperature Thermochronology. Geochem Geophys Geosystems 25:e2023GC011074. https://doi.org/10.1029/2023GC011074

Mémin A, Spada G, Boy J-. P et al (2014) Decadal geodetic variations in Ny-Ålesund (Svalbard): role of past and present ice-mass changes. Geophys J Int 198:285–297. https://doi.org/10.1093/gji/ggu134

Midtkandal I, Svensen HH, Planke S et al (2016) The Aptian (Early Cretaceous) oceanic anoxic event (OAE1a) in Svalbard, Barents Sea, and the absolute age of the Barremian-Aptian boundary. Palaeogeogr Palaeoclimatol Palaeoecol 463:126–135. https://doi.org/10.1016/j.palaeo.2016.09.023

Millikin AEG, Strauss JV, Halverson GP et al (2022) Calibrating the Russøya excursion in Svalbard, Norway, and implications for Neoproterozoic chronology. Geology 50:506–510. https://doi.org/10.1130/G49593.1

Minakov A (2018) Late Cenozoic lithosphere dynamics in Svalbard: Interplay of glaciation, seafloor spreading and mantle convection. J Geodyn 122:1–16. https://doi.org/10.1016/j.jog.2018.09.009

Minakov A, Yarushina V, Faleide JI et al (2018) Dyke emplacement and crustal structure within a continental large igneous province, northern Barents Sea. In: Pease V, Coakley B (eds) Circum-Arctic Lithosphere Evolution. Geological Society of London, pp 371–395

Mitchell BJ, Bungum H, Chan WW, Mitchell PB (1990) Seismicity and present-day tectonics of the Svalbard region. Geophys J Int 102:139–149. https://doi.org/10.1111/j.1365-246X.1990.tb00536.x

Nakrem HA, Lindemann F-J, Hurum JH, Hammer Ø (2023) Fossils From the Arctic in the Collections of the Natural History Museum in Oslo, Norway. Collections 19:420–441. https://doi.org/10.1177/15501906231159039

Nathorst AG (1910) Beiträge zur Geologie der Bären-Insel, Spitzbergen und des König-Karl-Landes. Bull Geol Institutionen Upps Univ 10:261–416

Nemec W (1992) Depositional controls on plant growth and peat accumulation in a braidplain delta environment: Helvetiafjellet Formation (Barremian-Aptian), Svalbard. In: McCabe PJ, Parrish JT (eds) Controls on the Distribution and Quality of Cretaceous Coals. Geological Society of America, pp 209–226

Nield GA, Barletta VR, Bordoni A et al (2014) Rapid bedrock uplift in the Antarctic Peninsula explained by viscoelastic response to recent ice unloading. Earth Planet Sci Lett 397:32–41. https://doi.org/10.1016/j.epsl.2014.04.019

Nordenskiöld AE (1867) Sketch of the geology of Spitsbergen. Norstedt, Stockholm

Nøttvedt A, Livbjerg F, Midbøe PS, Rasmussen E (1993) Hydrocarbon potential of the Central Spitsbergen Basin. Nor Pet Soc Spec Publ 2:333–361

Ogata K, Weert A, Betlem P et al (2023) Shallow and deep subsurface sediment remobilization and intrusion in the Middle Jurassic to Lower Cretaceous Agardhfjellet Formation (Svalbard). Geosphere 19:801–822. https://doi.org/10.1130/GES02555.1

Ohm SE, Larsen L, Olaussen S et al (2019) Discovery of shale gas in organic-rich Jurassic successions, Adventdalen, Central Spitsbergen, Norway. Nor J Geol 99:349–376. https://doi.org/10.17850/njg007

Okay N, Crane K (1993) Thermal rejuvenation of the Yermak Plateau. Mar Geophys Res 15:243–263. https://doi.org/10.1007/BF01982384

Olaussen S, Grundvåg S-A, Senger K et al (2025) Svalbard Composite Tectono-Sedimentary Element, Barents Sea. Geol Soc Lond Mem 57:M57-2021–36. https://doi.org/10.1144/M57-2021-36

Olaussen S, Senger K, Braathen A et al (2019) You learn as long as you drill; research synthesis from the Longyearbyen CO2 Laboratory, Svalbard, Norway. Nor J Geol 99:157–187. https://doi.org/10.17850/njg008

Olichwer T, Tarka R (2018) Thermal and mineral springs of southern Spitsbergen. Pol Polar Res 39:331–348. https://doi.org/10.24425/118750

Pace F, Vergnano A, Godio A et al (2024) A new repository of electrical resistivity tomography and ground-penetrating radar data from summer 2022 near Ny-Ålesund, Svalbard. Earth Syst Sci Data 16:3171–3192. https://doi.org/10.5194/essd-16-3171-2024

Petersen TG, Thomsen TB, Olaussen S, Stemmerik L (2016) Provenance shifts in an evolving Eurekan foreland basin: the Tertiary Central Basin, Spitsbergen. J Geol Soc 173:634–648. https://doi.org/10.1144/jgs2015-076

Pettersson CH, Pease V, Frei D (2009) U–Pb zircon provenance of metasedimentary basement of the Northwestern Terrane, Svalbard: Implications for the Grenvillian–Sveconorwegian orogeny and development of Rodinia. Precambrian Res 175:206–220. https://doi.org/10.1016/j.precamres.2009.09.010

Piepjohn K, von Gosen W, Tessensohn F (2016) The Eurekan deformation in the Arctic: an outline. J Geol Soc 173:1007–1024. https://doi.org/10.1144/jgs2016-081

Piepjohn K, Stange R, Jochmann M, Hübner C (2012) The Geology of Longyearbyen. Longyearbyen Feltbiologiske Forening 36

Pirli M, Schweitzer J, Paulsen B (2013) The Storfjorden, Svalbard, 2008–2012 aftershock sequence: Seismotectonics in a polar environment. Tectonophysics 601:192–205. https://doi.org/10.1016/j.tecto.2013.05.010

Pirli M, Schweitzer J, Paulsen B et al (2021) Two Decades of Seismicity in Storfjorden, Svalbard Archipelago, from Regional Data. Seismol Res Lett 92:2695–2704. https://doi.org/10.1785/0220200469

Polteau S, Hendriks BWH, Planke S et al (2016) The Early Cretaceous Barents Sea Sill Complex: Distribution, 40Ar/39Ar geochronology, and implications for carbon gas formation. Palaeogeogr Palaeoclimatol Palaeoecol 441:83–95. https://doi.org/10.1016/j.palaeo.2015.07.007

Portnov A, Vadakkepuliyambatta S, Mienert J, Hubbard A (2016) Ice-sheet-driven methane storage and release in the Arctic. Nat Commun 7:10314. https://doi.org/10.1038/ncomms10314

Prestvik T (1978) Cenozoic plateau lavas of Spitsbergen-a geochemical study. Nor Polarinst Årb 1977:129–143

Reeve MA, Kolstad EW (2011) The Spitsbergen South Cape tip jet. Q J R Meteorol Soc 137:1739–1748. https://doi.org/10.1002/qj.876

Rizzo RE, Inskip NF, Fazeli H et al (2024) Modelling geological CO2 leakage: Integrating fracture permeability and fault zone outcrop analysis. Int J Greenh Gas Control 133:104105. https://doi.org/10.1016/j.ijggc.2024.104105

Rodes N, Betlem P, Senger K et al (2023) Active gas seepage in western Spitsbergen fjords, Svalbard archipelago: spatial extent and geological controls. Front Earth Sci 11:. https://doi.org/10.3389/feart.2023.1173477

Rudge JF, Shaw Champion ME, White N et al (2008) A plume model of transient diachronous uplift at the Earth's surface. Earth Planet Sci Lett 267:146–160. https://doi.org/10.1016/j.epsl.2007.11.040

Sættem J, Bugge T, Fanavoll S et al (1994) Cenozoic margin development and erosion of the Barents Sea: Core evidence from southwest of Bjørnøya. Mar Geol 118:257–281. https://doi.org/10.1016/0025-3227(94)90087-6

Schneider DA, Faehnrich K, Majka J, Manecki M (2019) 40Ar/39Ar geochronologic evidence of Eurekan deformation within the West Spitsbergen Fold and Thrust Belt. In: Piepjohn K, Strauss JV, Reinhardt L, McClelland WC (eds) Circum-Arctic Structural Events: Tectonic Evolution of the Arctic Margins and Trans-Arctic Links with Adjacent Orogens. Geological Society of America, p 0

Schweitzer J, Paulsen B, Antonovskaya GN et al (2021) A 24-Yr-Long Seismic Bulletin for the European Arctic. Seismol Res Lett 92:2758–2767. https://doi.org/10.1785/0220210018

Scotese CR, Song H, Mills BJW, van der Meer DG (2021) Phanerozoic paleotemperatures: The earth's changing climate during the last 540 million years. Earth-Sci Rev 215:103503. https://doi.org/10.1016/j.earscirev.2021.103503

SEAICE Portal, Alfred Wegener Institute (2024) Overview of the Climate System and Its Subsystems. https://www.meereisportal.de/en/maps-graphics/infographics. Accessed 11 Jun 2024

Selway K, Smirnov MY, Beka T et al (2020) Magnetotelluric Constraints on the Temperature, Composition, Partial Melt Content, and Viscosity of the Upper Mantle Beneath Svalbard. Geochem Geophys Geosystems 21:e2020GC008985. https://doi.org/10.1029/2020GC008985

Senger, K., Ammerlaan, F., & SVALGEOL team. (2024a). Geology of Svalbard: Deep-time and Deep-Earth (Digital Appendix to SESS Report Chapter SVALGEOL). Zenodo. https://doi.org/10.5281/zenodo.14216541

Senger K, Betlem P, Birchall T et al (2021) Using digital outcrops to make the high Arctic more accessible through the Svalbox database. J Geosci Educ 69:123–137. https://doi.org/10.1080/10899995.2020.1813865

Senger K, Betlem P, Braathen A et al (2024b) Longyearbyen CO2 lab project – from a vision of a CO2-neutral Svalbard to a geoscience data eldorado. Arct Sci. https://doi.org/10.1139/as-2024-0019

Senger K, Betlem P, Helland-Hansen A et al (2024c) Multi-disciplinary geoscientific expedition to Woodfjorden, NW Svalbard: Field sites, methods, and preliminary results. Czech Polar Rep 13:142–161. https://doi.org/10.5817/CPR2023-2-12

Senger K, Brugmans P, Grundvåg S-A et al (2019) Petroleum, coal and research drilling onshore Svalbard: a historical perspective. Nor J Geol 99:377–407. https://doi.org/10.17850/njg99-3-1

Senger K, Galland O (2022) Stratigraphic and Spatial Extent of HALIP Magmatism in Central Spitsbergen. Geochem Geophys Geosystems 23:e2021GC010300. https://doi.org/10.1029/2021GC010300

Senger K, Kulhanek D, Jones MT et al (2023a) Deep-time Arctic climate archives: high-resolution coring of Svalbard's sedimentary record – SVALCLIME, a workshop report. Sci Drill 32:113–135. https://doi.org/10.5194/sd-32-113-2023

Senger K, Nuus M, Balling N et al (2023b) The subsurface thermal state of Svalbard and implications for geothermal potential. Geothermics 111:102702. https://doi.org/10.1016/j.geothermics.2023.102702

Senger K, Planke S, Polteau S et al (2014a) Sill emplacement and contact metamorphism in a siliciclastic reservoir on Svalbard, Arctic Norway. Nor J Geol 94:155–169

Senger K, Shephard G, Ammerlaan F et al (2024d) Arctic Tectonics and Volcanism: a multi-scale, multidisciplinary educational approach. Geosci Commun Discuss. https://doi.org/10.5194/gc-2024-3

Senger K, Tveranger J, Ogata K et al (2014b) Late Mesozoic magmatism in Svalbard: A review. Earth-Sci Rev 139:123–144. https://doi.org/10.1016/j.earscirev.2014.09.002

Skeie P, Grønås Sigbjørn (2000) Strongly stratified easterly flows across Spitsbergen. Tellus Dyn Meteorol Oceanogr 52:473–486. https://doi.org/10.3402/tellusa.v52i5.12281

Skjelkvåle B-L, Amundsen HEF, O'Reilly SY et al (1989) A primitive alkali basaltic stratovolcano and associated eruptive centres, Northwestern Spitsbergen: Volcanology and tectonic significance. J Volcanol Geotherm Res 37:1–19. https://doi.org/10.1016/0377-0273(89)90110-8

Śliwińska KK, Coxall HK, Hutchinson DK et al (2023) Sea surface temperature evolution of the North Atlantic Ocean across the Eocene–Oligocene transition. Clim Past 19:123–140. https://doi.org/10.5194/cp-19-123-2023

Śliwińska KK, Jelby ME, Grundvåg S-A et al (2020) Dinocyst stratigraphy of the Valanginian–Aptian Rurikfjellet and Helvetiafjellet formations on Spitsbergen, Arctic Norway. Geol Mag 157:1693–1714. https://doi.org/10.1017/S0016756819001249

Smelror M, Olaussen S, Dumais M-A et al (2024) Northern Svalbard Composite Tectono-Sedimentary Element. Geol Soc Lond Mem 57:M57-2023–2. https://doi.org/10.1144/M57-2023-2

Sorento T, Olaussen S, Stemmerik L (2020) Controls on deposition of shallow marine carbonates and evaporites – lower Permian Gipshuken Formation, central Spitsbergen, Arctic Norway. Sedimentology 67:207–238. https://doi.org/10.1111/sed.12640

Steel RJ, Worsley D (1984) Svalbard's post-Caledonian strata—An atlas of sedimentational patterns and palaeogeographic evolution. In: Spencer AM (ed) Petroleum Geology of the North European Margin. Springer, pp 109–135

Stensiö EA (1927) The Downtonian and Devonian Vertebrates of Spitsbergen: Part 1. Family Cephalaspidae. I kommisjon hos J. Dybwad

Straume EO, Gaina C, Medvedev S, Nisancioglu KH (2020) Global Cenozoic Paleobathymetry with a focus on the Northern Hemisphere Oceanic Gateways. Gondwana Res 86:126–143. https://doi.org/10.1016/j.gr.2020.05.011

Straume EO, Nummelin A, Gaina C, Nisancioglu KH (2022) Climate transition at the Eocene–Oligocene influenced by bathymetric changes to the Atlantic–Arctic oceanic gateways. Proc Natl Acad Sci 119:e2115346119. https://doi.org/10.1073/pnas.2115346119

Svensen H, Corfu F, Polteau S et al (2012) Rapid magma emplacement in the Karoo Large Igneous Province. Earth Planet Sci Lett 325–326:1–9. https://doi.org/10.1016/j.epsl.2012.01.015

Svensen H, Jerram DA, Polozov AG et al (2019) Thinking about LIPs: A brief history of ideas in Large igneous province research. Tectonophysics 760:229–251. https://doi.org/10.1016/j.tecto.2018.12.008

Svensen H, Planke S, Malthe-Sørenssen A et al (2004) Release of methane from a volcanic basin as a mechanism for initial Eocene global warming. Nature 429:542–545. https://doi.org/10.1038/nature02566

Svensen H, Planke S, Polozov AG et al (2009) Siberian gas venting and the end-Permian environmental crisis. Earth Planet Sci Lett 277:490–500. https://doi.org/10.1016/j.epsl.2008.11.015

Torsvik TH, Løvlie R, Sturt BA (1985) Palaeomagnetic argument for a stationary Spitsbergen relative to the British Isles (Western Europe) since late Devonian and its bearing on North Atlantic reconstruction. Earth Planet Sci Lett 75:278–288. https://doi.org/10.1016/0012-821X(85)90109-8

Tozer ET (1973) Lower and Middle Triassic ammonoids and bivalves from Nordaustlandet (Spitsbergen) collected by Dr Oskar Kulling in 1931. Geol Fören Stockh Förh 95:99–104. https://doi.org/10.1080/11035897309455429

Tripati A, Darby D (2018) Evidence for ephemeral middle Eocene to early Oligocene Greenland glacial ice and pan-Arctic sea ice. Nat Commun 9:1038. https://doi.org/10.1038/s41467-018-03180-5

University of California UGC Berkely (2024) Understanding Global Change - Earth Scene. https://ugc.berkeley.edu/teaching-download/earth-scene/. Accessed 6 Jun 2024

von Appen W-J, Schauer U, Somavilla R et al (2015) Exchange of warming deep waters across Fram Strait. Deep Sea Res Part Oceanogr Res Pap 103:86–100. https://doi.org/10.1016/j.dsr.2015.06.003

Weerdesteijn MFM, Conrad CP, Naliboff JB (2022) Solid Earth Uplift Due To Contemporary Ice Melt Above Low-Viscosity Regions of the Upper Mantle. Geophys Res Lett 49:e2022GL099731. https://doi.org/10.1029/2022GL099731

Wegener A (1912) Die Entstehung der Kontinente. Geol Rundsch 3:276–292. https://doi.org/10.1007/BF02202896

Westerhold T, Marwan N, Drury AJ et al (2020) An astronomically dated record of Earth's climate and its predictability over the last 66 million years. Science 369:1383–1387. https://doi.org/10.1126/science.aba6853

Westoby MJ, Brasington J, Glasser NF et al (2012) 'Structure-from-Motion' photogrammetry: A low-cost, effective tool for geoscience applications. Geomorphology 179:300–314. https://doi.org/10.1016/j.geomorph.2012.08.021

Whipple KX (2009) The influence of climate on the tectonic evolution of mountain belts. Nat Geosci 2:97–104. https://doi.org/10.1038/ngeo413

Wilson JT (1966) Did the Atlantic Close and then Re-Open? Nature 211:676–681. https://doi.org/10.1038/211676a0

Zagórski P, Jarosz K, Superson J (2020) Integrated Assessment of Shoreline Change along the Calypsostranda (Svalbard) from Remote Sensing, Field Survey and GIS. Mar Geod 43:433–471. https://doi.org/10.1080/01490419.2020.1715516

Zhang Y, Ogg JG, Minguez D et al (2021) Magnetostratigraphy of U-Pb–dated boreholes in Svalbard, Norway, implies that magnetochron M0r (a proposed Barremian-Aptian boundary marker) begins at 121.2 ± 0.4 Ma. Geology 49:733–737. https://doi.org/10.1130/G48591.1

Zuchuat V, Sleveland ARN, Twitchett RJ et al (2020) A new high-resolution stratigraphic and palaeoenvironmental record spanning the End-Permian Mass Extinction and its aftermath in central Spitsbergen, Svalbard. Palaeogeogr Palaeoclimatol Palaeoecol 554:109732. https://doi.org/10.1016/j.palaeo.2020.109732

9. Appendix 1: Detailed list of recommendations

In the main report we have highlighted five main recommendations for how SIOS can assist the geosphere community, and integrate the geosphere more strongly into SIOS activities. Here we list these again, but with additional concrete goals that pave the way to reaching those. We recommend that SIOS:

1. Promotes the geosphere as a central and important element within the SIOS community through:
   a. Inclusion of geosphere-themed sessions at key conferences (SIOS Polar Night Week, Svalbard Science Conference)
   b. Supporting and promoting geosphere-themed globally relevant international research projects in and around Svalbard, specifically scientific drilling under the auspices of the International Continental Scientific Drilling Programme (ICDP) and the International Ocean Drilling Programme (IODP and its successor IODP-3)
   c. Continuing to consider the geosphere in SIOS-led infrastructure proposals (for instance for a national polar geophysical equipment pool or enhanced spatial coverage of GNSS stations including eastern Svalbard to quantify ongoing uplift)
   d. Soliciting geosphere-themed SESS reports, specifically on the Quaternary, evolution of life in Svalbard's record, seismicity, controlling factors on ongoing uplift and key geoscientific data types (e.g., geochemistry, geodetic data, sedimentary logs)
   e. Including geosphere-themed elements in its outreach activity

2. Utilises its data management expertise to support the geoscientific community in Svalbard to make the heterogeneous geoscientific data FAIRly available through:
   a. Providing transformation tools, workflows and resources for geologists to make geoscientific data compliant with SIOS-endorsed data portals
   b. Providing recommendations on which repositories are suitable for storing and using various geoscientific data, considering aspects including the discipline's global preference, technical suitability and SIOS-interoperability
   c. Considering extending the long time-series SIOS core data with more static regional geological data (e.g., digital outcrop models, photospheres, subsurface data)
   d. Considering providing data services (e.g., visualisation) for FAIR-compliant geological data
   e. Working actively with the Svalbard Science Forum to improve the post-fieldwork registration of metadata from geological campaigns
   f. Optimising the interaction between global thematic geodatabases (Table AT4 in Senger et al. 2024a) and Svalbard portals (Appendix 2)
   g. Soliciting data papers, perhaps through a SIOS-led special issue, on geoscientific topics such as palaeoclimate, sedimentary logs, geophysical (seismic, ERT, GPR etc.) data
   h. Considering how unstructured data from centuries of geoscientific exploration of Svalbard can be made available and interoperable to the community
   i. Influencing policy makers to work towards a user-centred Svalbard-wide geospatial data portal to enhance cross-disciplinary research

3. Takes an active role in adequate documentation, long-term storage and active re-use of physical material (i.e., rock samples, drill cores) by:

   a. Re-vitalising the Svalbard Rock Vault concept with the relevant partners (UNIS, SNSK, NPI, NHM, NGU, Mining Commissioner, international partners) to provide a location for long-term storage and active re-use of physical material
   b. Working actively with the Svalbard Science Forum to enhance the capability of the RiS Portal to register sample metadata and sample physical locations
   c. Providing an overview of the physical storage sites of geological objects from Svalbard, building on the efforts by the Svalbard Rock Vault initiative

4. Strives to transform "data" (geosphere-related and otherwise) into "products", with societal or scientific relevance through:
   a. Conducting a questionnaire with key stakeholders on their knowledge needs and map this to existing competence clusters (e.g., depth to basement in Longyearbyen area, regional land uplift map)
   b. Providing regularly updated geospatial data packages (with QGreenland[2] as a role model) to enhance relevant data usage and maximise cross-disciplinary research time
   c. Organising hackathons linking the geo-scientific and data analytics communities on clearly defined goals (e.g., automatic extraction of data from unstructured data sets like publications, reports etc.)
   d. Considering how data can be best presented to society and the scientific community, with inspiration from climatearchive[3].

5. Serves as a platform connecting the geosphere-community with other scientific communities by:
   a. Considering organising regular (user-funded) boat-based multidisciplinary expeditions to defined areas of Svalbard (reducing the environmental impact by joint logistics)
   b. Enhancing focus on using existing SIOS tools like the aircraft for geosphere application (e.g., update the hyperspectral sensor with wavelengths suitable for bedrock geological mapping)
   c. Being active in the development of large-scale geoscience projects leading up to the International Polar Year 2032–33.

2 https://qgreenland.org/
3 https://climatearchive.org/

Appendix 2: Overview of relevant online resources

Useful geoscientific online resources from Svalbard, including maps and data portals.

Resources	Comment	URL
Online resources (viewing mostly)		
GeoSvalbard	Geological maps (vector and images), selected cross-sections, sample and DOM locations	https://geokart.npolar.no/geologi/GeoSvalbard/
Svalbardkartet	Multi-disciplinary online portal including geology, an outdated claim map, national parks etc.	https://geokart.npolar.no/Html5Viewer/index.html?viewer=Svalbardkartet
TopoSvalbard	Topographic map including aerial imagery, old oblique aerial images	https://toposvalbard.npolar.no/
VRSvalbard	Photosphere-based atlas of Svalbard's geology	http://www.vrsvalbard.com
Svalbox	Digital outcrop models in the context of regional geology	http://portal.svalbox.no
Online resources (for direct streaming to GIS software and data download)		
Norwegian Polar Institute (NPI) geodata	Basemap services from NPI, including topography, satellite imagery and most layers as available on Svalbardkartet	https://geodata.npolar.no/
Svalbox	Digital outcrop models in the context of regional geology	http://portal.svalbox.no
Data portals		
BGR Arctic Repository	Data repository of Germany's Geological Survey (BGR) with an Arctic focus, including outcrop data and geophysical profiles	https://arctic.bgr.de/mapapps4/resources/apps/arktis/index.html?lang=en
AWI seismic profile map	The map will be linked very soon with the Pangaea database to directly access available profiles there. The navigation is not yet available that way.	https://maps.awi.de/awimaps/projects/public/?cu=geophysics_arctic#home
AWI sediment echosounder data	e.g., from cruises on RV Polarstern, RV Maria S. Merian, RV Heincke	Archived on PANGAEA, https://www.pangaea.de/?q=sediment+echo+sounding&maxlat=81.27311926447925&minlon=2.348750948196061&maxlon=33.63781344819606&minlat=76.88785354508799
NGU geodata portal	Data portal of the Norwegian Geological Survey	https://geo.ngu.no/geoscienceportalopen/Results?bookmark=0bf79eb071474cd7a92240d4360b84db
Norwegian Offshore Directorate data portal	Area around Svalbard is not open for petroleum exploration and seismic data are not available for open download	https://www.sodir.no/en/diskos/public-portal/

Appendix 3: Geophysical methods of imaging different parts of the Earth's structure

Summary of the different geological and geophysical techniques used by geoscientists to infer the physical parameters of the Earth's internal structures and their surface expression. Ordered in roughly deep-to-shallow segments, noting that many processes cross domains over geological timescales.

Target interval	Indicative depth range (km) (focussed on continental domains unless otherwise specified)	Main geological and geophysical technique(s)	Comment	References
Lower mantle	~660–2890 km	Seismic tomography; Gravity/geoid	Structures include subducted slabs, mantle plumes, core boundary dynamics. Seismic data typically developed from global models. Limited resolution, coverage and sensitivity.	Jakovlev et al. (2012), Rickers et al. (2013), Panet et al. (2014), Gaina et al. (2014), Toyokuni et al. (2020a, b), Celli et al. (2021)
Upper mantle (including mantle transition zone)	~100–660 km Lithosphere–asthenosphere boundary (LAB) to base of the transition zone	Receiver functions of converted seismic waves, seismic tomography, gravity/ geoid	Structures include subducting slabs, mantle plumes, mineral phase change in transition zones. Data limitations as for lower mantle.	Schaeffer and Lebedev (2013), Wilde-Piórko (2015)
Lithosphere–asthenosphere boundary (LAB)	~60–280 km under continents ~30–120 km under oceans	seismic, electromagnetic, petrological, thermal and gravity data	Major lateral variation from thin (12 km) lithosphere at the mid-ocean ridge to 90–100 km beneath the Barents Sea	Klitzke et al. (2015), Minakov (2018), Grad and Majorowicz (2020)
Deeper parts of the crust and uppermost mantle	~20–100 km	wide-angle reflection/ refraction seismic and seismological methods; Magnetotelluric data; Volcanic rocks (i.e., xenoliths)	Provides insights into electrical conductivity (i.e., fluid content)	Amundsen et al. (1987), Skjelkvåle et al. (1989), Ionov et al. (2002a, b), Griffin et al. (2012), Wilde-Piórko (2015), Goncharov et al. (2015), Czuba (2017), Selway et al. (2020), Senger et al. (2024)
Deep to shallow crust	~0–40 km	Magnetotelluric data; Seismic reflection data; Gravity and magnetic data (potential field). GNSS stations	Used for geothermal exploration near Longyearbyen and Ny-Ålesund; Provides insights onto the subsurface structures, and outcrop-seismic correlations. Burial and exhumation history of various rocks; Calculate exposure ages and erosion rates	Eiken (1985, 1994), Faleide et al. (1988), Olesen et al. (2020), Bælum et al. (2012), Dörr et al. (2012), Senger et al. (2013); Blinova et al. (2013); Gjermundsen et al. (2015), Beka et al. (2015, 2016, 2017), Dumais and Brönner (2020)
Surface and uppermost crust (including sediments)	~0–10 km	GNSS stations; Apatite fission track; Cosmogenic nucleides/exposure dating; Heat flow and thermal conductivity; outcropping geology	Quaternary geology and surface outcrops. Recent and ongoing uplift, mostly located in western Svalbard. Onshore and offshore data. Heat flow measured offshore Svalbard increases from 80 mW/m^2 near the continental slope to >300 mW/m^2 along the mid-ocean spreading zones	Crane et al. (1991), Okay and Crane (1993), Geissler et al. (2014), Dumke et al. (2016), Klitzke et al. (2016), Grad and Majorowicz (2020), Kierulf et al. (2022b, a) Senger et al. 2023b)

References

Amundsen HEF, Griffin WL, O'Reilly SY (1987) The lower crust and upper mantle beneath northwestern Spitsbergen: evidence from xenoliths and geophysics. Tectonophysics 139:169–185. https://doi.org/10.1016/0040-1951(87)90095-3

Bælum K, Johansen TA, Johnsen H et al (2012) Subsurface structures of the Longyearbyen CO 2 Lab study area in Central Spitsbergen (Arctic Norway), as mapped by reflection seismic data. Nor J Geol 92:377–389

Beka TI, Bergh SG, Smirnov M, Birkelund Y (2017) Magnetotelluric signatures of the complex tertiary fold–thrust belt and extensional fault architecture beneath Brøggerhalvøya, Svalbard. Polar Res 36:. https://doi.org/10.1080/17518369.2017.1409586

Beka TI, Smirnov M, Bergh SG, Birkelund Y (2015) The first magnetotelluric image of the lithospheric-scale geological architecture in central Svalbard, Arctic Norway. Polar Res 34:. https://doi.org/10.3402/polar.v34.26766

Beka TI, Smirnov M, Birkelund Y et al (2016) Analysis and 3D inversion of magnetotelluric crooked profile data from central Svalbard for geothermal application. Tectonophysics 686:98–115. https://doi.org/10.1016/j.tecto.2016.07.024

Blinova M, Faleide JI, Gabrielsen RH, Mjelde R (2013) Analysis of structural trends of sub-sea-floor strata in the Isfjorden area of the West Spitsbergen Fold-and-Thrust Belt based on multichannel seismic data. J Geol Soc 170:657–668. https://doi.org/10.1144/jgs2012-109

Celli NL, Lebedev S, Schaeffer AJ, Gaina C (2021) The tilted Iceland Plume and its effect on the North Atlantic evolution and magmatism. Earth Planet Sci Lett 569:117048. https://doi.org/10.1016/j.epsl.2021.117048

Crane K, Sundvor E, Buck R, Martinez F (1991) Rifting in the northern Norwegian-Greenland Sea: Thermal tests of asymmetric spreading. J Geophys Res Solid Earth 96:14529–14550. https://doi.org/10.1029/91JB01231

Czuba W (2017) 3-D seismic tomographic modelling of the crustal structure of northwestern Svalbard based on deep seismic soundings. Geophys J Int 208:508–520. https://doi.org/10.1093/gji/ggw418

Dörr N, Lisker F, Clift PD et al (2012) Late Mesozoic–Cenozoic exhumation history of northern Svalbard and its regional significance: Constraints from apatite fission track analysis. Tectonophysics 514–517:81–92. https://doi.org/10.1016/j.tecto.2011.10.007

Dumke I, Burwicz EB, Berndt C et al (2016) Gas hydrate distribution and hydrocarbon maturation north of the Knipovich Ridge, western Svalbard margin. J Geophys Res Solid Earth 121:1405–1424. https://doi.org/10.1002/2015JB012083

Eiken O (1985) Seismic mapping of the post-Caledonian Svalbard. Polar Res 3:167–176. https://doi.org/10.3402/polar.v3i2.6950

Eiken O (1994) Seismic Atlas of Western Svalbard: A Selection of Regional Seismic Transects. Norsk Polarinstitutt, Oslo

Faleide JI, Gudlaugsson ST, Eiken O, Hanken NM (1988) Seismic structure of Spitsbergen: Implications for Tertiary deformation. Nor Polarinst Rapp 46:46–50

Gaina C, Medvedev S, Torsvik TH et al (2014) 4D Arctic: A Glimpse into the Structure and Evolution of the Arctic in the Light of New Geophysical Maps, Plate Tectonics and Tomographic Models. Surv Geophys 35:1095–1122. https://doi.org/10.1007/s10712-013-9254-y

Geissler WH, Pulm PV, Jokat W, Gebhardt AC (2014) Indications for the Occurrence of Gas Hydrates in the Fram Strait from Heat Flow and Multichannel Seismic Reflection Data. J Geol Res 2014:582424. https://doi.org/10.1155/2014/582424

Gjermundsen EF, Briner JP, Akçar N et al (2015) Minimal erosion of Arctic alpine topography during late Quaternary glaciation. Nat Geosci 8:789–792. https://doi.org/10.1038/ngeo2524

Goncharov AG, Nikitina LP, Borovkov NV et al (2015) Thermal and redox equilibrium conditions of the upper-mantle xenoliths from the Quaternary volcanoes of NW Spitsbergen, Svalbard Archipelago. Russ Geol Geophys 56:1578–1602. https://doi.org/10.1016/j.rgg.2015.10.006

Grad M, Majorowicz J (2020) Geophysical properties of the crust and upper mantle of the ocean-continent transition in Svalbard area. Pol Polar Res 41:1–22. https://doi.org/10.24425/ppr.2020.132567

Griffin WL, Nikolic N, O'Reilly SY, Pearson NJ (2012) Coupling, decoupling and metasomatism: Evolution of crust–mantle relationships beneath NW Spitsbergen. Lithos 149:115–135. https://doi.org/10.1016/j.lithos.2012.03.003

Ionov DA, Bodinier J-L, Mukasa SB, Zanetti A (2002a) Mechanisms and Sources of Mantle Metasomatism: Major and Trace Element Compositions of Peridotite Xenoliths from Spitsbergen in the Context of Numerical Modelling. J Petrol 43:2219–2259. https://doi.org/10.1093/petrology/43.12.2219

Ionov DA, Mukasa SB, Bodinier J-L (2002b) Sr–Nd–Pb Isotopic Compositions of Peridotite Xenoliths from Spitsbergen: Numerical Modelling Indicates Sr–Nd Decoupling in the Mantle by Melt Percolation Metasomatism. J Petrol 43:2261–2278. https://doi.org/10.1093/petrology/43.12.2261

Jakovlev AV, Bushenkova NA, Koulakov IYu, Dobretsov NL (2012) Structure of the upper mantle in the Circum-Arctic region from regional seismic tomography. Russ Geol Geophys 53:963–971. https://doi.org/10.1016/j.rgg.2012.08.001

Kierulf HP, Kohler J, Boy J-P et al (2022a) Time-varying uplift in Svalbard—an effect of glacial changes. Geophys J Int 231:1518–1534. https://doi.org/10.1093/gji/ggac264

Kierulf HP, van Pelt WJJ, Petrov L et al (2022b) Seasonal glacier and snow loading in Svalbard recovered from geodetic

observations. Geophys J Int 229:408–425. https://doi.org/10.1093/gji/ggab482

Klitzke P, Faleide JI, Scheck-Wenderoth M, Sippel J (2015) A lithosphere-scale structural model of the Barents Sea and Kara Sea region. Solid Earth 6:153–172. https://doi.org/10.5194/se-6-153-2015

Klitzke P, Sippel J, Faleide JI, Scheck-Wenderoth M (2016) A 3D gravity and thermal model for the Barents Sea and Kara Sea. Tectonophysics 684:131–147. https://doi.org/10.1016/j.tecto.2016.04.033

Minakov A (2018) Late Cenozoic lithosphere dynamics in Svalbard: Interplay of glaciation, seafloor spreading and mantle convection. J Geodyn 122:1–16. https://doi.org/10.1016/j.jog.2018.09.009

Okay N, Crane K (1993) Thermal rejuvenation of the Yermak Plateau. Mar Geophys Res 15:243–263. https://doi.org/10.1007/BF01982384

Panet I, Pajot-Métivier G, Greff-Lefftz M et al (2014) Mapping the mass distribution of Earth's mantle using satellite-derived gravity gradients. Nat Geosci 7:131–135. https://doi.org/10.1038/ngeo2063

Rickers F, Fichtner A, Trampert J (2013) The Iceland–Jan Mayen plume system and its impact on mantle dynamics in the North Atlantic region: Evidence from full-waveform inversion. Earth Planet Sci Lett 367:39–51. https://doi.org/10.1016/j.epsl.2013.02.022

Schaeffer AJ, Lebedev S (2013) Global shear speed structure of the upper mantle and transition zone. Geophys J Int 194:417–449. https://doi.org/10.1093/gji/ggt095

Selway K, Smirnov MY, Beka T et al (2020) Magnetotelluric Constraints on the Temperature, Composition, Partial Melt Content, and Viscosity of the Upper Mantle Beneath Svalbard. Geochem Geophys Geosystems 21:e2020GC008985. https://doi.org/10.1029/2020GC008985

Senger K, Betlem P, Braathen A et al (2024) Longyearbyen CO2 lab project – from a vision of a CO2-neutral Svalbard to a geoscience data eldorado. Arct Sci. https://doi.org/10.1139/as-2024-0019

Senger K, Nuus M, Balling N et al (2023) The subsurface thermal state of Svalbard and implications for geothermal potential. Geothermics 111:102702. https://doi.org/10.1016/j.geothermics.2023.102702

Senger K, Roy S, Braathen A et al (2013) Geometries of doleritic intrusions in central Spitsbergen, Svalbard: an integrated study of an onshore-offshore magmatic province with implications for CO2 sequestration. Nor J Geol 93:143–166

Skjelkvåle B-L, Amundsen HEF, O'Reilly SY et al (1989) A primitive alkali basaltic stratovolcano and associated eruptive centres, Northwestern Spitsbergen: Volcanology and tectonic significance. J Volcanol Geotherm Res 37:1–19. https://doi.org/10.1016/0377-0273(89)90110-8

Toyokuni G, Matsuno T, Zhao D (2020a) P Wave Tomography Beneath Greenland and Surrounding Regions: 1. Crust and Upper Mantle. J Geophys Res Solid Earth 125:e2020JB019837. https://doi.org/10.1029/2020JB019837

Toyokuni G, Matsuno T, Zhao D (2020b) P Wave Tomography Beneath Greenland and Surrounding Regions: 2. Lower Mantle. J Geophys Res Solid Earth 125:e2020JB019839. https://doi.org/10.1029/2020JB019839

Wilde-Piórko M (2015) Crustal and upper mantle seismic structure of the Svalbard Archipelago from the receiver function analysis. Pol Polar Res 36:89–107. https://doi.org/10.1515/popore-2015-0009

Appendix 4 – Data packages

The data packages described below can be found in the digital appendix:[4]

Data package ADP1 – QGIS data package

QGIS data package with QGIS projects and a selection of key geological and geophysical data in Svalbard (see Table AT3 in Senger et al. 2024a). Package includes navigational files of the available geophysical data in Svalbard.

Data package ADP2 – GPlates data package

GPlates data package including the global GeoData data set by Zahirovic (2023) and corresponding publications. Relevant data was added to the project, and the full data set is included for further personalisation by the user. The geological map (Dallmann 2015) and various geophysical data as described in data package ADP1 were also included.

Data package ADP3 – Thermochronology data compilation

Example data set of Apatite fission track data from Svalbard compiled in .csv and NET-CDF format as a showcase for thematic data harvesting and the still existing mismatch between the NET-CDF formatting and the heterogenous nature of geological data.

Data compiled by Cornelia Spiegel, adapted by Fenna Ammerlaan.

Data from: Blythe and Kleinspehn (1998); Dörr et al. (2012, 2019a, b), Schaaf et al. (2021), Japsen et al. (2023), Meier et al. (2024)

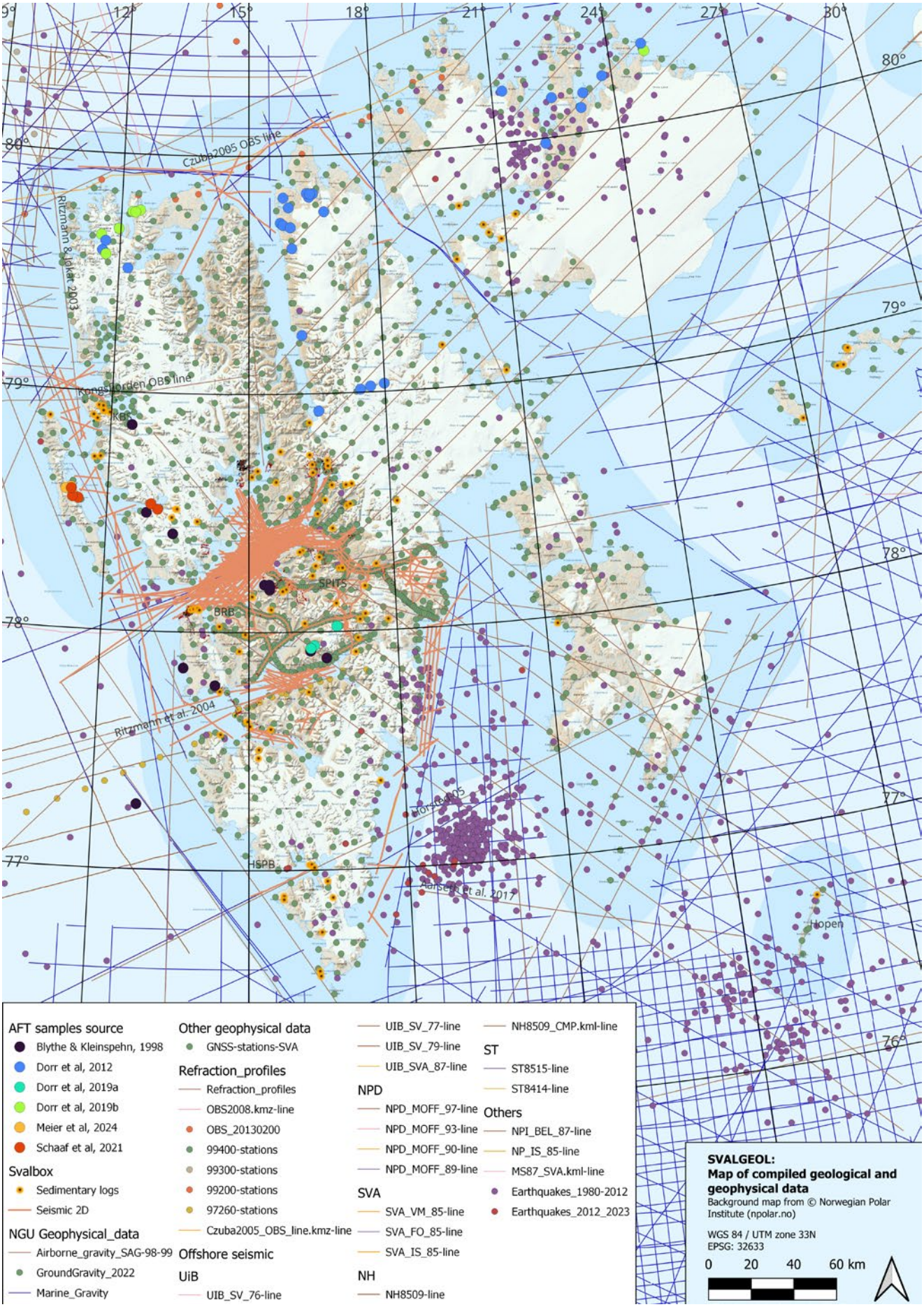
Data package ADP4 – Reference collection

Zotero RDF and Bibtex file of the collection of references used in both the main text and appendix. This collection contains the key publications of both geological and geophysical work done in Svalbard and can be imported in other reference management systems.

Data package ADP5 – Research in Svalbard portal and google scholar data

Data set used for the analysis of the geological research done in Svalbard as discussed in section 2.1 and illustrated in Figure 2. Data retrieved from Google Scholar[5] and from the Research in Svalbard Portal (RiS)[6].

4 https://doi.org/10.5281/zenodo.14216541
5 https://scholar.google.com/
6 https://www.researchinsvalbard.no/



Coverage map of various geological and geophysical data points acquired in Svalbard. Data is available through the QGIS data package and relevant publications can be found in the complementary Table A6.

Surging glaciers in Svalbard: Current knowledge and perspectives for monitoring (SvalSurge)

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1. Introduction

Around 56% of the Svalbard archipelago is covered by glaciers and ice caps (RGI 7.0 2023). Several of these have displayed unstable ice flow called a "surge", where a glacier accelerates over just a few years following multiple decades of slow flow. These surge-type glaciers can lead to enhanced mass loss over decades (McMillan et al. 2014; Morris et al. 2020). The cycle between fast and slow flow results from a switch in the subglacial hydrological system from one with efficient drainage and low water pressure, to one with inefficient drainage and high water pressure, leading to enhanced basal sliding (Thøgersen et al. 2019). Benn et al. (2019a) aimed to generalise this process, whereby surges initiate due to a change in basal enthalpy (water and temperature), i.e., a low enthalpy state with low subglacial water pressure to a high enthalpy state with high basal water pressure. However, coupling enthalpy changes to sliding remains difficult (Terleth et al. 2021).

The number of surge-type glaciers in Svalbard has been estimated to be between 10% and 90% depending on the classification technique used, although ~21% have displayed surge behaviour (Sevestre and Benn 2015; Kääb et al. 2023; Koch et al. 2023). Although historical aerial photographs and archival maps have revealed past surges as far back as 1850 (Lefauconnier and Hagen 1991; Hagen et al. 1993; Geyman et al. 2022), these are snapshots and do not document surge velocities, terminus advance rates, mass transfer, triggers or subglacial conditions. Palaeo-glaciological studies have partially bridged this gap (Farnsworth et al. 2016; Flink et al. 2018; McCerery et al. 2024) but these studies can only infer past dynamics from the landform record, which can be censored by weathering and postglacial sedimentation. Even in the satellite era with dense observations that can detect active surges (Kääb et al. 2023; Koch et al. 2023) we have relied on in situ geophysical observations to study subglacial drivers of a surge (Sevestre et al. 2015; Bouchayer et al. 2024). In this chapter, we review the current state of the art in detecting and monitoring glacier surges in Svalbard from Earth Observation (EO) data, geophysics and palaeo-glaciological landforms. From this review, we construct a new database (Appendix 1) of observed and inferred surges in Svalbard along with their associated characteristics (e.g., start and end of a surge, maximum velocity). We use both the literature review and the new database to recommend priority areas for future research and the development of research infrastructure (RI) that will help researchers achieve these goals.

2. Previous Compilations of Surging Glaciers in Svalbard

There have been several attempts to compile a database of surge-type glaciers in Svalbard based on different methodologies. Lefauconnier and Hagen (1991) compiled a detailed list of surge-type glaciers in eastern Svalbard that terminate into the ocean and discharge icebergs into the Barents Sea. Based on their analysis, they estimated that 90% of glaciers in Svalbard are likely to be surge-type. Similarly, Hagen et al. (1993) developed the first Svalbard-wide inventory of surge-type glaciers, documenting recorded surges from historical observations, satellite imagery and archival aerial photographs. In comparison, statistical analysis of variables that control surging (e.g., bed lithology, glacier geometry) have suggested that only 13% of Svalbard's glaciers are surge-type (Jiskoot et al. 1998, 2000). To improve upon these earlier methodologies, Sevestre and Benn (2015) compiled a global database of surge-type glaciers from ice flow velocities, detected terminus advances and geomorphological evidence (e.g., crevasse-squeeze ridges, eskers, looped moraines). An updated version of this database is currently available in the Randolph Glacier Inventory version 7 (RGI

v7) (RGI 7.0 Consortium 2023). In RGI v7, there are 1,583 glaciers in Svalbard, of which Sevestre and Benn (2015) estimated that 17% (263) have shown signatures of past surge activity (n.b. this differs slightly from the original publication due to updated documentation on surges). Only 8% (125) have been directly observed to surge, which is lower than the statistical studies of Jiskoot et al. (1998; 2000). A total of 83% (1,320) have shown no signatures of surge behaviour.

Other studies have suggested that the presence of diagnostic landforms associated with surging, such as crevasse-squeeze ridges (CSRs) (Evans and Rea 1999; Lovell and Boston 2017), represents direct evidence of past surge activity. Farnsworth et al. (2016) interrogated centimetre resolution aerial imagery and found that 431 forefields in Svalbard contained CSRs, which equates to 43% of glaciers in Svalbard (although only 27% of the RGI 7.0, see discussion below). Because of the difficulty of directly observing glacier surges before the satellite era, statistical models have been developed to classify the probability of a glacier being surge-type. Hamilton and Dowdeswell (1996) found that Svalbard glaciers had a higher probability of being surge-type as they were generally longer than other glaciers. This agrees with other findings using logistic regression (Jiskoot et al. 1998, 2000), which found length and surface slope to be key determinants of surge prevalence in Svalbard. Bouchayer et al. (2022) trained several machine learning models with data on mass balance, glacier geometric features and climatic data and found that 17% of all glaciers larger than 1 km^2 could be surge-type, although when considering glaciers of all size classes, this equates to only 10%.

3. Monitoring Contemporary Glacier Surges

3.1. Observational Pyramid

Comprehensive monitoring of modern-day surges in Svalbard and their associated dynamics relies upon remote sensing at multiple scales using the so-called "Observational Pyramid" (Figure 1). This requires the integration of various technologies such as satellite imaging, aerial drones (UAVs), geophysical instruments, on-ice GPS, autonomous surface vehicles (USVs), and autonomous underwater vehicles (AUVs). Satellites offer long-term, Svalbard-wide monitoring through sensors such as visible imaging cameras, synthetic aperture radar (SAR), and hyperspectral instruments, although with coarse (5-50 m) spatial resolution. UAVs, by contrast, capture high-resolution data at lower altitudes, using a range of sensors to focus on specific areas such as glacier fronts, or to map entire glaciers with more complex missions. Geophysical sensors, such as seismometers and ground-penetrating radar (GPR), can detect subsurface processes and are crucial for observing subglacial conditions driving surges In situ monitoring of ice dynamics is best achieved using on-ice GPS devices connected to the Global Navigation Satellite System (GNSS). Meanwhile, USVs operate near the water's surface, collecting key data on processes such as meltwater discharge rates. AUVs dive deeper, using sonar to map the seafloor, which aids both palaeo-glaciological surveys and the mapping of subsurface calving fronts. Improving the accuracy, resolution, and coordination of these observational methods is critical for acquiring more precise, integrated data to better understand surging glacier dynamics.

3.2. Satellite Earth Observation (EO)

The most detailed record of glacier surge behaviour in Svalbard has been recorded over the satellite era extending back to the 1960s. An actively surging glacier in Svalbard typically undergoes a multi-year speed-up and then decelerates gradually (Figure 2) and this pattern can be used to detect an active surge from continuous satellite monitoring (Koch et al. 2023). Before 2000, velocity maps were restricted to accessibility of image pairs covering a region of Svalbard due to the longer revisit periods of satellites (Dowdeswell and Collin 1990; Rolstad

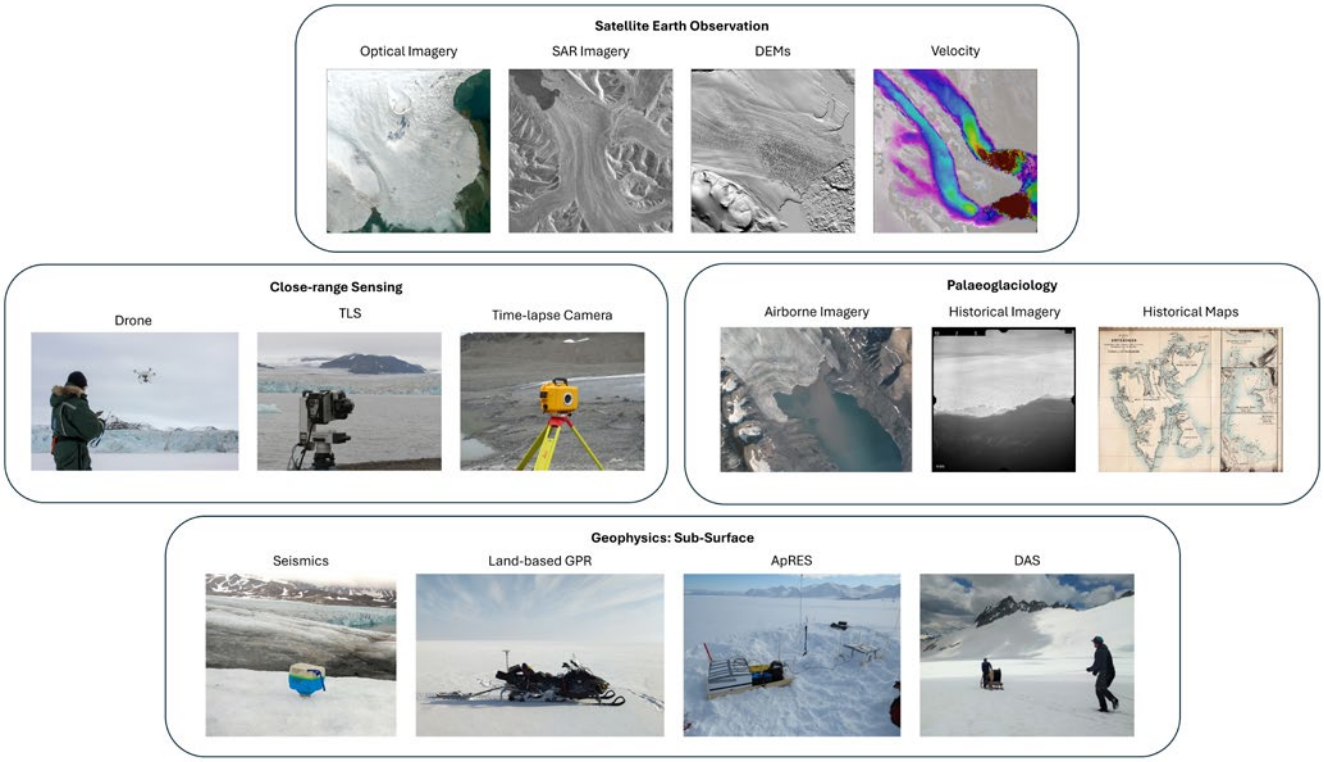

Figure 1: Illustration of the different methods used to monitor and detect glacier surges in Svalbard. Photo Credits: 'Drone' image – Richard Hann. 'TLS', 'Time-lapse Camera' and 'ApRES' images: William Harcourt. 'Airborne Imagery' and 'Historical Imagery' images – TopoSvalbard. 'Historical Maps' and 'Land-based GPR' image – Erik Mannerfelt. 'Seismics' and 'DAS' image – Wojciech Gajek.

et al. 1997). Furthermore, despite the relative paucity of appropriate SAR images over Svalbard, InSAR has successfully been used to detect unstable ice flow during a surge (Murray et al. 2003). Now, with the open release of historical satellite imagery, long-term velocity time series are available (e.g., Strozzi et al. 2017), enabling the detection of historical surges (Nuth et al. 2019). In the 2000s, velocity data were acquired primarily from satellites such as ERS-1/2, RADARSAT and ASTER data (Mansell et al. 2012; Murray et al. 2003) but also high resolution TerraSAR-X images (Luckman et al. 2015). Since 2014, the density of ice velocity observations has significantly increased due to the simultaneous orbits of Sentinel-1, Sentinel-2, Landsat 8 and Landsat 9, leading to several global open access databases (Friedl et al. 2021; Lei et al. 2022; Figure 2). The higher temporal resolution also enables tracking of surge dynamics in more detail, such as the impact of seasonal ice flow variations which may be imprinted on the surge velocity pattern (Benn et al. 2022). However, these measurements struggle to detect anomalous flow patterns on smaller valley glaciers where flow rates are typically much lower. The surge of Scheelebreen (Figure 2b) is somewhat of an anomaly in that it is a small valley glacier but has accelerated from 0.5 m/d to ~9.5 m/d in a short time period.

Surges typically lead to pervasive surface crevassing due to the high strain rates induced by the sudden discharge of ice downglacier. This leads to a change in surface texture which is visible between satellite images taken before and during a surge and is particularly pronounced in SAR imagery as the heavy crevassing increases surface roughness and consequently radar backscatter. Leclercq et al. (2021) found that by differencing SAR imagery between 2018 and 2019, locations of increases in radar backscatter can be related to surge activity. They identified 11 ongoing surges in Svalbard using this approach. Kääb et al. (2023) used the same methodology but applied it to a longer time series (2017-2022) to detect additional surges in Svalbard. Such analysis could be extended to other satellite SAR time series (e.g., ERS-1/2, Sentinel-1, ALOS) but this has not yet been attempted. Texture changes in optical imagery has not been tried but also has the potential to be used as a tool for monitoring and detecting surges.

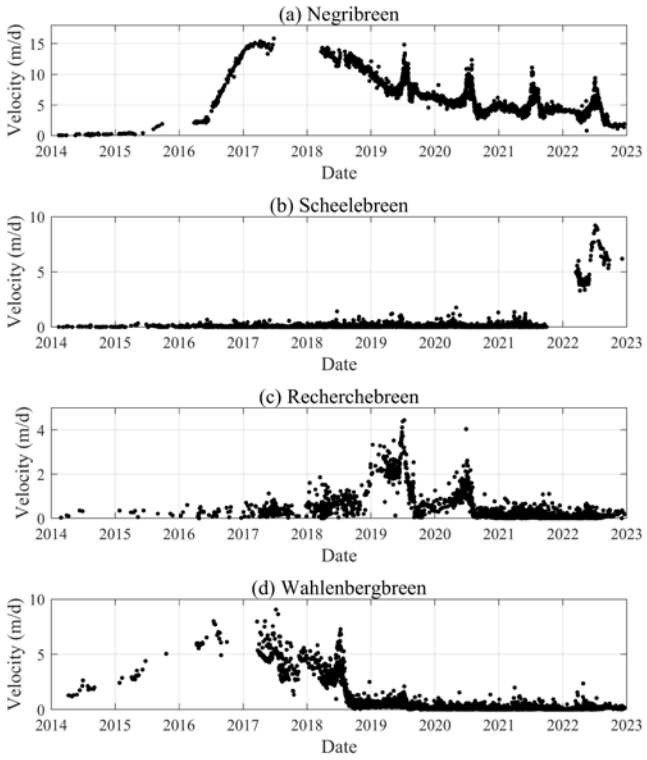

Figure 2: Velocities from selected ongoing and recent surges in Svalbard, data taken from the ITS_LIVE velocity catalogue.

Differencing Digital Elevation Models (DEMs) can be used to measure ice build-up before a surge, surface lowering during a surge, then the subsequent high elevation thinning and low elevation thickening after a surge (Sund et al. 2009; Sevestre et al. 2018). Long-term changes in ice volume can be readily quantified by differencing a modern-day DEM with a DEM generated from historical aerial photographs, e.g., in the 1930s (Geyman et al. 2022; Mannerfelt et al. 2024) and 1990s (Rolstad et al. 1997; King et al. 2016), but is likely to miss surges with small ice fluxes. 3D mapping of Svalbard surges increased significantly after 2000 with the availability of repeat stereoscopic satellite imagery such as ASTER and has been used to analyse surge cycles at individual catchments (Nuth et al. 2019) and over a larger spatial region (Sund et al. 2009; Rolstad et al. 1997; Sund et al. 2014; Sevestre et al. 2018). More recently, 2 m resolution ArcticDEM data has been used to assess 3D changes alongside other DEMs from ASTER and Tandem-X (Haga et al. 2020; Kavan et al. 2022). Since 2003, regional surface elevation maps have been available covering the entire archipelago and derived from ICESat (Nuth et al. 2010), CryoSat-2 (Jakob and Gourmelen 2023) and more recently ICESat-2 (Sochor et al. 2021). Although these do not specifically target the detection of surges and are generally coarser resolution compared to ASTER, aerial photos and ArcticDEMs, the measurements have high temporal resolution and enable detailed mapping of elevation changes suitable for monitoring geometric changes of glaciers during a surge. Combined with similar repositories of terminus changes (Li et al. 2024), mass balance can be quantified.

3.3. Close-Range Sensing

Close-range sensors operating near glaciers provide high-resolution data and are able to observe detailed surface processes associated with a surge such as iceberg calving, surface melt, and flow patterns. The use of Terrestrial Laser Scanners (TLS) for monitoring surges is limited despite showing significant potential for 3D monitoring of tidewater calving fronts (Pętlicki et al. 2015; Köhler et al. 2019). In comparison, commercial multirotor drones (UAVs) like DJI's Phantom and Mavic series, combined with photogrammetric techniques (Smith et al. 2016) to extract DEMs and orthomosaics, makes UAVs ideal for remote and harsh Arctic environments (Hann et al. 2023). One example is the quantification of aerodynamic roughness of calving margins of surge-type glaciers (Dachauer et al. 2021). Time-lapse photography is more commonly used for monitoring glacier surges in Svalbard, particularly to generate dense observations of terminus conditions during an active surge (Sund and Eiken 2010), such as the dynamics between adjacent flow-units during the 2005 surge of the Paulabreen system (Kristensen and Benn 2012). For surging glaciers, time-lapse photography is especially useful in capturing fast and transient changes that are often missed by other monitoring techniques, such as the transition from quiescence to an active surge (Vallot et al. 2019). Our review reveals that close-rage sensors are not widely used for monitoring the dynamics of glacier surges. A significant reason for this is the unpredictability of surges and an inability to plan and fund the deployment of close-range

sensors during the short time window of a surge. Permanent installations at glacier systems that repeatedly surge (e.g., Nathorstbreen, Paulabreen, Tunabreen) or are predicted to surge soon (e.g., Kongsvegen, Sonklarbreen, Stonebreen) might enhance monitoring efforts.

3.4. Geophysical Measurements: Surface

Global Navigation Satellite System (GNSS) measurements using GPS systems deployed on a glacier surface have high temporal resolution (seconds), hence they can be used to detect subtle changes at the start of a surge when flow rates are close to quiescent velocity values. This was crucial in detecting the onset of surge activation at Basin-3, Austfonna (Dunse et al. 2012, 2015) and is now being used to analyse the initiation of a surge at Kongsvegen. They may also detect elevation variations associated with surge activity, particularly the downglacier movement of a surge bulge. For example, Hodgkins et al. (2007) measured ice accumulation of Finsterwalderbreen during quiescence and downwasting in the ablation zone, highlighting the processes that generate a mass gradient imbalance that ultimately leads to a surge. Similar processes have been measured at Kongsvegen (Eiken et al. 1997; Hagen et al. 2005), hence GNSS measurements can fill the temporal gap of satellite EO-based methods. However, the installation and maintenance of GNSS instruments is complicated by the highly deformable and fractured surface of surging glaciers, meaning suitable deployment areas are often inaccessible, whilst the instruments themselves may be at risk of loss and damage. Similar to the close-range sensing methods, the installation of GNSS sensors prior to surge initiation requires prediction of when the surge might occur. This might be possible for glaciers with several surge-type tributaries (e.g., Nathorstbreen, Paulabreen/Bakaninbreen), but a suitable sampling strategy is required to ensure the deployment of such instruments if scientifically and cost effective. If this can be realised, the data may be used to inform models of surging (e.g., Benn et al. 2019a; Thøgersen et al. 2021) to improve our understanding of the underlying dynamics.

3.5. Geophysical Measurements: Subsurface

3.5.1. Ground-Penetrating Radar (GPR)

Ground Penetrating Radar (GPR) is a non-invasive method that uses high-frequency electromagnetic waves to penetrate and image the subsurface. *Land-based GPR systems* are manually dragged or towed over a glacier surface, which is relatively slow and challenging across heavily crevassed surfaces, hence they are usually restricted to being used on quiesecent surge-type glaciers. *Airborne GPR systems* (e.g., Navarro et al. 2016; Sevestre et al. 2018; Ignatiuk et al. 2022) mounted on helicopters or UAVs can map the subsurface rapidly and are particularly useful for surveying inaccessible areas, e.g., highly crevassed surfaces. Both land-based and airborne GPR systems may reveal detailed internal structures (Hodson et al. 1997; Woodward et al. 2003b), internal stratigraphy (Dunse et al. 2009; Barzycka et al. 2019, 2020), thicknesses and volumes of ice (Navarro et al. 2014; Karušs et al. 2022), water routing channels (Church et al. 2019), and subglacial topography (Smith et al. 2002; Saintenoy et al. 2013). Its sensitivity to water may provide information about the thermal structure of the ice (Murray et al. 2000; Bælum and Benn 2011) and water-filled areas (Barrett et al. 2008). Repeat surveys can be used to track changes in the internal structure, particularly the spatial locations of meltwater which is crucial in surge processes.

Autonomous phase-sensitive Radio Echo Sounder (ApRES) is a type of land-based GPR system that provides phase-sensitive fixed-point measurements, allowing it to detect small changes in the distance between the radar and reflective targets (such as ice layers, bedrock, or subglacial water). The temporal resolution of these measurements can be high (although this requires a suitable power supply) and can be used to measure subtle changes in deformation and strain rates (Gillet-Chaulet et al. 2011), flow velocities (Kingslake et al. 2014), or basal melting (Lok et al. 2014). ApRES has been applied previously in the Antarctic (Kingslake et al. 2014; Lok et al. 2014) and Greenland (Gillet-Chaulet et al. 2011). In Svalbard, its first glaciological

application took place in 2024 to study the surge of Borebreen (Harcourt et al. 2024a).

Although glacier ice is a favourable medium for electromagnetic wave propagation due to the limited number of internal scatterers, there must be a trade-off between vertical resolution and depth penetration. Whilst GPR systems can image the first tens of metres of the subsurface with centimetre resolution, the signal wavelength of the GPR must be increased to obtain information from the glacier base, which decreases the vertical resolution to metres. Within temperate ice there are a larger number of internal scattering bodies; thus to measure the glacier bed even longer wavelengths are required which further degrades the vertical resolution. Therefore, GPR surveys are often limited to the spring months when the ice surface is snow-covered, air temperatures are below freezing and GPR systems can be towed behind motorised vehicles. On the other hand, airborne GPR systems may survey larger areas regardless of snow cover presence but often at lower resolution. In both cases, the presence of surface melt and heavily crevassed surfaces can significantly attenuate the GPR signal and reduce reflections from the subglacial environment; hence further research is required to understand the feasibility of GPR surveys in such cases. Additionally, integrating GPR data with other geophysical methods such as seismic surveys, GPS measurements, and satellite EO techniques can provide a more comprehensive understanding of glacier surges and their controlling factors.

3.5.2. Seismology

Seismology measures ground shaking activity below ground and can be used to infer the mechanical properties of ice and subglacial activity such as from basal meltwater which is critical to the study of sliding during a surge. It has been used to study glaciers in Svalbard for decades (Röthlisberg 1955; Lewandowska and Teisseyre 1964) and is now a well-developed branch of applied seismology called cryosseismology. Several reviews are available (Podolskiy and Walter 2016; Aster and Winberry 2017) including one focusing on the state of cryoseismology in Svalbard (Köhler et al. 2020). Köhler et al. (2020) found that cryoseismology is a powerful method for improving our understanding of glacier dynamic processes and inferring englacial and subglacial conditions in previously inaccessible areas, complementing traditional glaciological observations from field or satellite EO. Cryoseismology is independent from visibility conditions (e.g., the polar night), can achieve wide spatial imaging beyond single observation points, and has a high temporal resolution (sub-second scale). Moreover, systematic analysis of long and continuous seismic records enables the identification of long-term trends and changes in seasonal patterns of glacier dynamics over years or even decades (e.g., Köhler et al. 2016; Gajek et al. 2017).

Glacier surges have been investigated using cryoseismological methods in several case-studies from Svalbard: on Bakaninbreen (Stuart et al. 2005), Tunabeen and Nathorstbreen (Köhler et al. 2015), Kongsvegen (Bouchayer et al. 2024), and Borebreen (ongoing; Harcourt et al. 2024a). Local short-term and multi-season deployments of seismic instruments provide precise data since they can be installed in close proximity of, or directly on, glaciers. Such setups are capable of providing information on englacial phenomena, e.g., ongoing crevassing by detecting thousands of surface icequakes per day (Mikesell et al. 2012; Walter et al. 2015); sliding properties such as slip dynamics (Gräff and Walter 2021) or ice–meltwater interactions (Gajek et al. 2021) from analysing basal icequake signals; and the identification of meltwater system geometries (Zhan 2019; Nanni et al. 2020) or moulin activity (Walter et al. 2015) by utilising information contained in low-frequency noise. These applications demonstrate the usefulness of seismology for monitoring surge-type glaciers.

New technologies, such as Distributed Acoustic Sensing (DAS), which consist of kilometres-long fibre-optic cables converted into seismic receivers, offer great potential for surge monitoring. DAS has already proven to be effective in studying icequakes in alpine glaciers (Walter et al. 2020) and Antarctic ice streams (Hudson et al. 2021),

providing unprecedented insight into the details of dynamic processes due to the sensor density and spatial sampling down to the metre scale. The first on-ice installation of DAS in Svalbard took place in 2023 on Hansbreen (RIS ID[1] 12246), but the full potential of DAS for surging glaciers has not been explored yet. Another way to install seismic stations is to use Ocean Bottom Seismometers (OBS) which, after being dropped and sunk in the glacial fjord, records seismic waves at a single location at the seabed. Such stations installed close to the terminus are less hazardous to maintain and offer less noisy recordings. Podolskiy et al. (2021) have demonstrated that OBS data may be used to monitor calving rates and as a proxy for glacial sliding velocity, even using a single station. The ability of these new techniques to provide high-resolution cryoseismological data, and the potential to use pre-existing fibres (e.g., ocean bottom telecom cables) suggests they should be seriously considered for future monitoring of surges.

3.6. Alternative Observation Methods

A significant observation gap for understanding glacier surges is the submarine environment, where subglacial outflow, iceberg calving processes, and fjord circulation are key components impacting surge activity. AUVs may be used to collect high-resolution bathymetric data, map the submarine portion of a calving front, and measure subglacial meltwater plumes into the fjord (Howe et al. 2019). Furthermore, passive underwater acoustics can potentially be used to quantify the ice loss from surging glaciers, provided the mooring system is deployed at safe distance from the fast-moving glacier terminus and the sound propagation is modelled accurately (Glowacki et al. 2016; Glowacki and Deane 2020). Moreover, autonomous underwater recorders are cheap compared to other specialised instruments and simultaneously collect information of interest for other disciplines, e.g., the vocalisation of marine mammals, shipping noise (e.g., Podolskiy and Sugiyama 2020). Finally, the concept of leveraging citizen science to document glacier surge dynamics has gained attention. For example, tourists could assist in collecting drone imagery for scientific purposes, such as tracking glacier terminus locations, but tourism operators in Svalbard are bound by strict guidelines (e.g., from the Association of Arctic Expedition Cruise Operators (AECO) and do not permit guests to operate drones, primarily due to safety and wildlife protection concerns). This could be solved by allowing researchers to join their trips, where the researchers can operate drones themselves. However, there is a risk of "greenwashing" the tourism industry by framing such ventures as purely scientific.

4. Palaeo-Glaciological Observations

4.1. The surging glacier landsystem

Sediment and landform assemblages associated with surging have been documented in both terrestrial and marine settings in Svalbard (Ottesen and Dowdeswell 2006; Streuff et al. 2015; Lovell et al. 2018a, b; McCerery et al. 2024). To interpret such emerging glacial landscapes, Svalbard scientists, as elsewhere, typically employ a "landsystems" approach. This concept seeks to identify, describe, and interpret the diverse range of sediments and landforms to reconstruct processes and thus the dynamics of the ice that previously covered the terrain (cf. Evans 2003; Evans and Rea 1999). Unlike other glacial environments, where changes may occur gradually over time, surging glaciers produce rapid, extensive modifications to the landscape that leave behind a specific suite of landforms known as a surging landsystem. Surging glacier landsystems are most accessible in terrestrial settings (Figure 3), which can be investigated in the field and from remote imagery, but preservation of features can be heavily impacted by subaerial ice stagnation. In contrast,

1 https://researchinsvalbard.no/

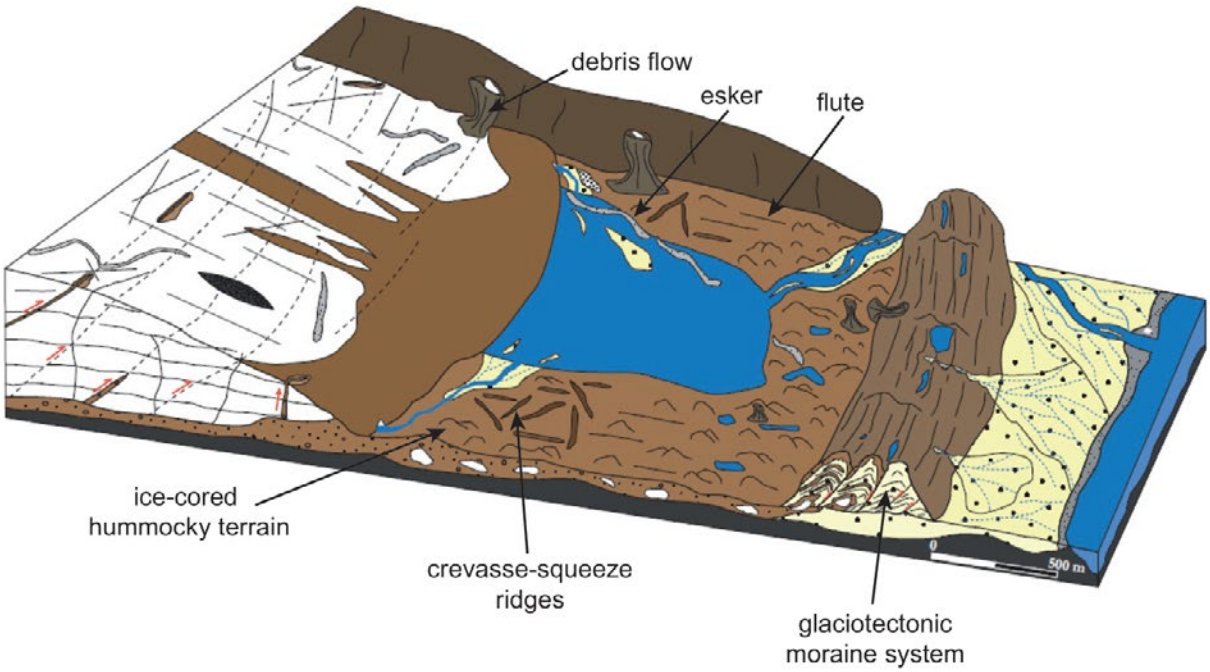

Figure 3: Land-terminating surging glacier landsystem (Lovell 2014).

landforms associated with tidewater glacier surges are often excellently preserved in a submarine setting (Figure 4), but analysis of these is reliant on the availability of high-resolution bathymetry data (Ottesen and Dowdeswell 2006). However, in most cases, tidewater glacier surges also leave behind landform evidence on the adjacent terrestrial fjord margins (Bennett et al. 1996; Lovell et al. 2018b).

4.2. Key component of a surging glacier landsystem

Glaciotectonic moraines: In Svalbard, the maximum extent of a surge can be delineated by a large moraine system (Evans et al. 2022; McCerery et al. 2024). These are most common in a marine setting, where they typically have a low-gradient debris flow lobe extending from the distal flank (e.g., Ottesen and Dowdeswell 2006). In terrestrial settings, the moraine systems often have multiple ridge crests, forming complexes known as composite ridge systems (Croot 1988; Lovell and Boston 2017). These features have also been referred to as "push moraines/complexes", although these terms can be problematic since they are employed for a broad range of landforms at various scales. In both terrestrial and marine settings, these moraine systems are formed by glaciotectonic deformation as the glacier advances rapidly into unconsolidated sediment in the proglacial zone.

Crevasse-Squeeze Ridges (CSRs): CSRs form when highly-saturated, deformable subglacial sediment is squeezed into a highly fractured glacier base (Evans and Rea 1999). During recession, CSRs melt out to form a system of cross-cutting ridges composed of diamicton that are aligned ice-flow transverse to subparallel (i.e., 40-60°), mimicking surface crevasse patterns. During the early parts of the quiescent phase, CSRs can often be observed emerging from crevasses. The required conditions for their formation are (1) a saturated subglacial environment, (2) a glacier base fractured by extensive ice flow, and (3) ice mass stagnation during quiescence to promote preservation, making CSRs arguably the most diagnostic landform evidence for surging (Farnsworth et al. 2016). CSRs are found in both terrestrial and submarine settings and have been studied extensively in Svalbard (e.g., Bennett et al. 1996; Boulton et al. 1996; Woodward et al. 2002; 2003; Rea and Evans 2011; Flink et al. 2015; Lovell et al. 2015; Farnsworth et al. 2016). They form a key line of evidence for identifying past surges with no direct observational data (e.g., Farnsworth et al. 2016; Ben-Yehoshua et al. 2023). Because CSRs form beneath surging

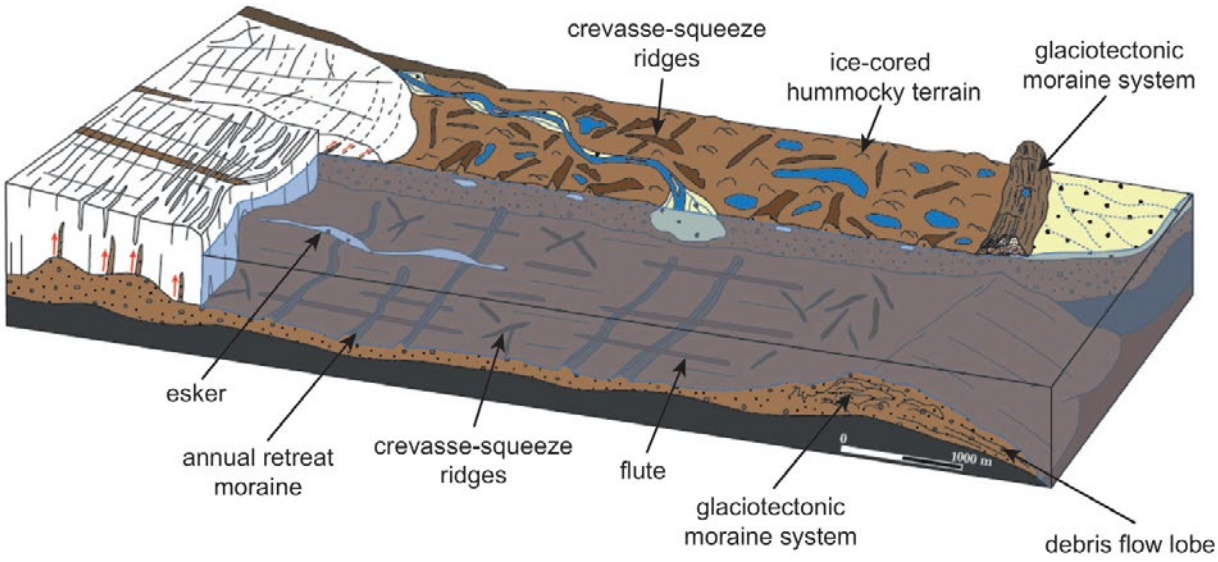

Figure 4: Marine-terminating glacier landsystem showing both submarine and terrestrial components (Lovell 2014).

glaciers, in-situ geotechnical measurements could provide a valuable dataset on stresses and strains in the subglacial environment during surges.

Flutes: Flutes are streamlined ridges of sediment formed subglacially and are often found in front of surging glaciers in Svalbard, both in terrestrial and marine settings. Their formation during surges is associated with rapid advance causing deformation of the underlying basal sediments. In marine settings they can be over 1 km in length (e.g., Borebukta, Ottesen and Dowdeswell 2006). Flutes often form a close geomorphological association with CSRs, with both forming in the subglacial environment (e.g., Christoffersen et al. 2005).

Eskers: Eskers are sinuous ridges of sand and gravel that form in channelised subglacial or englacial meltwater systems, which can be preserved in the foreland during glacier retreat. Their formation is not uniquely linked to surging, but eskers are often found as part of the Svalbard surging landsystem (e.g., McCerery et al. 2024). In some cases, geometrical ridge networks similar to CSRs but composed of sand and gravels have been reported (Evans et al. 2022). These likely reflect pressurised meltwater exploiting the heavily fractured glacier towards the end of a surge and are probably similar to "concertina" eskers reported from some surging glacier forelands in Iceland (Rea and Evans 1999). Morphologically, such eskers are hard to distinguish from CSR networks without detailed sedimentological investigations.

Quiescent phase stagnation and retreat: Most surging landforms form during fast ice flow, frontal advance and a highly saturated glacier bed. The geomorphological signature of the quiescent phase is less diagnostic of surging but can still be identified. In terrestrial settings, the cessation of surging leads to widespread stagnation and subaerial downwasting of the over-extended glacier front. Surging glaciers often transport large volumes of debris, creating extensive areas of ice-stagnation topography in the form of ice-cored hummocky moraine (e.g., Schomacker and Kjaer 2008). Debris flows and kettle holes are common as buried ice degrades over time, which can impact the preservation of other landforms such as CSRs and flutes. At tidewater surging glaciers, small annual retreat moraines can form on the seafloor during quiescent phase retreat (e.g., Ottesen and Dowdeswell 2006; Flink et al. 2015), whilst subaerial stagnation terrain will likely be common along the terrestrial margins (e.g., Lovell et al. 2018b).

Historical observations and archival evidence:

Nineteenth and early 20th century expeditions to Svalbard produced a wealth of maps, photographs and written observations (e.g., Hamberg 1894; Conway 1897; Gregory et al. 1897; Garwood and Gregory 1898; Hoel 1914; Gripp 1929), which both directly and indirectly provide insight into the state of glaciers at that time. Sometimes, the evidence clearly demonstrates that glaciers were actively surging. Combined with Norwegian Polar Institute (NPI) aerial photography from the 1930s and 1960s, and geomorphological evidence as outlined above, surge activity can be reconstructed prior to the satellite era. Examples include the historical mapping of glacier frontal positions to identify periods of rapid advance (e.g., Melvold and Hagen 1998; Ottesen et al. 2008; Lovell et al. 2018b; Mannerfelt et al. 2024), correlating evidence for surging in geomorphological record with evidence in historical photographs, observations and maps (e.g., Lovell et al. 2018b; Zagórski et al. 2023; Mannerfelt et al. in 2024), and identifying surging evidence, such as widespread crevassing and the presence of looped moraines, in historical observations and photographs (e.g., Glasser et al. 2004; Mannerfelt et al. 2024).

5. New Glacier Surge Database

5.1. Directly Observed Surges (S_Direct)

Direct observations of glacier surges have been recorded in all of the compilations apart from F2016, which only inferred surges from the landform record. In addition, the project team are currently studying ongoing surges not captured in the literature, e.g., Borebreen (Harcourt et al. 2024a), hence these are manually included. A total of 143 surges have been directly observed in Svalbard (Lefauconnier and Hagen 1991; Hagen et al. 1993; Kääb et al. 2021; Koch et al. 2023), which accounts for 9% of all the glaciers in Svalbard. Figure 5 shows the distribution of the directly observed surges. Many direct observations come from the historical records (Lefauconnier and Hagen 1991; Hagen et al. 1993) and were biased towards the eastern margins of the archipelago due to interests in calving glaciers and their impact on offshore structures and shipping routes. Most of the direct observations are of the largest glaciers, particularly where they terminate into the ocean, where a surge can be detected through an increase in icebergs. Surges on smaller glaciers have generally not been detected, especially across Andrée Land (Figure 5b) and Nordenskiöld land (Figure 5c). This may be due to the inability of a smaller glacier to discharge large volumes of ice over a short period of time, but could also be due to an inability of current sensing systems to detect lower magnitude ice flow changes during a surge.

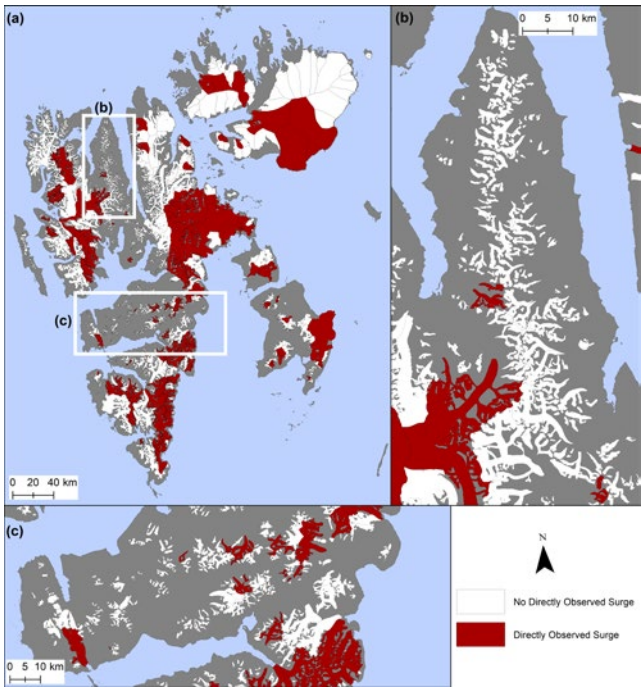

Figure 5: Directly observed surges in Svalbard.

5.2. Indirectly Observed Surges (S_Palaeo)

The locations of glaciers where indirect evidence of surges has been found through the presence of CSRs (Farnsworth et al. 2016) reveals the potential distribution of surge-type glaciers across the

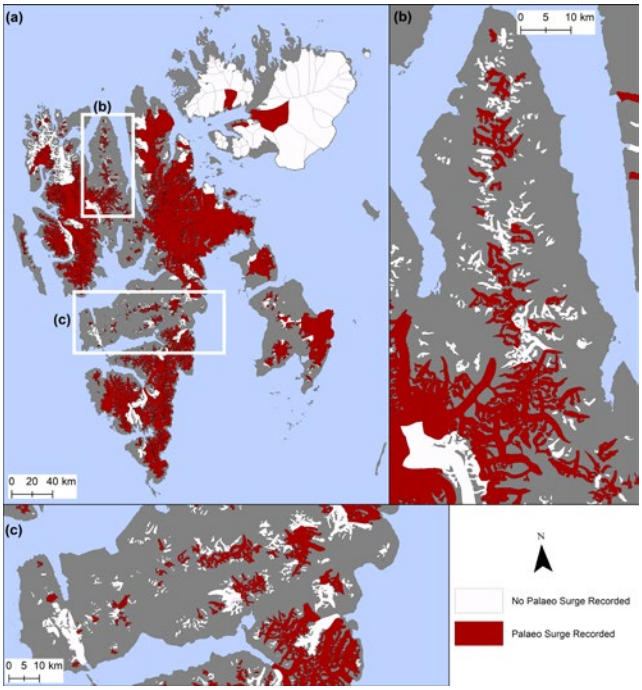

Figure 6: Indirectly observed surges in Svalbard.

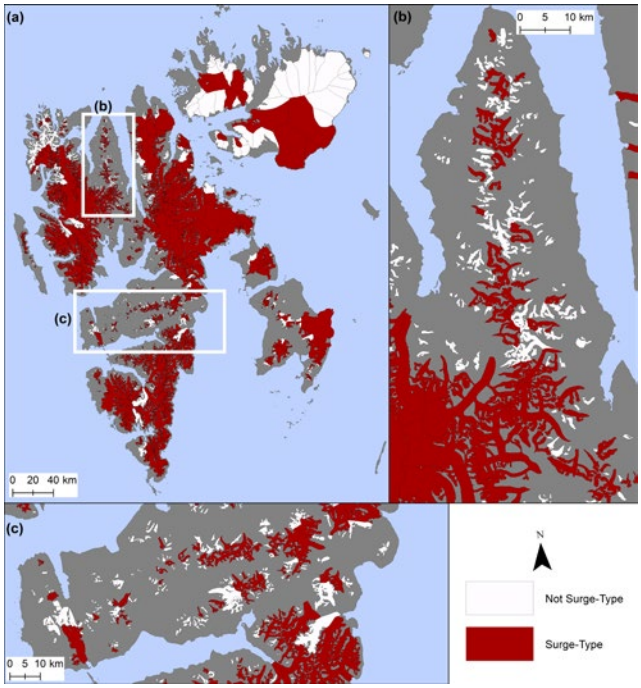

Figure 7: All surge-type glaciers in Svalbard.

archipelago as mapped in Figure 6. Strikingly, many glaciers never previously considered to be surge-type contain CSRs in their foreland, suggesting these glaciers may have quiescent periods towards the longer end of the scale for Svalbard (e.g., over 150 years). This includes glaciers with long-term observational records (e.g., Hansbreen, Kronebreen, Nordenskiöldbreen) which have explicitly been categorised as not surge-type (e.g., Błaszczyk et al. 2021; Kavan et al. 2023). The compiled palaeo-record has documented a total of 520 glaciers with evidence of past surges, representing 32% of all glaciers in Svalbard. This is undoubtedly an underestimate, as Farnsworth et al. (2016) focused on the terrestrial landform record and therefore did not explore marine-terminating glacier forefields, such as several of the outlets of Austfonna, Vestfonna and Kvitøyjøkulen. Furthermore, 70% of the glaciers directly observed to surge, 101 in total, also contained CSRs in their forefield, leaving 42 glaciers with direct evidence for surging with no past evidence for surging in the palaeo-landform record.

5.3. All Observed / Inferred Surges (S_All)

Compiling both the contemporary and palaeo-glaciological databases together, our new estimate of the number of surge-type glaciers in Svalbard is 562, accounting for 36% of the total number of glaciers across the archipelago. If we remove all glaciers with a surface area below 1 km^2, which might be considered a lower limit on an ability for glaciers to surge, 508 glaciers remain in the database which equates to 51%. Through this calculation, approximately half of the glaciers in Svalbard are surge-type. Furthermore, 54 glaciers with a surface area smaller than 1 km^2 were found to be surge-type in the original compilation, suggesting that, despite our initial hypothesis that such glaciers were unlikely to be able to surge, very small glaciers can still surge in Svalbard. This suggests that some of these glaciers, which equate to 987 (62%) of all glaciers in Svalbard, may be undergoing very long quiescence periods and their active surge is yet to be observed, or they have surged in the past but are now unable to because of climate warming and excessive thinning.

Figure 7 shows the spatial distribution of surge-type glaciers across Svalbard. The ice fields in northwest, northeast and south Spitsbergen contain several large catchment glaciers, many of which have exhibited surge behaviour, with only a collection of outlets showing no evidence of past

surge behaviour. Regions with many small valley glaciers (Figure 7b and 7c) generally have fewer surge-type glaciers but this pattern may be due to slower dynamics related to surge behaviour with lower ice fluxes. Surge observations in Vestfonna and Austfonna are limited, most likely due to fewer in situ observations of palaeo-glaciological landforms on the seafloor. We expect that several of the outlets from both ice caps may surge in the future given past surge history (Robinson and Dowdeswell 2011).

5.4. Characteristics of Svalbard Surges

From the directly observed surges in Svalbard analysed in Figure 5, a general pattern emerges. Surge activation is gradual with a slow rise in velocity over a year or two, after which there is a peak, and then a gradual decline back to quiescence. This is further demonstrated in Figure 2, particularly the surges of Negribreen and Wahlenbergbreen. Although not all surges share this characteristic, this general pattern has been observed previously (e.g., Jiskoot et al. 2000; Benn et al. 2022). The velocity pattern of a surge may reveal the internal dynamics that lead to a surge, but the documentation of this is limited to a few well-studied glaciers with dense satellite and in situ observations (e.g., Kongsvegen, Nathorstbreen, Basin-3 in Austfonna). Furthermore, the return period of a surge may range between 40 (e.g., Tunabreen) and 100 years, according to the available literature, but this does not account for slower moving glaciers with smaller ice fluxes. Improved documentation of the start and end of a surge through our new database will improve our understanding of surge dynamics in Svalbard.

The impact of surges on glacier mass balance is poorly documented. A surge of large basins can have large impacts on regional mass balance (Schuler et al. 2020a), such as Basin-3 on Austfonna which led to sudden ice discharge at 7 Gt per year (McMillan et al. 2014; Dunse et al. 2015; Morris et al. 2020). Furthermore, where a surge advances and ice surface elevation lowers due to the transfer of mass from high to low elevation, a greater surface area of the glacier lies below the Equilibrium Line Altitude (ELA), predisposing it to future increased melt and mass loss. Modelling of this process during the Monacobreen surge (1991-1997) suggests mass loss via this mechanism may be small (Oerlemans 2018). Long-term observations are needed to understand the impact of glacier surges on mass balance, but these are severely lacking. Flink et al. (2015) found that the surges of Tunabreen between 1870 and 2005 reached successively less-extensive positions in the fjord, suggesting that mass build-up was smaller during each intervening quiescent period due to a negative mass balance.

6. Contributions to interdisciplinarity

Surges in Svalbard directly link to the wider Earth System in and around Svalbard, particularly the Arctic water cycle which Christiansen et al. (2024) highlighted as a major knowledge gap in Svalbard. However, as highlighted by Schuler et al. (2020a, b), the impact of surges in not well accounted for. For example, the rapid discharge of ice during a surge impacts mass balance (McMillan et al. 2014), can lead to a greater production of icebergs, impacts the amount of snow cover that melts each summer, can also disrupt continuous permafrost, increasing the release of trapped gases such as methane (Smith et al. 2002), and potentially have downstream impacts on marine mammals and seabirds (Lydersen et al. 2014). Glacier surges are therefore central to the cryosphere system that ultimately impacts hydrology (Nowak et al. 2020) and has cascading effects on ecosystems, oceanography, geomorphology (e.g., landslides, delta development) and more. Critically, surges are unpredictable and their impact on the Svalbard environmental system will be detached from the long-term climate signal. Therefore, we require an holistic, interdisciplinary approach to understand the wider importance of surges in Svalbard which necessitates collaborative research across disciplines.

In this chapter, we have reviewed the methods used to detect and monitor surges, highlighting the need to bridge the temporal observational gap between modern-day monitoring using satellite data and geophysics with palaeo-glaciological analysis. The benefit of combining these disciplines has been well illustrated, e.g., understanding the dynamics of multiple surges at Tunabreen (Flink et al. 2015) and the long-term surge history of glaciers in southwest Svalbard (Zagórski et al. 2023). We illustrate the complementary benefit of each method to understand surge characteristics (e.g., satellite EO, palaeo-glaciological analysis) and drivers (e.g., geophysics). In doing so, we show that a complete understanding of glacier surges is only possibly by bringing together glaciologists, geophysicists, satellite EO practitioners and those developing new technology. Co-producing fieldwork plans with those working with satellite data and physical modelling initiatives is critical in generating an holistic view of glacier surges and their impacts on society. In this way, local people can be fully involved in the production of new knowledge which is lacking and requires robust community engagement.

7. Unanswered questions

What are the characteristics of Svalbard glacier surges?

Documented evidence of surging glacier dynamics remains scarce. Therefore, we need to extend our observational record of physical changes during surges (e.g. velocity, terminus position, surface elevation) in order to assess why glaciers in Svalbard surge in the way they do.

How is climate change impacting surge behaviour?

The typically long return periods of surges in Svalbard makes it difficult to assess the impact of climate change on surge dynamics. Whilst there is evidence that some glaciers that have surged in the past are no longer able to surge, the influence of long-term climate change requires further research.

How can we bridge the gap between modern-day sensing and inferences from palaeo-observations?

To acquire a long-term time series of surges we need to bridge the observation gap between palaeo-glaciological inference and satellite-based surge detection. This may be achieved using historical data sets, analysis of glacial geomorphological evidence of surging and archival material from expeditions.

What triggers surges in Svalbard?

Surges result from an interconnected set of processes that occur before it becomes obvious that a surge is underway. Documenting the processes during surge build-up, peak and subsequent decline now and in the past will enable a better understanding of glacier instabilities and the mechanisms leading to unstable ice flow.

What are the long-term impacts of glacier surges on Svalbard mass balance?

We know that surges from large glacier catchments lead to large mass loss over a short period of time, but the long-term impacts are not known given the short time period of detailed observations. Future work should consider how to generate long-term observations to better understand the impacts surges have on glacier mass balance, particularly as climate continues to warm.

8. Recommendations for the future

- We recommend developing a portable "glacier observing system" consisting of geophysical instruments (e.g., seismometers, GPR, ApRES) and GPS sensors that can be rapidly deployed on an active surging glacier to study subglacial conditions and ice dynamics. This new Research Infrastructure (RI), which may be administered by SIOS, should be based in a central location in Svalbard (e.g., Longyearbyen) for rapid accessibility and deployment.
- Initiate systematic cataloguing of fundamental surge behaviour (e.g., surge onset year, surge termination year, terminus change, maximum velocity, mean velocity in quiescence) to better understand surge drivers. This should combine existing monitoring from different research groups and include analysis of satellite imagery, modelling studies, and artificial intelligence methods.
- Generate long-term data sets of Svalbard glacier surges by bridging the gap between palaeo-observations and the contemporary satellite record by developing methods to detect surges in the historical record (e.g., developing a new 1960/61 DEM from available aerial imagery) as well through new satellite observations now and in the future. This will require collaboration across the SIOS consortium and beyond to ensure all necessary expertise is utilised.
- Improve quantification of the impact of surges on mass balance, e.g., combining close-range sensors with satellite observations of surface elevation change. This should also include studying the evolution of a glacier before and after a surge. Integrated field campaigns and combining simultaneous monitoring efforts will be critical in achieving this.
- Improved analysis of the processes that lead to a surge is recommended. In particular, the distinction between events happening after a long succession of internal changes and events happening as the result of some distinct environmental "push".

9. Data availability

Dataset	Parameter	Period	Location	Metadata access (URL)	Dataset provider
ITS_LIVE	- Glacier Velocity	2014-2023	Svalbard Archipelago	https://n5eil01u.ecs.nsidc.org/MEASURES/NSIDC-0776.001/	NSIDC
GLIMS / RGI	- Glacier Extent - Glacier Characteristics	1936-2010	Svalbard Archipelago	https://data.npolar.no/dataset/89f430f8-862f-11e2-8036-005056ad0004	Norwegian Polar Institute (NPI / Global Land and Ice Measurements from Space (GLIMS) / Randolph Glacier Inventory (RGI)

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11. References

Aster RC, Winberry JP (2017) Glacial seismology. Reports on Progress in Physics 80(12):126801. https://doi.org/10.1088/1361-6633/aa8473

Bælum K, Benn DI (2011) Thermal structure and drainage system of a small valley glacier (Tellbreen, Svalbard), investigated by ground penetrating radar. The Cryosphere 5(1):139-149. https://doi.org/10.5194/tc-5-139-2011

Barrett BE, Murray T, Clark R, Matsuoka K (2008) Distribution and character of water in a surge-type glacier revealed by multifrequency and multipolarization ground-penetrating radar. Journal of Geophysical Research: Earth Surface 113(F4). https://doi.org/10.1029/2007JF000972

Barzycka B, Błaszczyk M, Grabiec M, Jania J (2019) Glacier facies of Vestfonna (Svalbard) based on SAR images and GPR measurements. Remote Sensing of Environment 221:373-385. https://doi.org/10.1016/j.rse.2018.11.020

Barzycka B, Grabiec M, Błaszczyk M, Ignatiuk D, Laska M, Hagen JO, Jania J (2020) Changes of glacier facies on Hornsund glaciers (Svalbard) during the decade 2007-2017. Remote Sensing of Environment 251:1-22. https://doi.org/10.1016/j.rse.2020.112060

Ben-Yehoshua D, Aradóttir N, Farnsworth WR, Benediktsson ÍÖ, Ingólfsson Ó (2023) Formation of crevasse-squeeze ridges at Trygghamma, Svalbard. Earth Surface Processes and Landforms 48:2334-2348. https://doi.org/10.1002/esp.5631

Benn DI, Fowler AC, Hewitt I, Sevestre H (2019a) A general theory of glacier surges. Journal of Glaciology 65:701-716. https://doi.org/10.1017/jog.2019.62

Benn DI, Jones RL, Luckman A, Fürst JJ, Hewitt I, Sommer C (2019b) Mass and enthalpy budget evolution during the surge of a polythermal glacier: A test of theory. Journal of Glaciology 65:717-731. https://doi.org/10.1017/jog.2019.63

Benn DI, Hewitt IJ, Luckman AJ (2022) Enthalpy balance theory unifies diverse glacier surge behaviour. Annals of Glaciology 63:88-94. https://doi.org/10.1017/aog.2023.23

Bennett MR, Hambrey MJ, Huddart D, Ghienne JF (1996) The formation of a geometrical ridge network by the surge-type glacier Kongsvegen, Svalbard. Journal of Quaternary Science: Published for the Quaternary Research Association, 11(6):437-449. https://doi.org/10.1002/(SICI)1099-1417(199611/12)11:6<437::AID-JQS269>3.0.CO;2-J

Błaszczyk M, Jania JA, Ciepły M, Grabiec M, Ignatiuk D, Kolondra L, Kruss A, Luks B, Moskalik M, Pastusiak T, Strzelewicz A, Walczowski W, Wawrzyniak T (2021) Factors controlling terminus position of Hansbreen, a tidewater glacier in Svalbard. Journal of Geophysical Research: Earth Surface 126:1-20. https://doi.org/10.1029/2020JF005763

Bouchayer C, Aiken JM, Thøgersen K, Renard F, Schuler TV (2022) A machine learning framework to automate the classification of surge-type glaciers in Svalbard. Journal of Geophysical Research: Earth Surface 127:1-26. https://doi.org/10.1029/2022JF006597

Bouchayer C, Nanni U, Lefeuvre P-M, Hult J, Schmidt LS, Kohler J, Renard F, Schuler TV (2024) Multi-scale variations of subglacial hydro-mechanical conditions at Kongsvegen glacier, Svalbard. Cryosphere 18:2939-2968. https://doi.org/10.5194/tc-18-2939-2024

Boulton GS, Van Der Meer JJM, Hart J, Beets D, Ruegg GHJ, Van Der Wateren FM, Jarvis J (1996) Till and moraine emplacement in a deforming bed surge – An example from a marine environment. Quaternary Science Reviews 15:961-987. https://doi.org/10.1016/0277-3791(95)00091-7

Church G, Bauder A, Grab M, Rabenstein L, Singh S, Maurer H (2019) Detecting and characterising an englacial conduit network within a temperate Swiss glacier using active seismic, ground penetrating radar and borehole analysis. Annals of Glaciology 60(79):193-205. https://doi.org/10.1017/aog.2019.19

Christoffersen P, Piotrowski JA, Larsen NK (2005) Basal processes beneath an Arctic glacier and their geomorphic imprint after a surge, Elisebreen, Svalbard. Quaternary Research 64(2):125-137. https://doi.org/10.1016/j.yqres.2005.05.009

Conway WM (1897) The First Crossing of Spitsbergen. London : J.M. Dent & Co.; New York: C. Scribner's Sons.

Croot DG (1988) Glaciotectonics and surging glaciers: a correlation based on Vestspitsbergen, Svalbard, Norway. In: Croot DG (ed) Glaciotectonics: forms and processes. Balkema, Amsterdam, pp 49–62

Dachauer A, Hann R, Hodson AJ (2021) Aerodynamic roughness length of crevassed tidewater glaciers from UAV mapping. Cryosphere 15:5513-5528. https://doi.org/10.5194/tc-15-5513-2021

Dowdeswell JA, Collin RL (1990) Fast-flowing outlet glaciers on Svalbard ice caps. Geology 18:778-781. https://doi.org/10.1130/0091-7613(1990)018%3C0778:FFOGOS%3E2.3.CO;2

Dunse T, Schuler TV, Hagen JO, Eiken T, Brandt O, Høgda KA (2009) Recent fluctuations in the extent of the firn area of Austfonna, Svalbard, inferred from GPR. Annals of Glaciology 50(50):155-162. https://doi.org/10.3189/172756409787769780

Dunse T, Schuler TV, Hagen JO, Reijmer CH (2012) Seasonal speed-up of two outlet glaciers of Austfonna, Svalbard, inferred from continuous GPS measurements. Cryosphere 6:453-466. https://doi.org/10.5194/tc-6-453-2012

Dunse T, Schellenberger T, Hagen JO, Kääb A, Schuler TV, Reijmer CH (2015) Glacier-surge mechanisms promoted by a hydro-thermodynamic feedback to summer melt. The Cryosphere 9(1):197-215. https://doi.org/10.5194/tc-9-197-2015

Eiken T, Hagen JO, Melvold K (1997) Kinematic GPS survey of geometry changes on Svalbard glaciers. Annals of Glaciology 24:157-163. https://doi.org/10.3189/S0260305500012106

Evans DJA, Rea BR (1999) Geomorphology and sedimentology of surging glaciers: A land-systems approach. Annals of Glaciology 28:75-82. https://doi.org/10.3189/172756499781821823

Evans D (2003) Surging glacier. In S. Goudie (Ed.), Encyclopeida of Geomorphology (1028-1029) Routledge

Evans DJA, Ewertowski M, Roberts DH, Tomczyk AM (2022) The historical emergence of a geometric and sinuous ridge network at the Hørbyebreen polythermal glacier snout, Svalbard and its use in the interpretation of ancient glacial landforms. Geomorphology 406:1-22. https://doi.org/10.1016/j.geomorph.2022.108213

Farnsworth WR, Ingólfsson Ó, Retelle M, Schomacker A (2016) Over 400 previously undocumented Svalbard surge-type glaciers identified. Geomorphology 264:52-60. https://doi.org/10.1016/j.geomorph.2016.03.025

Flink AE, Noormets R, Kirchner N, Benn DI, Luckman A, Lovell H (2015) The evolution of a submarine landform record following recent and multiple surges of Tunabreen glacier, Svalbard. Quat Sci Rev 108:37-50. https://doi.org/10.1016/j.quascirev.2014.11.006

Flink AE, Hill P, Noormets R, Kirchner N (2018) Holocene glacial evolution of Mohnbukta in eastern Spitsbergen. Boreas 47:390-409. https://doi.org/10.1111/bor.12277

Friedl P, Seehaus T, Braun M (2021) Global time series and temporal mosaics of glacier surface velocities derived from Sentinel-1 data. Earth Syst Sci Data 13:4653-4675. https://doi.org/10.5194/essd-13-4653-2021

Gajek W, Trojanowski J, Malinowski M (2017) Automating long-term glacier dynamics monitoring using single-station seismological observations and fuzzy logic classification: a case study from Spitsbergen. Journal of Glaciology 63(240):581-592. https://doi.org/10.1017/jog.2017.25

Gajek W, Gräff D, Hellmann S, Rempel AW, Walter F (2021) Diurnal expansion and contraction of englacial fracture networks revealed by seismic shear wave splitting. Communications Earth & Environment 2(1):209. https://doi.org/10.1038/s43247-021-00279-4

Garwood EJ. Gregory JW (1898) Contributions to the Glacial Geology of Spitsbergen. Quarterly Journal of the Geological Society 54(1-4):197–227. https://doi.org/10.1144/GSL.JGS.1898.054.01-04.18

Geyman EC, van Pelt WJJ, Maloof AC, Aas HF, Kohler J (2022) Historical glacier change on Svalbard predicts doubling of mass loss by 2100. Nature 601:374-379. https://doi.org/10.1038/s41586-021-04314-4

Gillet-Chaulet F, Hindmarsh RC, Corr HF, King EC, Jenkins A (2011) In-situ quantification of ice rheology and direct measurement of the Raymond Effect at Summit, Greenland using a phase-sensitive radar. Geophysical Research Letters 38(24). https://doi.org/10.1029/2011GL049843

Glasser NF, Coulson SJ, Hodkinson ID, Webb NR (2004) Photographic evidence of the return period of a Svalbard surge-type glacier: A tributary of Pedersenbreen, Kongsfjord. Journal of Glaciology 50:307-308. https://doi.org/10.3189/172756504781830060

Glowacki O, Moskalik M, Deane GB (2016): The impact of glacier meltwater on the underwater noise field in a glacial bay. J Geophys Res Oceans 121(12):8455–8470. https://doi.org/10.1002/2016JC012355

Glowacki O, Deane GB (2020) Quantifying iceberg calving fluxes with underwater noise. The Cryosphere 14:1025–1042. https://doi.org/10.5194/tc-14-1025-2020

Gräff D, Walter F (2021) Changing friction at the base of an Alpine glacier. Scientific reports, 11(1), 10872. https://doi.org/10.1038/s41598-021-90176-9

Gregory JW, Garwood M, Trevor-Battye M (1897) The First Crossing of Spitsbergen: Discussion. The Geographical Journal, 9(4):365–368

Gripp K (1929) Glaciologische und geologische Ergebnisse der Hamburgischen Spitzbergen-Expedition 1927. Abhandlungen aus dem Gebiete der Naturwissenschaften 22(3/4):145-249

Haga ON, McNabb R, Nuth C, Altena B, Schellenberger T, Kääb A (2020) From high friction zone to frontal collapse: Dynamics of an ongoing tidewater glacier surge, Negribreen, Svalbard. J Glaciol 66:742-754. https://doi.org/10.1017/jog.2020.43

Hagen JO, Liestøl O, Roland E, Jørgensen T (1993) Glacier Atlas of Svalbard and Jan Mayen, Norwegian Polar Institute, Oslo, Norway.

Hagen JO, Eiken T, Kohler J, Melvold K (2005) Geometry changes on Svalbard glaciers: Mass-balance or dynamic response. Annals of Glaciology 42:255-261. https://doi.org/10.3189/172756405781812763

Hamberg A (1894) En resa till norra Ishafvet sommaren 1892. Ymer 14:25-61

Hamilton GS, Dowdeswell JA (1996) Controls on glacier surging in Svalbard. Journal of Glaciology 42:157-168. https://doi.org/10.3189/S0022143000030616

Hann R, Betlem P, Deja K, Ewertowski M, Harm-Altstädter B, Jonassen M, Lampert A, Laska M, Sobota I, Storvold R, Tomczyk A, Zagorski P (2023) Practical Guidelines for Scientific Application of Uncrewed Aerial Vehicles in Svalbard (UAV Svalbard 3). In: Gevers et al (eds) SESS report 2022, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 142-152. https://doi.org/10.5281/zenodo.7371141

Harcourt WD, Gajek W, Pearce D, Hann R, Luckman A, Rea BR, Benn DI, James MR, Spagnolo M, Nanni U (2024a) Surge initiation at the terminus of Borebreen (Svalbard): Drivers and impact on calving. EGU General Assembly 2024, Vienna, Austria. https://doi.org/10.5194/egusphere-egu24-1505

Hodgkins R, Fox A, Nuttall A-M (2007) Geometry change between 1990 and 2003 at Finsterwalderbreen, a Svalbard surge-type glacier, from GPS profiling. Annals of Glaciology 46:131-135. https://doi.org/10.3189/172756407782871189

Hodson T, Gooch DL, Stuart GW (1997) Structures within the surge front at Bakaninbreen, Svalbard, using ground-penetrating radar. Annals of Glaciology 24:122-129. https://doi.org/10.3189/S0260305500012040

Hoel A (1914) Exploration du Nord-ouest Spitsbergen entreprise sous les auspices de S.A.S. le Prince de Monaco par la Mission Isachsen. Troisieme partie. Resultats des campagnes scientifiques accomplies sur son yacht par le Prince Souverain de Monaco, farc. XLII, 1-160

Howe JA, Husum K, Inall ME, Coogan J, Luckman A, Arosio R, Abernethy C, Verchili D (2019) Autonomous underwater vehicle (AUV) observations of recent tidewater glacier retreat, western Svalbard. Marine Geology 417:1-17. https://doi.org/10.1016/j.margeo.2019.106009

Hudson TS, Baird AF, Kendall JM, Kufner SK, Brisbourne AM, Smith AM, Butcher A, Chalari A, Clarke A (2021) Distributed Acoustic Sensing (DAS) for natural microseismicity studies: A case study from Antarctica. Journal of Geophysical Research: Solid Earth 126(7):e2020JB021493. https://doi.org/10.1029/2020JB021493

Ignatiuk D, Dunse T, Gallet J-C, Girod L, Grabiec M, Kępski D, Kohler J, Laska M, Luks B, van Pelt W, Pettersson R, Pohjola V, Schuler TV (2022) Ground penetrating radar measurement of snow in Svalbard – past, present, future (SnowGPR). In: Gevers, M. et al. (eds). SESS Report 2022, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 116-141. https://doi.org/10.5281/zenodo.7371725

Jakob L, Gourmelen N (2023) Glacier mass loss between 2010 and 2020 dominated by atmospheric forcing. Geophysical Research Letters 50:1-10. https://doi.org/10.1029/2023GL102954

Jiskoot H, Boyle P, Murray T (1998) The incidence of glacier surging in Svalbard: Evidence from multivariate statistics. Computers and Geoscience 24:387-399. https://doi.org/10.1016/S0098-3004(98)00033-8

Jiskoot H, Murray T, Boyle P (2000) Controls on the distribution of surge-type glaciers in Svalbard. Journal of Glaciology 46:412-422. https://doi.org/10.3189/172756500781833115

Kääb A, Bazilova V, Leclercq PW, Mannerfelt ES, Strozzi T (2023) Global clustering of recent glacier surges from radar backscatter data, 2017-2022. Journal of Glaciology 69:1515-1523. https://doi.org/10.1017/jog.2023.35

Karušs J, Lamsters K, Ješkins J, Sobota I, Džeriņš P (2022) UAV and GPR data integration in glacier geometry reconstruction: a case study from Irenebreen, Svalbard. Remote Sensing 14(3):456. https://doi.org/10.3390/rs14030456

Kavan J, Tallentire GD, Demidionov M, Dudek J, Strzelecki MC (2022) Fifty years of tidewater glacier surface elevation and retreat dynamics along the south-east coast of Spitsbergen (Svalbard Archipelago). Remote Sensing 13:1-16. https://doi.org/10.3390/rs14020354

Kavan J, Luláková P, Małecki J, Strzelecki C (2023) Capturing the transition from marine to land-terminating glacier from the 126-year retreat history of Nordenskiöldbreen, Svalbard. Journal of Glaciology 1-11. https://doi.org/10.1017/jog.2023.92

King O, Hambrey MJ, Irvine-Flynn TDL, Holt TO (2016) The structural, geometric and volumetric changes of a polythermal Arctic glacier during a surge cycle: Comfortlessbreen, Svalbard. Earth Surface Processes and Landforms 41:162-177. https://doi.org/10.1002/esp.3796

Kingslake J, Hindmarsh RC, Aðalgeirsdóttir G, Conway H, Corr HF, Gillet-Chaulet F, Martín C, King EC, Mulvaney R, Pritchard HD (2014) Full-depth englacial vertical ice sheet velocities measured using phase-sensitive radar. Journal of Geophysical Research: Earth Surface 119(12):2604-2618. https://doi.org/10.1002/2014JF003275

Koch M, Seehaus T, Friedl P, Braun M (2023) Automated detection of glacier surges from Sentinel-1 surface velocity time series – An example from Svalbard. Remote Sensing 15:1-16. https://doi.org/10.3390/rs15061545

Köhler A, Nuth C, Schweitzer J, Weidle C, Gibbons SJ (2015) Regional passive seismic monitoring reveals dynamic glacier activity on Spitsbergen, Svalbard. Polar Research 34(1):26178. https://doi.org/10.3402/polar.v34.26178

Köhler A, Nuth N, Kohler J, Berthier B, Weidle C, Schweitzer J (2016) A 15 year record of frontal glacier ablation rates estimated from seismic data. Geophysical Research Letters 43(23): 12,555-12,164. https://doi.org/10.1002/2016GL070589

Köhler A, Pętlicki M, Lefeuvre P-M, Buscaino G, Nuth C, Weidle C (2019) Contribution of calving to frontal ablation quantified from seismic and hydroacoustic observations calibrated with lidar volume measurements. Cryosphere 13:3117-3137. https://doi.org/10.5194/tc-13-3117-2019

Köhler A, Gajek W, Malinowski M, Schweitzer J, Majdanski M, Geissler WH, ... & Wuestefeld, A (2020) Seismological monitoring of Svalbard's cryosphere: current status and knowledge gaps (CRYOSEIS) In: Van den Heuvel et al (eds) SESS report 2019, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 137-15. https://doi.org/10.5281/zenodo.4704584

Kristensen L, Benn DI (2012) A surge of the glaciers Skobreen-Paulabreen, Svalbard, observed by time-lapse photographs and remote sensing data. Polar Research 31:1-9. https://doi.org/10.3402/polar.v31i0.11106

Leclercq PW, Kääb A, Altena B (2021) Brief communication: Detection of glacier surge activity using cloud computing of Sentinel-1 radar data. Cryosphere 15:4901-4907. https://doi.org/10.5194/tc-15-4901-2021

Lefauconnier B, Hagen JO (1991) Surging and calving glaciers in eastern Svalbard, Norsk Polarinstitutt, Meddelelser NR. 116

Lei Y, Gardner AS, Agram P (2022) Processing methodology for the ITS_LIVE Sentinel-1 ice velocity products. Earth System Science Data 14:5111-5137. https://doi.org/10.5194/essd-14-5111-2022

Lewandowska H, Teisseyre R (1964) Investigations of the ice microtremors on Spitsbergen in 1962. Biul Inf Komisji Wypraw Geof PAN 37:1-5

Li T, Heidler K, Mou L, Ignéczi Á, Zhu XX, Bamber JL (2024) A high-resolution calving front data product for marine-terminating glaciers in Svalbard. Earth System Science Data

16:919-939. https://doi.org/10.5194/essd-16-919-2024

Lok LB, Brennan PV, Nicholls KW, Corr HF (2014) ApRES: Autonomous phase-sensitive FMCW radar, for basal monitoring and imaging of Antarctic ice shelves. IET Colloquium on Antennas, Wireless and Electromagnetics. https://doi.org/10.1049/ic.2014.0019

Lovell H, Fleming EJ, Benn DI, Hubbard B, Lukas S, Rea BR, Noormets R, Flink AE (2015) Debris entrainment and landform genesis during tidewater glacier surges. Journal of Geophysical Research: Earth Surface 120:1574-1595. https://doi.org/10.1002/2015JF003509

Lovell H, Boston CM (2017) Glacitectonic composite ridge systems and surge-type glaciers: An updated correlation based on Svalbard, Norway. Arktos 3:1-16. https://doi.org/10.1007/s41063-017-0028-5

Lovell H, Benn DI, Lukas S, Spagnolo M, Cook SJ, Swift DA, Clark CD, Yde JC, Watts T (2018a) Geomorphological investigation of multiphase glacitectonic composite ridge systems in Svalbard. Geomorphology 300:176-188. https://doi.org/10.1016/j.geomorph.2017.10.024

Lovell H, Benn DI, Lukas S, Ottesen D, Luckman A, Hardiman M, Barr ID, Bosotn CM, Sevestre H (2018b) Multiple late Holocene surges of a high-Arctic tidewater glacier system in Svalbard. Quaternary Science Reviews 201:162-185. https://doi.org/10.1016/j.quascirev.2018.10.024

Luckman A, Benn DI, Cottier F, Bevan S, Nilsen F, Inall M (2015) Calving rates at tidewater glaciers vary strongly with ocean temperature. Nature Communications 8566_1-7. https://doi.org/10.1038/ncomms9566

Łupikasza WB, Ignatiuk D, Grabiec M, Cielecka-Nowak K, Laska M, Jania J, Luks B, Uszczyk A, Budzik T (2019) The role of winter rain in the glacial system on Svalbard. Water 11:1-20. https://doi.org/10.3390/w11020334

Lydersen C, Assmy P, Falk-Petersen S, Kohler J, Kovacs KM, Reigstad M, Steen H, Strøm H, Sundfjord A, Varpse Ø, Walczowski W, Weslawski JM, Zajaczkowski M (2014) The importance of tidewater glaciers for marine mammals and seabirds in Svalbard, Norway. Journal of Marine Systems 129:452-471. https://doi.org/10.1016/j.marsys.2013.09.006

Mannerfelt ES, Hodson AJ, Håkansson L, Lovell H (2024). Dynamic LIA advances hastened the demise of small valley glaciers in central Svalbard. Arctic Science, https://doi.org/10.1139/as-2024-0024

Mansell D, Luckman A, Murray T (2012) Dynamics of tidewater surge-type glaciers in northwest Svalbard. Journal of Glaciology 58:110-118. https://doi.org/10.3189/2012JoG11J058

McCerery R, Davies BJ, Lovell H, Pearce DA, Calvo-Ryan R, Małecki J, Woodward J (2024) Terrestrial glacial geomorphology of surge-type and non-surge-type glaciers on Svalbard. Journal of Maps 20:1-14. https://doi.org/10.1080/17445647.2024.2362277

McMillan M, Shepherd A, Gourmelen N, Dehecq A, Leeson A, Ridout A, Flament T, Hogg A, Gilbert L, Benham T, van den Broeke M, Dowdeswell JA, Fettweis X, Noël B, Strozzi T (2014) Rapid dynamic activation of a marine-based Arctic ice cap. Geophys Res Lett 41:8902-8909. https://doi.org/10.1002/2014GL062255

Melvold K, Hagen JO (1998) Evolution of a surge-type glacier in its quiescent phase: Kongsvegen, Spitsbergen, 1964-95. Journal of Glaciology 44:394-404. https://doi.org/10.3189/S0022143000002720

Mikesell TD, van Wijk K, Haney MM, Bradford JH, Marshall HP, Harper JT (2012) Monitoring glacier surface seismicity in time and space using Rayleigh waves. Journal of Geophysical Research: Earth Surface 117(F2). https://doi.org/10.1029/2011JF002259

Morris A, Moholdt G, Gray L (2020) Spread of Svalbard glacier mass loss to Barents Sea margins revealed by CryoSat-2. Journal of Geophysical Research: Earth Surface 125:1-20. https://doi.org/10.1029/2019JF005357

Murray T, Stuart GW, Miller PJ, Woodward J, Smith AM, Porter PR, Jiskoot H (2000) Glacier surge propagation by thermal evolution at the bed. Journal of Geophysical Research: Solid Earth 105(B6):13491-13507. https://doi.org/10.1029/2000JB900066

Murray T, Luckman A, Strozzi T, Nuttall A-M (2003) The initiation of glacier surging at Fridtjovbreen, Svalbard. Annals of Glaciology 36:110-116. https://doi.org/10.3189/172756403781816275

Murray T, James TD, Macheret Y, Lavrentiev I, Glazovsky A, Sykes H (2012) Geometric changes in a tidewater glacier in Svalbard during its surge cycle. Arctic, Antarctic, and Alpine Research 44:359-367. https://doi.org/10.1657/1938-4246-44.3.359

Nanni U, Gimbert F, Vincent C, Gräff D, Walter F, Piard L, Moreau L (2020) Quantification of seasonal and diurnal dynamics of subglacial channels using seismic observations on an Alpine glacier. The Cryosphere 14(5):1475-1496. https://doi.org/10.5194/tc-14-1475-2020

Navarro FJ, Martín-Español A, Lapazaran JJ, Grabiec M, Otero J, Vasilenko EV, Puczko D (2014) Ice volume estimates from ground-penetrating radar surveys, Wedel Jarlsberg Land glaciers, Svalbard. Arctic, Antarctic, and Alpine Research 46(2):394-406. https://doi.org/10.1657/1938-4246-46.2.394

Navarro FJ, Lapazaran J, Martín-Espanol A, Otero, J (2016) Ground-penetrating radar studies in Svalbard aimed to the calculation of the ice volume of its glaciers. Cuadernos de Investigación Geográfica 42:399-314. https://doi.org/10.18172/cig.2929

Nowak A, Hodgkins R, Nikulina A, Osuch M, Wawrzyniak W, Kavan J, Łepkowska E, Majerska M, Romashova K, Vasilevich I, Sobota I, Rachlewicz G (2021) In: Morine-Ibánez et al. (eds). SESS Report 2020, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 176-201. https://doi.org/10.5281/zenodo.4294063

Nuth C, Moholdt G, Kohler J, Hagen JO, Kääb A (2010) Svalbard glacier elevation changes and contribution to sea level rise. J Geophys Res 115:F01008. https://doi.

org/10.1029/2008JF001223

Nuth C, Gilbert A, Köhler A, McNabb R, Schellenberger T, Sevestre H, Weidle C, Girod L, Luckman A, Kääb A (2019) Dynamic vulnerability revealed in the collapse of an Arctic tidewater glacier. Scientific Reports 9:1-13. https://doi.org/10.1038/s41598-019-41117-0

Nuttall A-M, Hagen JO, Dowdeswell J (1997) Quiescent-phase changes in velocity and geometry of Finsterwalderbreen, a surge-type glacier in Svalbard. Annals of Glaciology 24:249-254. https://doi.org/10.3189/S0260305500012258

Oerlemans J (2018) Modelling the late Holocene and future evolution of Monacobreen, northern Spitsbergen. Cryosphere 12:3001-3015. https://doi.org/10.5194/tc-12-3001-2018

Ottesen D, Dowdeswell JA (2006) Assemblages of submarine landforms produced by tidewater glaciers in Svalbard. Journal of Geophysical Research: Earth Surface 11:1-16. https://doi.org/10.1029/2005JF000330

Ottesen D, Dowdeswell JA, Benn DI, Kristensen L, Christiansen HH, Christensen O, Hansen L, Lebesbye E, Forwick M, Vorren TO (2008) Submarine landforms characteristic of glacier surges in two Spitsbergen fjords. Quaternary Science Reviews 27:1583-1599. https://doi.org/10.1016/j.quascirev.2008.05.007

Pętlicki M, Ciepły M, Jania JA, Promińska A, Kinnard C (2015) Calving of a tidewater glacier driven by melting at the waterline. Journal of Glaciology 61(229):851-863. https://doi.org/10.3189/2015JoG15J062

Podolskiy EA, Walter F (2016) Cryoseismology. Reviews of Geophysics 54(4):708-758. https://doi.org/10.1002/2016RG000526

Podolskiy EA, Sugiyama S (2020) Soundscape of a narwhal summering ground in a glacier fjord (Inglefield Bredning, Greenland). Journal of Geophysical Research: Oceans 125:e2020JC016116. https://doi.org/10.1029/2020JC016116

Podolskiy EA, Murai Y, Kanna N, Sugiyama S (2021) Ocean-bottom and surface seismometers reveal continuous glacial tremor and slip. Nature communications 12(1):3929. https://doi.org/10.1038/s41467-021-24142-4

Rea BR, Evans DJA (2011) An assessment of surge-induced crevassing and the formation of crevasse squeeze ridges, Journal of Geophysical Research: Earth Surface, 16, 1-17. https://doi.org/10.1029/2011JF001970

RGI 7.0 Consortium (2023) Randolph Glacier Inventory - A Dataset of Global Glacier Outlines, Version 7.0. Boulder, Colorado USA. NSIDC: National Snow and Ice Data Center. doi:10.5067/f6jmovy5navz. Online access: https://doi.org/10.5067/f6jmovy5navz

Robsinson P, Dowdeswell JA (2011) Submarine landforms and the behavior of a surging ice cap since the last glacial maximum: The open-marine setting of eastern Austfonna, Svalbard. Marine Geology 286:82-94. https://doi.org/10.1016/j.margeo.2011.06.004

Rolstad C, Amlien J, Hagen JO, Lundén B (1997) Visible and near-infrared digital images for determination of ice velocities and surface elevation during a surge on Osbornebreen, a tidewater glacier in Svalbard. Ann Glaciol 24:255-261. https://doi.org/10.3189/S026030550001226X

Röthlisberg H (1955) Studies in glacier physics on the Penny Ice Cap, Baffin Island, 1953: Part III: seismic sounding. Journal of Glaciology 2(18):539-552. https://doi.org/10.3189/002214355793702064

Saintenoy A, Friedt JM, Booth AD, Tolle F, Bernard E, Laffly D, Marlin C, Griselin M (2013) Deriving Ice Thickness, Glacier Volume and Bedrock Morphology of Austre Lovénbreen (Svalbard) Using GPR. Near Surf Geophys 11:253–262. https://doi.org/10.3997/1873-0604.2012040

Schomacker A, Kjær KH (2008) Quantification of dead-ice melting in ice-cored moraines at the high-Arctic glacier Holmströmbreen, Svalbard. Boreas 37:211-225. https://doi.org/10.1111/j.1502-3885.2007.00014.x

Schuler TV, Glazovsky A, Hagen JO, Hodson A, Jania J, Kääb A, Kohler J, Luks B, Małecki J, Moholdt G, Pohjola V, Van Pelt W (2020a) New data, new techniques and new challenges for updating the state of Svalbard glaciers (SvalGlac). In: Van den Heuvel et al (eds) SESS report 2019, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 108-134 https://doi.org/10.5281/zenodo.4704584

Schuler TV, Kohler J, Elagina N, Hagen JOM, Hodson AJ, Jania JA, Kääb AM, Luks B, Małecki J, Moholdt G, Pohjola VA, Sobota I, van Pelt WJJ (2020b) Reconciling Svalbard glacier mass balance. Front Earth Sci 8:1-16. https://doi.org/10.3389/feart.2020.00156

Sevestre H, Benn DI (2015) Climatic and geometric controls on the global distribution of surge-type glaciers: Implications for a unifying model of surging. Journal of Glaciology 61:646-662. https://doi.org/10.3189/2015JoG14J136

Sevestre H, Benn DI, Hulton NRJ, Bælum K (2015) Thermal structure of Svalbard glaciers and implications for thermal switch models of glacier surging. Journal of Geophysical Research: Earth Surface 120:2220-2236. https://doi.org/10.1002/2015JF003517

Sevestre H, Benn DI, Luckman A, Nuth C, Kohler J, Lindbäck K, Pettersson R (2018) Tidewater glacier surges initiated at the terminus. Journal of Geophysical Research: Earth Surface 123:1035-1051. https://doi.org/10.1029/2017JF004358

Smith AM, Murray T, Davison BM, Clough AF, Woodward J, Jiskoot H (2002) Late surge glacial conditions on Bakaninbreen, Svalbard, and implications for surge termination. Journal of Geophysical Research: Solid Earth 107(B8):ESE-1. https://doi.org/10.1029/2001JB000475

Smith MW, Carrivick JL, Quincey DJ (2016) Structure from motion photogrammetry in physical geography. Progress in physical geography 40(2):247-275. https://doi.org/10.1177/0309133316158

Sochor L, Seehaus T, Braun MH (2021) Increased ice thinning over Svalbard measured by ICESat/ICESat-2 laser altimetry. Remote Sensing 13:1-19. https://doi.org/10.3390/rs13112089

Streuff K, Forwick M, Szczuciński W, Andreassen K, Ó Cofaigh C (2015) Submarine landform assemblages and sedimentary processes related to glacier surging in Kongsfjorden, Svalbard. Arktos 1:1-14. https://doi.org/10.1007/s41063-015-0003-y

Strozzi T, Paul F, Wiesmann A, Schellenberger T, Kääb A (2017) Circum-Arctic changes in the flow of glaciers and ice caps from satellite SAR data between the 1990s and 2017. Remote Sensing 9:1-21. https://doi.org/10.3390/rs9090947

Stuart G, Murray T, Brisbourne A, Styles P, Toon S (2005) Seismic emissions from a surging glacier: Bakaninbreen, Svalbard. Annals of Glaciology 42:151-157. https://doi.org/10.3189/172756405781812538

Sund M, Eiken T, Hagen JO, Kääb A (2009) Svalbard surge dynamics derived from geometric changes. Annals of Glaciology 50:50-60. https://doi.org/10.3189/172756409789624265

Sund M, Eiken T (2010) Recent surges on Blomstrandbreen, Comfortlessbreen and Nathorstbreen, Svalbard. Journal of Glaciology 56:182-184. https://doi.org/10.3189/002214310791190910

Sund M, Lauknes TR, Eiken T (2014) Surge dynamics in the Nathorstbreen glacier system, Svalbard. Cryosphere 8:623-638. https://doi.org/10.5194/tc-8-623-2014

Terleth Y, van Pelt WJJ, Pohjola VA, Pettersson R (2021) Complementary approaches towards a universal model of glacier surges. Frontiers in Earth Science 9:1-6. https://doi.org/10.3389/feart.2021.732962

Thøgersen K, Gilbert A, Schuler TV, Malthe-Sørenssen A (2019) Rate-and-state friction explains glacier surge propagation. Nature Communications 10:1-8. https://doi.org/10.1038/s41467-019-10506-4

Vallot D, Adinugroho S, Strand R, How P, Pettersson R, Benn DI, Hulton NR (2019) Automatic detection of calving events from time-lapse imagery at Tunabreen, Svalbard. Geoscientific Instrumentation, Methods and Data Systems 8:113-127. https://doi.org/10.5194/gi-8-113-2019

Walter F, Roux P, Roeoesli C, Lecointre A, Kilb D, Roux PF (2015) Using glacier seismicity for phase velocity measurements and Green's function retrieval. Geophysical Journal International 201(3):1722-1737. https://doi.org/10.1093/gji/ggv069

Walter F, Gräff D, Lindner F, Paitz P, Köpfli M, Chmiel M, Fichtner A (2020) Distributed acoustic sensing of microseismic sources and wave propagation in glaciated terrain. Nature Communications 11(1):2436. https://doi.org/10.1038/s41467-020-15824-6

Woodward J, Murray T, McCaig A (2022) Formation and reorientation of structure in the surge-type glacier Kongsvegen, Svalbard. Journal of Quaternary Science 17:201-209. https://doi.org/10.1002/jqs.673

Woodward J, Murray T, McCaig A (2023a) Reply: Formation and reorientation of structure in the surge-type glacier Kongsvegen, Svalbard. Journal of Quaternary Science 18:99-100. https://doi.org/10.1002/jqs.736

Woodward J, Murray T, Clark RA, Stuart GW (2003b) Glacier surge mechanisms inferred from ground-penetrating radar: Kongsvegen, Svalbard. Journal of Glaciology 49(167):473-480. https://doi.org/10.3189/172756503781830458

Zagórski P, Frydrych K, Jania J, Błaszczyk M, Sund M, Moskalik M (2023) Surges in three Svalbard glaciers derived from historic sources and geomorphic features. Annals of the American Association of Geographers 113:1835-1855. https://doi.org/10.1080/24694452.2023.2200487

Zhan, Z. (2019) Seismic noise interferometry reveals transverse drainage configuration beneath the surging Bering Glacier. Geophysical Research Letters, 46(9), 4747-4756. https://doi.org/10.1029/2019GL082411

Appendix 1: Database Structure

We have developed a new database of surge-type glaciers in Svalbard by combining existing compilations and reviewing studies examining their dynamics (Harcourt et al., 2024b[2]). Through this literature review, we have documented (if known) the following characteristics for each glacier in Svalbard:

- Surge Status (Yes / No) [S_all]
- Surge Onset (Year) [S_Onset]
- Surge Termination (Year) [S_Term]
- Max Active-Phase Velocity (m/d) [S_Act_Vel]
- Mean Quiescence Velocity (m/d) [S_Qui_Vel]
- Terminus Change (m) [S_Term_Ch]

2 https://doi.org/10.5281/zenodo.14229560

Our database is based upon the Global Land and Ice Measurements from Space (GLIMS) database (König et al. 2014), which is now incorporated into RGI 7.0 (RGI 7.0 Consortium 2023) and consists of 1,583 glaciers in Svalbard. Contemporary and palaeo-glaciological evidence of surges is generally limited to the period ~1850–present, which broadly corresponds to the end of the LIA through to the modern-day. Where multiple surges have been recorded, we separate these using ";" in the database, and use "NaN" where the details of the surge have not been recorded.

Our compilation of existing Svalbard-wide glacier surge databases is sourced from several studies: Lefauconnier and Hagen (1991) [LH1991]; Hagen et al. (1993) [H1993]; Sevestre and Benn (2015) [SB2015]; Farnsworth et al. (2016) [F2016]; Kääb et al. (2023) [KA2023]; and Koch et al. (2023) [KO2023]. The compilation of LH1991 only covers eastern Svalbard and is focused on marine-terminating glaciers but is included as it contains several important details on surge characteristics. H1993 is the original database of glaciers across Svalbard and similarly contains details of historical surges. The current RGI 7.0 database defines the "surge status" of each glacier according to Sevestre and Benn (2015): no evidence of surging (0); possible surge (1), probably surge (2), and observed surge (3). Where the SB2015 database does not have corresponding evidence from one of the other compilations, we determine the glaciers surge status to be 'undefined' and do not include it in the S_All field. The F2016 compilation was manually translated into the RGI 7.0 database. The glacier names described in F2016 often referred to tributaries which are now combined into single glacier catchments (e.g., Nuddbreen / Strongbreen), hence we manually combined these entries. The recent compilations from KA2023 and KO2023 were manually transcribed from tables in PDF files.

References

Farnsworth WR, Ingólfsson Ó, Retelle M, Schomacker A (2016) Over 400 previously undocumented Svalbard surgetype glaciers identified. Geomorphology 264:52-60. https://doi.org/10.1016/j.geomorph.2016.03.025

Hagen JO, Liestøl O, Roland E, Jørgensen T (1993) Glacier Atlas of Svalbard and Jan Mayen, Norwegian Polar Institute, Oslo, Norway.

Harcourt WD, Pearce D, Gajek W, Lovell H, Luckman A, Benn DI, Kohler J, Kääb A, Hann R (2024b). Svalbard Surge Database (RGI2000-v7.0-G-07) (Version 1) [Data set]. Zenodo. https://doi.org/10.5281/zenodo.14229560

Kääb A, Bazilova V, Leclercq PW, Mannerfelt ES, Strozzi T (2023) Global clustering of recent glacier surges from radar backscatter data, 2017-2022. Journal of Glaciology 69:1515-1523. https://doi.org/10.1017/jog.2023.35

Koch M, Seehaus T, Friedl P, Braun M (2023) Automated detection of glacier surges from Sentinel-1 surface velocity time series – An example from Svalbard. Remote Sensing 15:1-16. https://doi.org/10.3390/rs15061545

König M, Nuth C, Kohler J, Moholdt G, Pettersen R (2014) A digital glacier database for Svalbard. In Global land ice measurements from space (pp. 229-239) Berlin, Heidelberg: Springer Berlin Heidelberg

Lefauconnier B, Hagen JO (1991) Surging and calving glaciers in eastern Svalbard, Norsk Polarinstitutt, Meddelelser NR. 116

Sevestre H, Benn DI (2015) Climatic and geometric controls on the global distribution of surge-type glaciers: Implications for a unifying model of surging. Journal of Glaciology 61:646-662. https://doi.org/10.3189/2015JoG14J136

Methane in Svalbard (SvalGaSess)

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1. Introduction

1.1. Background

Understanding Arctic methane dynamics is critically important for climate science and will remain so over the next decades on account of its great relevance to greenhouse gas management. Significant progress has been made with respect to methane dynamics at continental shelf margins and in the wetlands, lakes and permafrost of Siberia, North America and Scandinavia (e.g., Schuur et al. 2022; Miner et al. 2022; Walter Anthony et al. 2016, 2024). However, Svalbard's contribution to this knowledge base has been patchy and there exists a significant bias towards just a few key terrestrial sites, such as Toolik Lake (Alaska) and Abisko (Sweden) (Metcalfe et al. 2018). There are good reasons to question how well this important knowledge resource can be applied to the Svalbard archipelago (Hodson et al. 2020). In fact, it is becoming increasingly clear that Svalbard's landscape and methane dynamics are markedly different to these locations because its high-relief, glacierised landscape is clearly different and underlain by an active hydrocarbon system that includes coal bed methane and extensive shale sequences hosting geogenic methane (Birchall et al. 2023; Ohm et al. 2019), and potentially gas hydrates (Betlem et al. 2019, 2021). The geologic record of Svalbard includes geogenic gas generation throughout deep-time, including catastrophic atmospheric degassing related to contact metamorphism during the Early Cretaceous, burial-related gas generation throughout the Cenozoic, and more recently, in response to the retreat of continental ice sheets. Consequently, shallow marine and terrestrial environments in Svalbard require appraisal as likely hotspots where both ancient geogenic methane and young microbial methane may be released into the atmosphere. A better understanding of methane dynamics in Svalbard will also provide much-needed insights into other high-relief, glaciated parts of the Arctic with similar shale-prone geologies. Such regions include the circum-Baffin Bay region of Canada and Greenland (e.g., Bylot Island, Ellesmere Island, Disko Island and the Nares Straight region), Eastern Greenland (Jamieson Land) and most of the Russian Arctic islands (Novaya Zemlya, Severnaya Zemlya and Frans Joseph Land). Collectively, these represent some of the least studied parts of the Arctic region.

Major advances in our understanding of geogenic methane release from source rocks exposed on land and in Svalbard's fjords and shelf environments have been achieved in recent years (e.g., Sahling et al. 2014; Kleber et al. 2023; Rodes et al. 2023). Insights into methane migration within source rocks (e.g., Birchall et al. 2023; Huq et al. 2017; Roy et al. 2019), near-surface hydrological networks (e.g., Kleber et al. 2024; Hodson et al. 2023; Kleber et al. In Press) and aquatic environments (Damm et al. 2005, 2021) have also been published, but have yet to be integrated into a holistic overview of the relevant processes operating across the archipelago. Since these processes are highly sensitive to climate change, we need to consider with some urgency how they will regulate methane emission in the near future. We should also be considering how they have done so in the past, because recent work in Svalbard has established that extensive out-gassing events occurred as recently as ca. 15 000 years ago, after the transition from the Last Glacial Maximum began (Cremière et al. 2016; Montelli et al. 2024; Portnov et al. 2016; Serov et al. 2017).

Research in Svalbard is also notable for revealing hotspots with appreciable rates of microbial methane release from the active layer (e.g., Pirk et al. 2015, 2017). These emissions are the consequence of active microbial methane production during the summer thaw season, and so the methanogenic archaea responsible have been examined in detail (Section 2.1). However, up-scaled, regional flux estimates from Svalbard's tundra are conspicuous for their absence due to a scarcity of measurements, which also prevents comparison of geogenic versus microbial methane emissions across the archipelago. A further area of uncertainty with respect to the role of microorganisms in Svalbard's methane budget is the consumption of both geogenic and microbial

methane by methanotrophs (Section 2.7). These removal processes are certainly effective in places, such as the water column around Svalbard (Mau et al. 2017), or within slow-moving active layer pore waters in the tundra (Graef et al. 2011), but early evidence suggests that this is not the case near terrestrial seeps of geogenic gas, where turbulent, methane-saturated springs allow rapid evasion of gas into the atmospheric boundary layer (Hodson et al. 2020; Kleber et al. In Press).

The above emphasis upon the likely importance of geogenic and microbial methane emission from Svalbard's terrestrial and shallow marine environments suggests that systematic measurements from the atmospheric boundary layer above them hold great potential. Long-term measurements of atmospheric methane do exist, and have been undertaken since 1989 at the Zeppelin Observatory, Ny-Ålesund (Platt et al. 2022). These important time series have been linked to the long-range atmospheric transport of well-known methane sources in the wetlands of Siberia and elsewhere, and document a clear increase in Svalbard that is similar to that observed elsewhere in the Arctic (Morimoto et al. 2006; Platt et al. 2022; Wittig et al. 2023). The influence of local sources upon these high elevation observations is presently thought to be small (Section 2.8), but its assessment is hampered by the lack of observations that has so far prevented any form of regional up-scaling to account for all the various emission sources in Svalbard.

Despite the challenges described above, the easily accessible and international research environment of Svalbard clearly has great potential for fostering knowledge transfer about methane dynamics in other parts of the Arctic where glacial and periglacial processes are active in landscapes with shale-prone lithologies, fjords subject to seasonal ice cover, and geomorphological processes conducive to the formation of wetlands. This potential, however, remains largely unfulfilled on account of there being some obvious measurement gaps and a knowledge base that remains fragmented by disciplinary boundaries. Identifying both the nature of these shortcomings and their potential solutions were major motivations behind this report.

1.2. Structure of this report

In order to better define the development needs of methane science in Svalbard, the following review places emphasis upon the dynamics of its local methane sources, rather than the fate of methane advected to the archipelago from distant sources by atmospheric transport. Since we wish to emphasise the role of changing cryospheric processes associated with sea ice, active glaciers and permafrost, we largely exclude the well-known continental shelf environment in West Spitsbergen. This includes Vestnesa, one of the best-known, methane hydrate-associated seep systems in the world (see Panieri et al. 2017, and references therein). We therefore begin this review with a description of geogenic and microbial methane sources in Svalbard, before discussing methane migration through terrestrial and shallow marine (principally fjord) environments. We then describe atmospheric methane observations from Svalbard before identifying critical development needs for future research on methane in the archipelago.

2. Overview of existing knowledge

2.1. Methane sources in Svalbard

Svalbard is very likely to be a net source of methane to the atmosphere on account of geogenic and microbial methane production within rocks, sediments (including soils and peat) and (to some extent) water bodies. A very significant partitioning between deeper sources of ancient geogenic methane (shale gas and coal bed methane) and shallower sources of younger microbial methane most likely exists across the archipelago due to the presence of continuous permafrost. This greatly

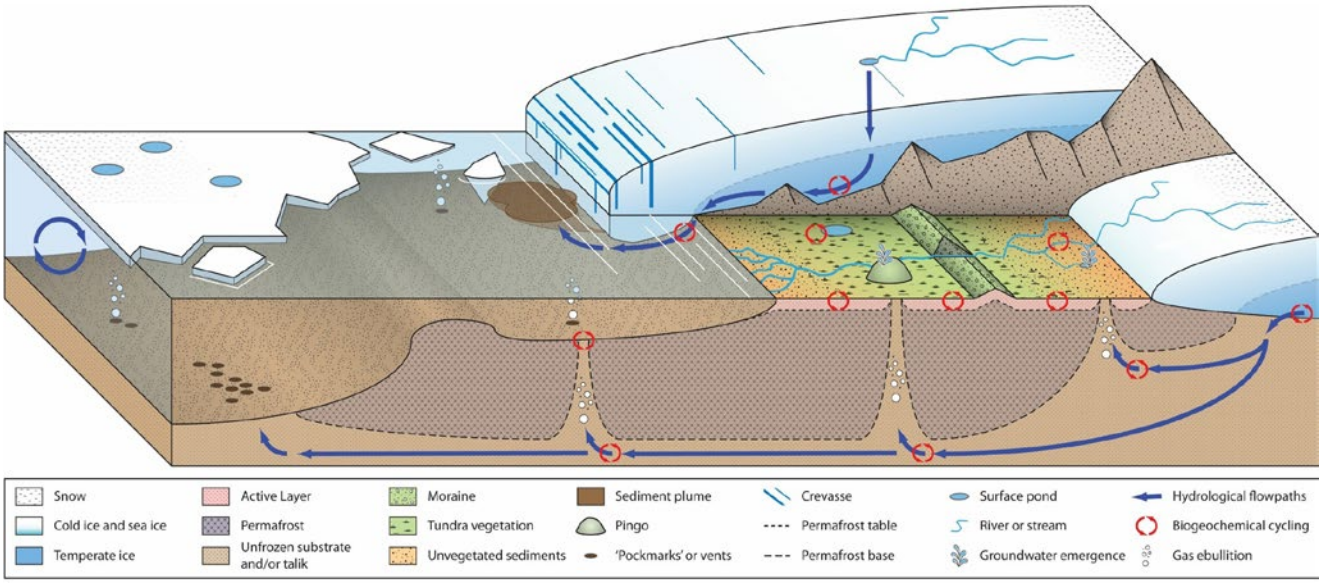

Figure 1: Conceptual illustration of the methane system in Svalbard, depicting the principal environments, migration pathways and emission sites near land- and marine-terminating glaciers.

suppresses the mixing of fluids (including free and dissolved methane) between the summer thaw layer (the supra-permafrost environment) and the sub-permafrost environment, especially when the intervening permafrost is hydraulically "tight" on account of its fine particle size or high ice content (Birchall et al. 2023). Therefore, sub-permafrost gas that is often (but not exclusively) dominated by geogenic sources beneath the permafrost (Birchall et al. 2023) can be advected directly into fjords by deeper groundwaters with minimal opportunities for discharge onto the land surface (Figure 1). Furthermore, free gas from deep geogenic sources is also more likely to be released directly into the fjord without the need for groundwater advection, because permafrost is largely absent here (Betlem et al. 2021). Collectively, these mechanisms might explain the dominance of geogenic methane within Svalbard's fjords (see Section 2.6) and groundwater springs (Kleber et al. 2023).

Geogenic methane in Svalbard is strongly associated with thick and organic-rich, shale-dominated successions (Ohm et al. 2019; Olaussen et al. 2024; Senger et al. 2025). Source rocks potentially hosting shale gas and coal bed methane occupy much of central, eastern and southern Spitsbergen in a total area of ca. 22 000 km^2, and the entirety of Barentsøya and Edgeøya (ca. 6 000 km^2), collectively representing almost half of the entire land surface area (Senger et al. 2025). Eighteen boreholes were previously drilled onshore Svalbard from 1961–1994, specifically to explore for hydrocarbons – and whilst none encountered commercial quantities, ten encountered gas shows (Senger et al. 2019; Olaussen et al. 2024). Studies from the exploration geologists working on coal, oil and gas across the archipelago have been synthesised by Birchall et al. (2023) and Demidov et al. (2020). The Longyearbyen and Barentsburg areas have received particular attention in this context, although all settlements in Svalbard except Hornsund have a mining heritage and thus offer lots of geological data resources for characterising the gas accumulations in the rocks and sub-permafrost sediments. Furthermore, the Longyearbyen CO_2 Project provided borehole data from Adventdalen allowing characterisation of shallow and deep gas accumulations (Braathen et al. 2012; Olaussen et al. 2019; Senger et al. In Press). Ohm et al. (2019) show how shale gas from the organic-rich, mudstone-dominated Middle Jurassic to Lower Cretaceous Agardhfjellet Formation is particularly significant. Huq et al. (2017) demonstrate that in Adventdalen this gas is capped by a layer of microbial methane in a groundwater aquifer that exploits highly fractured sandstone immediately above the shale sequences and beneath the 120 m thick permafrost layer (see also Birchall et al. 2023). These studies used hydrocarbons other than

methane (e.g., ethane and propane) in conjunction with stable isotopes of carbon to discriminate the two sources, producing valuable insights into the vertical distribution of methane to depths approaching 1 km. However, whilst shale gas is more easily discriminated by this process, coal bed methane is not, and so further studies are required to reveal its importance. Further insights into the geology of Svalbard and its relevance to methane are provided by the SESS chapter on the geosphere (Senger et al. 2025), where it is made clear that studies of methane migration along faults, fractures and permeable rocks have received significant attention in places.

Microbial methane production in Svalbard has been described both above the permafrost table (i.e., in the so-called active layer: Section 2.2), and also beneath it, in association with sub-permafrost groundwaters (Section 2.5). Microbial methane is also known to be present within permafrost, including both sediments (Jones 2019) and bedrock (Huq et al. 2017). However, it is not known whether this intra-permafrost microbial methane is present as a consequence of long-term storage following burial, migration or in-situ production. As is the case elsewhere, microbial methane in Svalbard is produced by archaea exploiting one of two well-known pathways: the hydrogenotrophic pathway and the acetotrophic pathway. Hydrogenotrophic methanogens reduce carbon dioxide using hydrogen to produce methane via a process also known as "carbonate reduction", whilst acetotrophic methanogens form methane via acetate fermentation (Whiticar 1999). Research from elsewhere in the Arctic has shown that the two pathways most likely respond differently to warming and disturbance associated with permafrost thaw and ice melt due to differences in their temperature optima and energy yield (e.g., Ernakovich et al. 2022). Understanding the distribution, activity and role of both hydrogenotrophic and acetotrophic methanogens within Svalbard's microbial communities are therefore important research priorities. Several works point towards hydrogenotrophic methanogenesis as the predominant pathway: for example, in saturated active layer sediments in Adventdalen (Jones 2018). The same has been inferred indirectly from ground water samples beneath the permafrost in Adventdalen (Huq et al. 2017; Hodson et al. 2020). Trubitsyn et al. (2023) characterised a novel hydrogenotrophic methanogen and proposed the name *Methanobacterium spitsbergense* sp. nov. after its isolation from permafrost sediments from Barentsburg. However, Blake et al. (2015) showed that a microbial community dominated by hydrogenotrophic methanogens (members of the Methanoregulaceae/WCHA2-08 family) could evolve to be dominated by acetotrophic methanogens following an increase in acetate concentrations, but only if incubated at higher temperatures (30°C). Tveit et al. (2015) also found acetotrophic methanogens to benefit from increasing temperatures, relative to hydrogenotrophs in peat soils from Knudsenheia, Ny-Ålesund. More work is required to better understand the effect of such temperature shifts on methane emissions, and better map the distribution, activity and abundance of different methanogens across Svalbard. This includes an understanding of locations where methanogenic archaea are conspicuous by their absence, especially where absence might be linked to ecological drivers (e.g., competition for substrate or available terminal electron acceptors) rather than being simply due to unfavourable soil moisture conditions (e.g., Müller et al. 2018). Community-scale molecular data analysis of methanogens should also be supplemented by the analysis of pure cultures to better understand the microorganisms themselves (Trubitsyn et al. 2023).

2.2. Methane in the active layer

The active layer is fundamental in regulating contemporary methane production and oxidation (methanotrophy) in Arctic soils, giving both a strong seasonality. However, multi-year measurements capturing the complete annual cycle and with an emphasis upon in-situ processes (rather than net emissions) have not yet been published in Svalbard and are generally rare in the Arctic region (N.B. Donateo et al. 2024). Active layer development typically starts following snowmelt in late May, and is followed by a rapid increase in depth, to reach

seasonal maximum values of one metre or more by September (Strand et al. 2021). Net methane emission to the atmosphere from the active layer was demonstrated from saturated, low centred polygons in the Adventdalen region (Pirk et al. 2017: Figure 2), wet moss tundra near Kapp Linne (Lindroth et al. 2022) and waterlogged soils near Ny-Ålesund (Chen et al. 2014) during summer. The three consecutive summers of observations presented by Pirk (2017) gave median values in the range 1–2 g m^{-2} for the interval 1 June until 30 September. These chamber studies, and others (e.g., Adachi et al. 2006), along with the only deployment of eddy covariance measurements in Svalbard (Donateo et al. 2024) have also established net methanotrophy in drier soils (see Section 2.7). Figure 2 uses the results from Pirk et al. (2017) to clearly demonstrate the variability encountered in emissions across even small landforms (in this case ice wedge polygons). As a consequence of this variability, we are far from understanding the net impact balance of emission versus uptake across the landscape throughout summer. During late winter, low methane emissions with depleted ^{13}C signatures attributed to storage and methanotrophy have been observed in Adventalen (Pirk et al. 2016). The formation of ice layers within the snowpack seems to enhance storage by greatly reducing the diffusion rate. However, the importance and dynamics of winter processes in Svalbard are unclear. In Alaska, winter emissions have been shown to contribute 50% of the annual budget (Zona 2016). Autumn emissions have also been highlighted (Bao 2021), because the active layer refreezes quickly from the top and more slowly from the bottom, thus severely limiting methane oxidation in the top layer before slowing down production in lower layers (Zona 2016, Walter Anthony et al. 2024). Such processes are likely to be influential in Svalbard as well.

Summer and winter methane fluxes from Arctic landscapes are both known for showing large spatial variability, even at small scales (Kutzbach 2004), and the above studies undertaken in Svalbard conform with this pattern. Work in the Adventdalen area shows how some of this variability may be accounted for by the different organic matter and

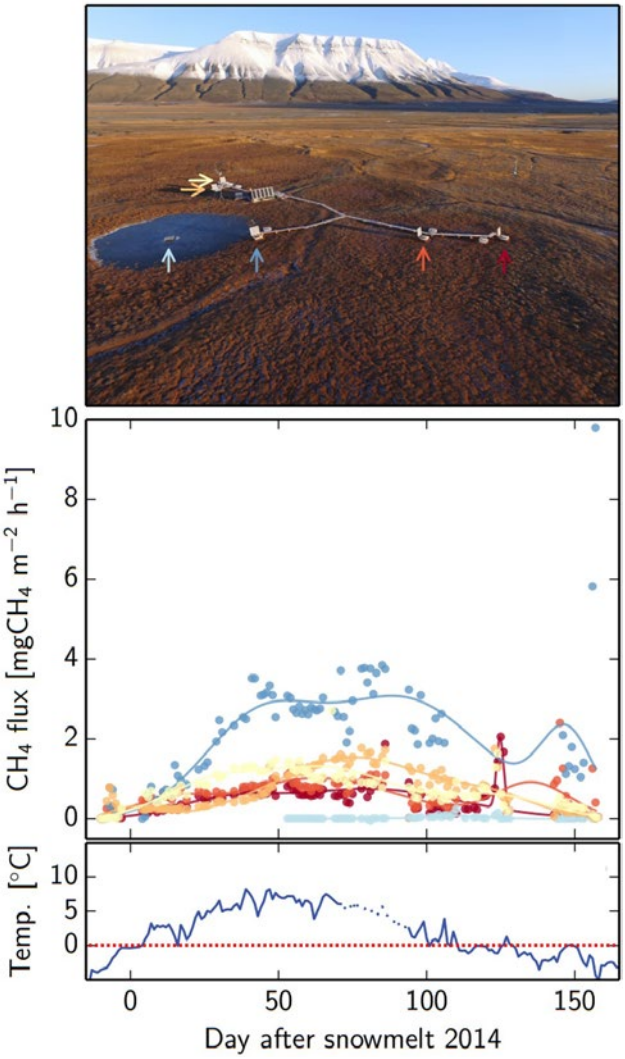

Figure 2: The automatic chamber system deployed in Adventdalen by Pirk et al. (2017). Panel a) shows the ice-wedge polygons and instruments (arrows show the chambers), b) the flux data from each chamber, colour-coded to match the arrows in a), and with each dot representing the daily median value. Panel c) shows the seasonal soil temperature record at 10 cm depth.

soil moisture conditions, resulting in a wide range of redox conditions across its tundra landscapes. This area is particularly well known for its ice wedge polygons (Christiansen 2005), which form in the uplifted marine, deltaic and aeolian sediments lying in the valley bottom (Cable et al. 2018; Gilbert et al. 2018). Localised, organic-rich and saturated active layer soils do exist in the polygons and other water-logged soils (e.g., near bird-cliffs or in heavily-grazed coastal lowlands), but it is important to note that the landscape does not produce the expansive yedoma-type sediments or thick peatlands found elsewhere in the Arctic, because the primary source of the soil-forming sediments is glacial

erosion. Furthermore, the high concentrations of sulphate and iron derived from the shale bedrock in Adventdalen and many other areas across Central and Eastern Svalbard can severely limit methane production, as methanogens are out-competed by microbes using these alternative electron acceptors for the breakdown of organic matter in anoxic conditions (Kolchev et al. 2020), and the presence of these electron acceptors can increase the depth for methane oxidation through anaerobic methane oxidation processes (Dean 2018).

It should also be noted that there are also important landscapes that are not readily accessible from key research infrastructure in Adventdalen, Ny-Ålesund, Barentsberg or Hornsund, yet their methane dynamics most likely warrant attention. For example, Svalbard's coastal strandflats accumulate fine sediment and organic matter between raised beach ridges (e.g., Jones et al. 2023) that can form expansive wetlands in places, such as Bohemanflya in Isfjorden. It is also notable that since the methods employed to directly measure fluxes across the tundra–atmosphere interface have been restricted to relatively few small-scale chamber studies, other techniques should be implemented that that help address the spatial variability and patchiness of methane-relevant processes in the active layer.

2.3. Transient storage of methane: the case for gas hydrates

Natural gas hydrates constitute a potentially important store of methane in Svalbard, enabling long-term storage following its encapsulation within an ice cage structure that prevents oxidation. Hydrate formation and stability in Svalbard is sensitive to pressure and temperature conditions, as well as to the composition of the gas and the salinity of the water forming the ice cage structure (Betlem et al. 2018, 2021). Shifts in pressure conditions due to ice sheet growth and decay have been shown to greatly influence the depth, persistence and timing of both methane hydrate formation and destabilisation, as demonstrated by Portnov et al. (2016). This sensitivity means gas hydrates require treatment as sources / sinks of both geogenic and microbial methane over timescales that could be in excess of 10^3 years in Svalbard's valley bottoms, and perhaps 10^5 years in its high mountains. The variation in history is unclear, but most likely results from more dynamic changes in sea level and ice sheet cover in the valley bottoms (for example, by causing the thermal erosion of permafrost: Humlum et al. 2003). Betlem et al. (2018) has shown that presently, methane hydrates are most likely found beneath the permafrost at depths exceeding 100 m in the eastern parts of the archipelago, whilst subsequent work also established that deep fjord basins also remain viable for methane hydrate preservation close to the sea floor (Betlem et al. 2021). Therefore, the microbial methane produced in the near-surface active layer on land seems unlikely to be affected by storage as methane hydrates. By contrast, the likelihood that hydrates are a source or sink of the geogenic methane in sub-permafrost groundwaters or deep fjord sediment pore waters seems much more certain. However, since reports of the recovery of hydrates in core samples remain largely anecdotal, we only really understand when their formation was likely during certain "snapshots" of Svalbard's landscape history (e.g., Portnov et al. 2016; Betlem et al. 2018). Understanding the distribution of hydrates through space and time across Svalbard therefore represents a major research priority.

2.4. Methane and glaciers

When glaciers advance and over-ride vegetation in their forefield, they can establish a subglacial reservoir of organic carbon that can be converted into methane through methanogenesis (Wadham et al. 2008). The advance can also change the methane hydrate stability field and induce hydrate formation beneath the glacier bed (Portnov et al. 2016; Wadham et al. 2012) following subglacial groundwater recharge (Kleber et al. 2023). However, where no such recharge occurs, for example due to low permeability beneath the glaciers, glacial meltwaters can export any residual, subglacially produced microbial methane that is not consumed by subglacial methanotrophs (see Dieser et al. 2014) to their glacier forefields or the sea, potentially resulting in degassing to the atmosphere (Figure 3). The mobilisation of subglacial microbial

methane in this way has been examined at a handful of sites, including Canada, Greenland, Alaska and Iceland (e.g., Burns et al. 2018; Christiansen et al. 2021; Konya et al. 2024; Lamarche-Gagnon et al. 2019; Sapper et al. 2023). In Svalbard, detailed studies of methane dynamics have only been conducted at the valley glacier Vallåkrabreen, which revealed no evidence for microbial methane, yet high concentrations of geogenic methane in summer runoff (up to 800 times the atmospheric equilibrium concentration: Kleber et al. 2023, 2024).

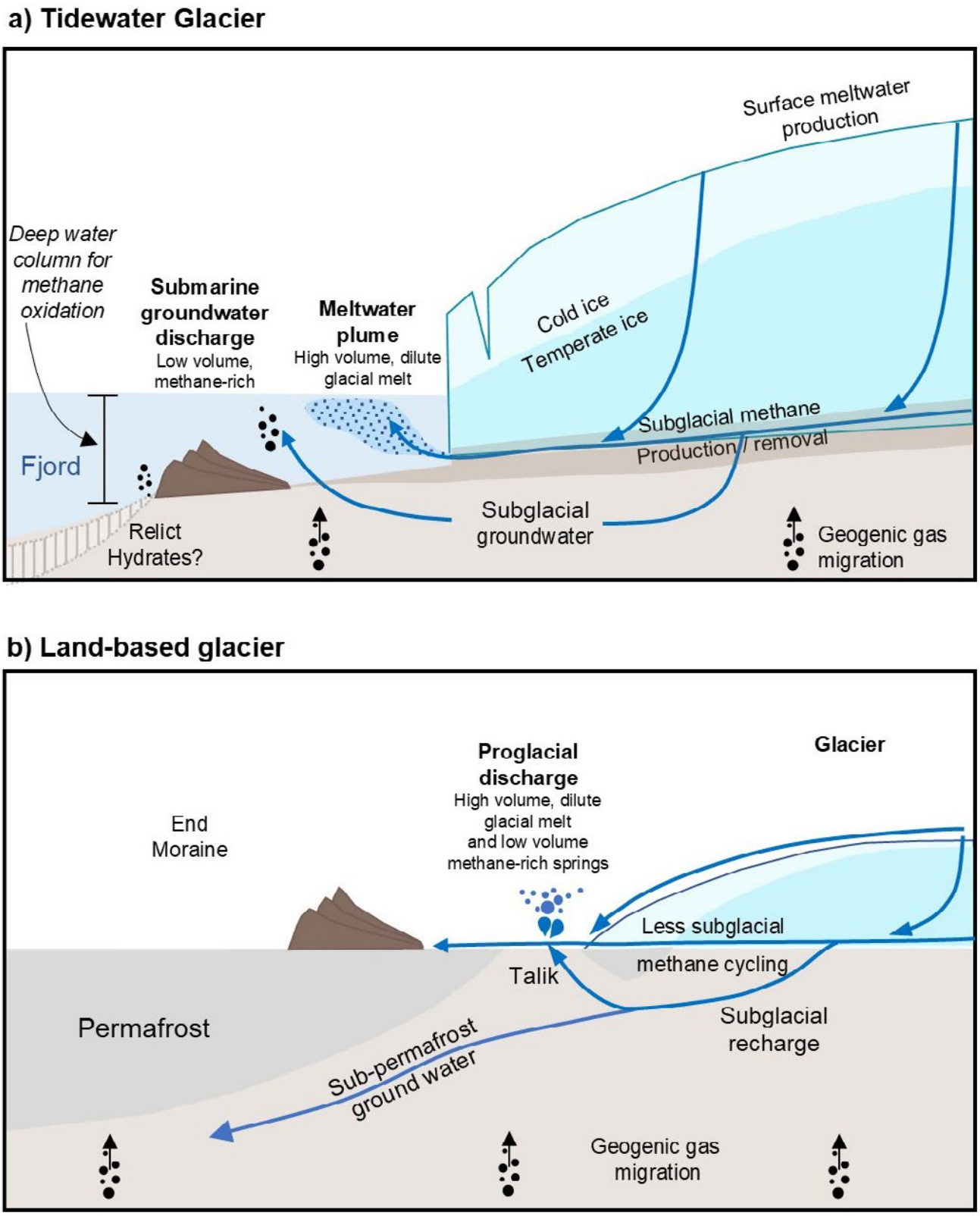

Figure 3: Methane migration routes and processes in marine-terminating and land-terminating glacier basins. The scenarios are intended to depict the present day.

Vallåkrabreen is representative of many valley glaciers in Svalbard and the rest of the Arctic because it has a complex thermal structure wherein only the thicker, upper region of the glacier lies at the melting point all year (Figure 3). The thinner margins are frozen to their bed and can remain so until the glacier undergoes a dynamic advance, or surge, resulting in significant heating of the ice due to increased strain and friction (Sevestre et al. 2015). The presence of permafrost beneath the frozen parts of these glaciers clearly complicates methane flushing. At Vallåkrabreen, only the lower glacier (at the time of study) was cold-based and so Kleber et al. (2024) demonstrated that the highest concentrations of methane were encountered in proglacial springs discharging ground waters that had followed deeper flow paths. Hodson et al. (2023) showed that such springs can persist even when the entire glacier has frozen to its bed (in response to the loss of its perennial snow cover), allowing the forefields of smaller, cold-based valley glaciers also to support springs that release methane into the atmosphere. These and other groundwater flowpaths are therefore given further attention in Section 2.5. Collectively, they are thought to be responsible for emissions of the order of 2.3×10^9 g CH_4 y^{-1} across the entire archipelago (Kleber et al. 2023). Proglacial springs therefore represent the largest single contributor to methane emission from the archipelago yet reported.

The work undertaken on Svalbard glaciers clearly shows that the glaciation of its gas-prone rocks leads to the migration of methane into glacier forefields, where they may degas. Glacial activity causes erosion and the activation of geological faults, both of which are likely to promote the migration of geogenic methane from underlying source rocks. The erosion also produces fine sediments whose deposits may then produce habitats conducive to either microbial methane production or methanotrophy, especially if they remain unfrozen (Figure 3). Longer-term dynamics of methane migration through polythermal glaciers such as those found on Svalbard therefore deserve much more research attention and the relative importance of subglacial microbial methane production and methanotrophy should be explored. The differences between land-based and marine-terminating glaciers should also receive attention, such that the implications of tidewater glacier retreat onto land can be predicted (Kleber et al. 2023).

2.5. Methane in intra- and sub-permafrost groundwater

Deeper groundwater flows are more likely to interact with geogenic methane than shallow groundwater flows confined to the active layer during summer. These flowpaths also support perennial springs whose discharge is often supersaturated with methane after exploiting taliks (unfrozen zones within the confining permafrost) on their way to the surface (Figure 1). The precise mechanisms which establish such flow and allow it to persist are unclear. However, since the movement of groundwater acts as an active heat transport mechanism, it clearly has the capacity to establish new intra-permafrost flowpaths, perhaps even resulting in the localised destabilisation of methane hydrates. The eventual surfacing of these groundwaters leads to the release of its methane to the atmosphere from springs, which typically flow all year to form seeps that support microbial communities capable of removing significant quantities of methane (see Section 2.7). Systematic mapping of all groundwater springs across Nordenskiöld Land clearly showed that these springs mostly exploit taliks revealed by the retreat of polythermal glaciers, rather than beneath deeper lakes or periglacial springs (Figure 4).

Intra- and sub-permafrost groundwater seepage from periglacial (i.e., non-glacial) sites in Svalbard appear to be (or have been) dominated by open-system pingos (Hodson et al. 2019, 2020: Figure 4). There are 136 pingos according to the most recent, comprehensive survey, all of which appear to be “Open System” type and thus hydraulically connected to groundwater systems, at least during their genesis (Demidov et al. 2023). The methane discharging from such Svalbard pingos includes both microbial and geogenic sources, with the former being particularly important in the Adventdalen area. Hodson et al. (2020) show

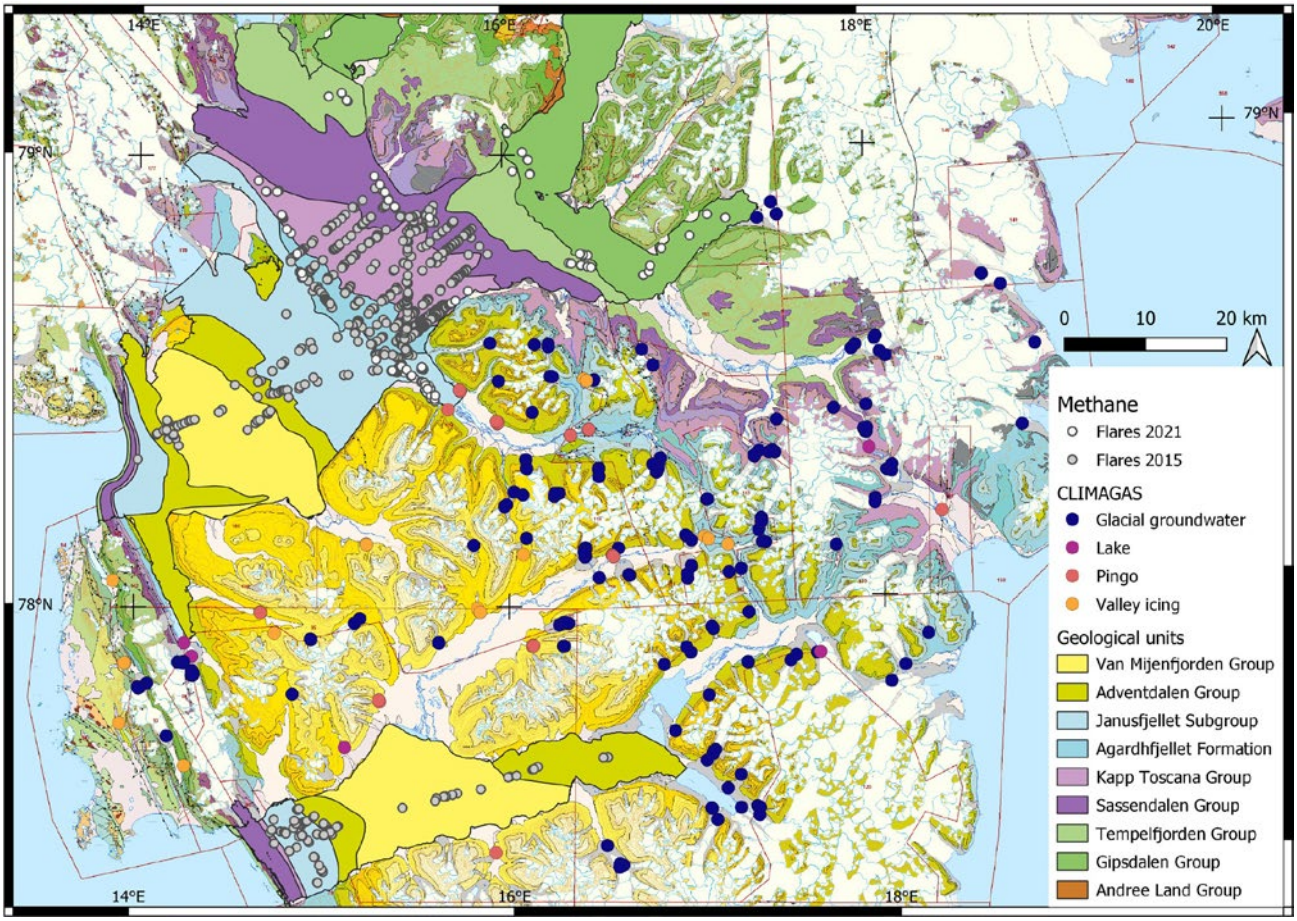

Figure 4: Methane flares (grey or white circles) and terrestrial seeps (coloured circles) mapped after sampling lakes, pingos and springs that form winter icings in the valleys of Central Svalbard, showing the underlying geology in areas without permanent glacier cover (white zones). Data on flares are from Rodes et al. (2023); data on seeps from the CLIMAGAS Project. (See Table 1)

that this gas discharges from at least three of four active pingo springs in Adventdalen and that it is the same gas as that described in a pressurised aquifer hosted by fractured sandstones immediately beneath the lower permafrost boundary (Huq et al. 2017). Emissions are difficult to estimate due to uncertainty in the groundwater outflows, but Hodson et al. (2020) reveal that they carry some of the highest levels of methane super-saturation in central Spitsbergen. At the smallest pingo (Lagoon Pingo), Hodson et al. (2019) show that emissions in summer are sometimes greatly reduced by the formation of a pond at the seep surface, which promotes methanotrophy and limits the methane emissions of a 0.36 L s^{-1} spring discharge to ca. 65 kg CH_4 y^{-1} (Hodson et al. 2019). Furthermore, Figure 4 shows that perennial springs in glacier forefields are by far the most abundant emission sources (Kleber et al. 2023).

The recharge sources of deeper groundwater aquifers by summer precipitation and the ablation of snow, ground ice and glaciers are all likely to change markedly due to warming temperatures and the prolongation of the melt-season. The subsequent impacts upon methane emissions from groundwater springs in Svalbard are uncertain. On the one hand increased water availability regionally might lead to greater pressures in the aquifer (enhancing gas migration and release), while on the other hand, ongoing shrinkage of smaller glaciers might reduce local aquifer recharge and pressures (e.g., Nowak et al. 2021). In the latter case, decreased sub-permafrost groundwater pressures seem less likely, as seemed to be the case in the glacier–groundwater system described by Hodson et al. (2023). Both Kleber et al. (2023) and Hodson et al. (2023) demonstrated that proglacial methane-saturated springs contain mixtures of

snowmelt and glacier melt, whilst Rotem et al. (2024) demonstrated that pingo springs, which might discharge some of the longest residence time waters in the archipelago (Hornum et al. 2020; Demidov et al. 2020), are also likely to contain relatively young meteoric waters. Therefore, the methane found in deeper groundwater aquifers is certainly not immune from modern climate change effects, at least in the case of those close to the lower permafrost boundary (Haldorsen et al. 2010). Other processes that might also influence groundwater pressure and thus methane fluxes include hydrate destabilisation, ongoing uplift and permafrost aggradation (Hornum et al. 2020). All of these processes deserve greater attention in order to assess whether perennial groundwater springs will continue to serve as hotspots for methane evasion.

2.6. Methane in the marine environment

Methane super-saturation in Svalbard coastal waters is very common and so we first describe studies of methane migration into the sea from land (laterally) or more directly via the sea floor (vertically), before reviewing its fate in the water column (Figure 1). The strong likelihood that lateral transport of methane occurs from land into Svalbard's fjords has only recently become clear following the study of sub-marine groundwater discharge. However, our understanding of sub-marine groundwater discharge requires much more development (Diak et al. 2023), because it is presently limited to one study of near-coastal groundwater modelling in Adventdalen (Hornum et al. 2020), and one inverse modelling study of sediment pore water profiles from methane-saturated fjords (e.g., Tempelfjorden: Kim et al. 2022). Far more achievements have instead been associated with the study of methane gas bubble releases directly from the sea floor, which have been linked to outcropping source rocks on the sea floor, rather than pathways for sub-marine ground water discharge (e.g., Rodes et al. 2023). This work has often exploited acoustic and marine geophysical survey methods from research ships, enabling thousands of active gas flares to be mapped in Svalbard's fjords, coastal and deeper shelf waters (Mau et al. 2017; Rodes et al. 2023; Sahling et al. 2014; Römer et al. 2024). In the fjords, Rodes et al. (2023) showed how identifying the geological controls upon geogenic gas migration and release are made easier in the absence of permafrost and glacier cover on the sea floor (Figure 4). The presence of pockmarks on the sea floor sediments is also easily discernible, yet seldom associated with active gas emission according to this work. This was surprising, because pockmarks are important fluid escape features in the Barents Sea (Serov et al. 2017) and have been linked to rapid methane escape following hydrate destabilisation after the Last Glacial Maximum (e.g., Portnov et al. 2016). Pockmark swarms are therefore an important part of sea floor surveys in Svalbard (Roy et al. 2019; Forwick et al. 2009). One reason they might no longer be important in the fjords could be due to the loss of hydrates here in contrast to the shelf edge offshore western Svalbard, where sub-marine gas hydrate formation and dissociation are thought to be important drivers of sea floor gas emissions (e.g., Berndt et al. 2014).

Methane bubbles released at the sea floor are greatly attenuated during their ascent to the water surface, because they dissolve and may be subject to consumption by methanotrophs (e.g., Mau et al. 2017: See Section 2.7). However, the same may not be the case for very shallow marine environments, or if the released bubbles are protected by an oil or gas hydrate shell from gas exchange processes. Ship-based observations have therefore sought to detect enhanced methane concentrations in the atmospheric boundary layer, especially above the active seeps in deeper waters, such as at the Vestnesa Ridge (Myhre et al. 2016). A model-supported analysis of atmospheric CH_4 measurements in the region during the summer of 2014 reported negligible or very small impact from these sources, with an upper limit of 3.5 µg CH_4 m^{-2} d^{-1} (Pisso et al. 2016). In other studies, average diffusive emission fluxes estimated using sea surface concentrations along a ship's track were 207 ± 134 µg CH_4 m^{-2} d^{-1} in West Spitsbergen coastal waters (Workman et al. 2024), whilst Mau et al. (2017) reported median values of 29.0 µg CH_4

m^{-2} d^{-1} from surface waters above the continental margin. The variability between the different techniques employed, their location and their spatial or temporal scales also suggest that more observations are required to gain a representative estimate for sea surface emission fluxes.

Despite the apparently low efficacy of sea surface emissions, at least further offshore, it is remarkable how prevalent methane saturation is in the water column of Svalbard coastal waters (Damm et al. 2005, 2021). This means the diffusive flux of methane to the atmosphere is likely to be significant when these waters are brought to the sea surface. Sea–air diffusive emissions are therefore enhanced by vertical water column mixing (e.g., buoyancy changes and convection), because it increases the concentration of methane in surface waters at certain times of the year. Damm et al. (2021) show how this is most important at the fjord scale during the winter months, for example, when convective mixing in Adventfjorden and Tempelfjorden is enhanced by surface water cooling. The same work showed how stratification obstructs water column ventilation, and so fresh water production during the summer season is associated with reduced sea–atmosphere methane fluxes in summer. Areas where this stratification is disrupted, such as in the vicinity of subglacial upwellings at tidewater glacier margins, in association with localised winds or areas where sea floor topography disrupts currents are therefore likely to produce enhanced summer-time emissions. The processes associated with the diffusive emissions of methane from fjords are therefore strongly seasonal and spatially variable during summer. This seasonality is greatly enhanced by meltwater in summer and sea ice in winter, which can trap methane near the surface in the vicinity of tidewater glaciers (Kleber et al. 2023). Whilst some methane becomes incorporated into the ice during its formation, other gas may become concentrated within the residual brines that form and/or be transformed by microbial activity (Damm et al. 2015). Methane can therefore be released to the water column during brine rejection and to the atmosphere following sea ice break up. However, freshening of the sea surface layer by sea ice melting during summer can also induce stratification and thus reduce diffusive release to the atmosphere in a similar way to freshwater runoff (Damm et al. 2015).

2.7. Methanotrophy: mitigating methane emissions

Microbial consumption of methane, or methanotrophy, is an important regulator of methane emissions from both marine and terrestrial environments in Svalbard (Malard et al. 2019). Furthermore, methane is an important carbon source for chemoautotrophic microorganisms and so methanotrophy enables highly specialised local ecosystems to evolve near methane seeps with "far-reaching" effects upon the carbon budget of sea floor ecosystems (Åström et al. 2020). Aerobic methanotrophy has been documented in oxygenated environments such as the water column (Graves et al. 2015; Mau et al. 2017) or soils in the upper active layer (e.g., Müller et al. 2018) and is clearly an important sink for methane in both terrestrial (e.g., Donateo et al. 2024) and marine (Graves et al. 2015) ecosystems. Studies from benthic marine sediments, pingos, and deeper, anoxic active layer sediments show the same is the case for anaerobic methane oxidation in Svalbard (e.g., Delpech et al. In Press). Pertinent case studies of active layer environments include the weakly acidic peat soils near Ny-Ålesund (e.g., Høj et al. 2005; Tveit et al. 2023; Wartiainen et al. 2003), which generally focus upon two genera of aerobic methanotrophs Methylobacter and Methylosinus. Significant attention has also been given to methanotrophy in glacial forefield soils of the same region (e.g., Yun et al. 2023). Nearer Longyearbyen, easier access to permafrost landforms that are conducive to the development of anaerobic microbial habitats has led to increasing recent research attention being given to its local pingos and ice-wedge polygons. For example, studies of the pingo seep at Lagoon Pingo (Hodson et al. 2019) have most recently identified novel, psychrotolerant (cold-loving) *Methylobacter* species (Patil et al. 2024) and anaerobic methane oxidation (Delpech et al. 2024). These environments suggest that high sulphate concentrations enabled by pyrite oxidation in shales are able to promote the coupling

of methanotrophy to sulphate reduction in a manner not unlike that seen in marine sediments (where the sulphate is acquired from sea water) (e.g., Jones et al. 2023). Svalbard's sulphidic hot springs have also been considered as hotspots for methanotrophs, with Reigstad et al. (2011) showing 16S rRNA sequences linked to both aerobic Methylobacter and anaerobic (ANME-1) methanotrophs in two of the southern springs (Trollosen and Fisosen), but concluding that methane is not a major source of energy in this saline, sulphidic system.

The impact of methanotrophy upon methane emissions from Svalbard's terrestrial and freshwater habitats has not received much attention yet, although a combination of mass balance and stable isotope measurements was used to show methanotrophy removes ~29% of the methane discharging from proglacial groundwater springs at Vallåkrabreen throughout the runoff season (Kleber et al. 2024). Greater efficacy of methane removal has been reported in the marine environment, especially to the west of Spitsbergen. For example, methanotrophy accounts for ~60% of the methane seeping from the landward limit of the gas hydrate stability zone offshore western Svalbard (Graves et al. 2015). However, more work is required to understand if the same is the case in shallow marine environments, especially at fjord headwaters.

Warmer temperatures in Svalbard are likely to cause landscape changes that alter the residence time of methane within habitats conducive to either aerobic or anaerobic methanotrophy. A warmer Svalbard also changes the production of oxygen-rich near-surface melt waters and their mixing with anoxic, deeper groundwaters (Hodson et al. 2023), thus allowing for more effective oxidation of methane near retreating glaciers and permafrost taliks. On the other hand, the decreasing solubility of methane at higher temperature reduces the methane oxidation efficiency, and warming can in any case lead to greater mobilisation of geogenic methane and increased microbial methane production. These and other impacts of climate change upon the overall efficacy of methanotrophy remain largely unexplored. From an organismal perspective, a further problem is that very few genome sequences of psychrophilic methane oxidisers have been reported (Patil et al. 2024) and we have only just started to understand that key taxa in Svalbard may respond rapidly to temperature changes, resulting in significant changes in cell growth and methane consumption kinetics (Tveit et al. 2023; Mateos-Rivera 2016). Thus, we are at a stage where we merely know which organisms contribute to methane cycling, and what their basic physiological responses to warming will be. However, the full impacts of increasing temperatures on biological methane cycling in Svalbard are complex and warrant further research. This should include not only physiological changes of key microbial taxa (affecting both methanogenesis and methanotrophy), but also changes at the community scale that are relevant to establishing the chemical environment and its control upon these processes.

2.8. Methane in the atmosphere: an emissions perspective

A key driver of environmental methane research on Svalbard is to understand and quantify the contribution of local methane sources, as discussed earlier, to the global atmospheric methane budget. Atmospheric methane concentrations have been measured at the Zeppelin Observatory since 2001, along with isotopic composition ($\delta^{13}C\text{-}CH_4$) in twice-weekly flask samples, making a crucial contribution to the Norwegian national monitoring programme and the Integrated Carbon Observation System (ICOS), with a major achievement being the quality control and archiving of these data on publicly accessible platforms such as EBAS (ebas.nilu.no) and the ICOS Carbon Portal (see Section 6).

Figure 5 shows the annual mean atmospheric methane concentrations at Zeppelin, Birkenes (southern Norway), and the global average. Zeppelinfjellet's mean methane concentrations are lower than Birkenes' due to its greater distance from mid-latitude emission sources (Platt et al. 2022), but greater than the global average. Observations at Zeppelin (and globally) also show a decline in $\delta^{13}C\text{-}CH_4$, suggesting a relative increase in microbial sources compared to fossil sources,

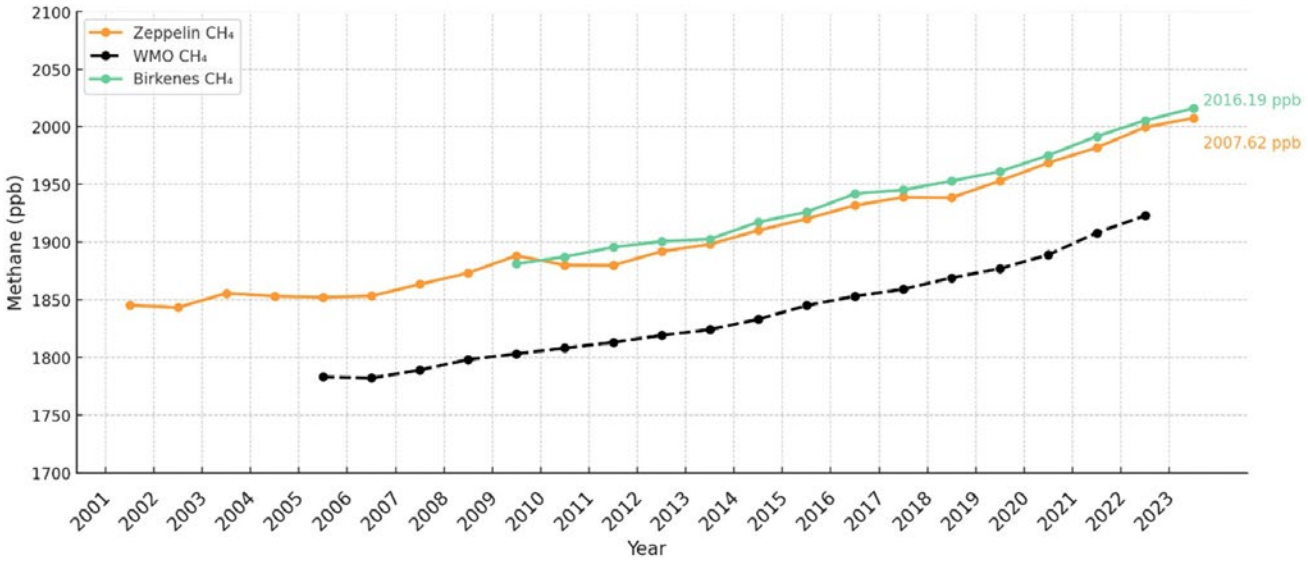

Figure 5: Development of the annual mean CH_4 mixing ratio for the period 2010 to 2023 at the Zeppelin Observatory, Svalbard (orange) and Birkenes, Norway (green), compared to global mean provided by WMO (black). Adapted from Platt et al. (2023).

though a smaller concurrent increase in fossil sources is not excluded (Nisbet et al. 2019). The leading hypothesis for CH_4 growth is emissions from microbial sources in wetland soils, coinciding with changes in wetland hydrology due to shifting rainfall patterns, and increased microbiological activity from rising temperatures. Top-down models also support this hypothesis (Thompson et al. 2017). However, this does not exclude other potential explanations, emphasising the need for further research to understand unexpected processes.

Global methane emissions are bloated by anthropogenic activities that are easier to control than natural emissions from the Arctic, and currently estimated at 669 (uncertainty range: 512 to 849) Tg CH_4 $year^{-1}$ using "bottom-up" methods and 575 (553 to 586) Tg CH_4 $year^{-1}$ using "top-down" models (Saunois et al. 2024). "Bottom-up" methods estimate emissions using process models, emission inventories, and extrapolation (upscaling), while "top-down" models refine these estimates using atmospheric methane concentrations. Inversion modelling, the most widely used top-down method, combines prior emission data with atmospheric constraints to produce posterior estimates via Bayesian statistical methods. Saunois et al. (2024) also show how high-latitude, northern (60°–90°N) emissions are between 4 and 6% of the global total. Although the proportion seems small, the corresponding flux is already one order of magnitude greater than the annual growth rate of the global atmospheric methane resource, and much of it comes from natural emissions from the Arctic that are almost impossible to control.

Although great progress has been made in understanding methane in Svalbard, the state of the science falls short of being able to scale up local atmospheric emission measurements to produce a bottom-up estimate for the entire archipelago (see Appendix 1 Table A1). However, a "top-down" atmospheric inversion modelling study incorporating the 2014 Zeppelin data has provided an upper limit of 0.2 Tg CH_4 $year^{-1}$ (Pisso et al. 2016) for Svalbard's combined landmass and shallow marine waters (< 400 m). This may be compared to the up-scaled (bottom-up) emission estimate of 0.0023 Tg CH_4 y^{-1} for groundwater springs in glacier forefields by Kleber et al. (2023). Great uncertainty remains with the other emission sources, but it might be possible to double this flux with groundwater springs, lakes/ponds and wetlands. For example, the 345 km^2 of vegetated wetlands and wet moss tundra across Svalbard (Johansen et al. 2012) would require average net emissions of ca. 7 g CH_4 m^{-2} y^{-1} to achieve this.

However, median seasonal rates were no greater than ca. 2 g CH_4 m^{-2} y^{-1} in wetlands or wet moss soils (Pirk et al. 2017; Lindroth et al. 2022). Open system pingos individually show potential for emissions of 10^4 to 10^6 g y^{-1}, but there are only 136 of them, with only ca. 10% showing signs of active methane release via groundwater springs (total emission potential therefore likely to be < 10^7 g CH_4 y^{-1}). Other pathways for sub-permafrost groundwater release, both terrestrial and sub-marine, are therefore likely to be more important from an emission perspective and deserve further study. Finally, evidence for significant rates of methane oxidation in dry tundra soils is emerging at the time of writing (0.08–0.18 g CH_4 m^{-2} y^{-1} for full year budgets at Ny-Ålesund: Donateo et al. 2024). These are far in excess of the oxidation rates which may be inferred from short-term chamber measurements in the same area (Chen et al. 2014; Adachi et al. 2006), but collectively suggest that regional up-scaling of methane sequestration is important for offsetting emissions and thus deserves greater attention.

3. Contributions to interdisciplinarity

This report has directly shown how chemical, physical, geological and biological processes must be addressed to understand methane dynamics in Svalbard. This means the subject is, by necessity, an interdisciplinary one – as is the case with all key greenhouse gases. At present, good examples of interdisciplinary research into the methane problem in Svalbard do exist, but they have been mostly employed by the oceanographic and atmospheric groups working offshore on the continental margin west of Svalbard (e.g., Pisso et al. 2016). Significant challenges were identified above, whose solutions therefore require more interdisciplinary research in Svalbard. For example, moving beyond a predictive understanding of organismal response to warming in a laboratory microcosm, to a field-scale predictive model that understands landscape change and its impact upon the entire microbial community's interaction with methane. This challenge is not dissimilar to that which led to the development of the highly successful, interdisciplinary framework for soil science that was the Critical Zone Network (Brantley et al. 2017). Drawing inspiration from developments like this and applying them to Svalbard methane science deserve consideration (and funding), as the benefits could be felt quickly on account of Svalbard's accessibility for many international groups who want to work in the Arctic. Other challenges linked to the lack of cross-disciplinary interaction require interaction between periglacial and glacial geosciences groups (glacier–permafrost interaction), or between geoscience and ocean science groups in the context of shallow marine processes. Earth observation tools are also virtually absent from terrestrial methane science in Svalbard. Broader considerations include the need to engage with electronic engineers capable of developing much-needed improvements to sensor technologies and (low cost) observation platforms (such as drones).

4. Unanswered questions

The following research priorities will greatly improve the state of the science with respect to methane in Svalbard, whilst also providing a solid basis for Svalbard science to contribute to the forthcoming International Polar Year, IPY, in 2032/33:

4.1) More measurements of atmospheric methane and also methane fluxes across the atmospheric boundary layer are needed from different marine and terrestrial environments in order to improve the representation of Svalbard in the pan-Arctic context and to provide the first, robust bottom-up estimates for the entire archipelago.

4.2) We are preoccupied with the near-future, albeit for good reasons, because methane is going to be highly relevant to the magnitude of planetary warming over the rest of the 21st Century. However, we should also use Svalbard to understand the impact of large-scale methane releases upon the Earth system both in the distant past (e.g., Early Cretaceous) and more recently, following the onset of abrupt changes after the Last Glacial Maximum.

4.3) The discovery of young, meteoric water within the groundwaters that mobilise microbial and geogenic methane from beneath permafrost and glaciers means that it is time to establish how a warmer, wetter Svalbard might pressurise these environments and influence methane migration towards the sea and the atmosphere.

4.4) Microbial methane production and methanotrophy, along with other climate-sensitive biogeochemical processes in the active layer, need incorporation into predictive, numerical models after quantitative insights into organismal and community-scale responses to climate-driven environmental change have been informed by an understanding of landscape change.

5. Recommendations for the future

Important recommendations (R1 – R5) are identified below. We assign highest priority (urgency) to R1-R3. R4 is going to be difficult to implement or control, as several of the platforms that require development have global, multi-purpose utility. In terms of cost, R1, 3 and 5 most likely require larger-scale international collaboration, whilst R2 is easy to implement incrementally through national research councils.

- R1: Promote Svalbard as an accessible node in pan-Arctic methane observation networks through investment in observational infrastructure (ground-based, sub-marine, and atmospheric) at representative sites near settlements or research stations that will encourage also the use of Svalbard for the ground-truthing of forthcoming satellite products.
- R2: Establish observatories at key type sites (especially proglacial, periglacial and sub-marine groundwater seeps, ice wedge polygons) to examine quantitative links between their microbial ecology and the physical and chemical conditions, and where climate-driven changes in biogenic methane production and removal can be established. Data from these observatories need to be incorporated into key pan-Arctic databases, such as BAWLD-CH4 (Kuhn et al. 2021) and MethDB (Stanley et al. 2016).
- R3: Coordinate work across the land–ocean interface to better understand fluid migration into the sea and the atmosphere in association with changing submarine inputs (especially near tidewater glaciers, but also via groundwater discharge), changing circulation in fjords and

changing sea ice.

- R4: Promote the standardisation and harmonisation of measurement techniques from fixed and mobile platforms, especially drones and low-cost sensor measurements, whose widespread deployment should be encouraged. Address technological challenges that currently limit the adequacy of sampling and/or monitoring (e.g., by increasing endurance to enable year-round observation).
- R5: Establish sub-surface monitoring to elucidate fluid composition and migration processes in representative landscapes, such as Adventdalen, where a rich history of geological data collection can help rapidly develop land system models of geogenic methane migration in the past, present and future.

6. Data availability

Table 1: Key long-term or regional datasets describing methane in Svalbard. Additional datasets associated with individual studies, along with sampling details, are documented in Appendix 1 Table A2.

Dataset	Parameter	Period	Location	Metadata access (URL)	Dataset provider
Atmospheric Methane	-Methane concentrations -Methane isotopes	2001–2024	Zeppelin Observatory, Ny-Ålesund	https://ebas.nilu.no/	NILU
Geogenic Methane	-Geochemistry, gas, and isotope data from 8 boreholes drilled around Longyearbyen	2011–2013	Adventdalen	https://doi.org/10.5281/zenodo.10813248 (Additional core metadata included in Table 2 of Senger et al. (In Press)	(UNIS CO2 Laboratory, 2024)
Groundwater methane	-Biogeochemical analyses from glacial and periglacial groundwater springs -Methane concentration -Methane isotopes	2018–2023	Svalbard	https://doi.org/10.5281/zenodo.13736679	CLIMAGAS Project
Gas hydrates	-Modelled natural gas hydrate stability zone (GHSZ)	2000–2029	Svalbard fjords	https://zenodo.org/records/5091765	(Betlem 2021)
Sea-air fluxes	-Eddy covariance methane fluxes	2019–2021	Offshore Svalbard (Arctic Ocean, Greenland Sea, Barents Sea)	https://doi.org/10.5285/c9ed4746-f104-4117-ba60-174c5275e2fe	(Workman et al. 2024)
Seafloor seeps	-Hydroacoustic gas flare detection	2015–2021	Western Spitsbergen fjords	https://doi.org/10.5281/zenodo.7822180	(Rodes et al. 2023)
Microbiology	Data reporting diversity, abundance and activity from community to single cell genomic levels	Ongoing	Active layer, permafrost sediments, benthic sediments, methane seeps, fjord water	See Appendix 1 Table A2	Multiple

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8. References

Adachi M, Ohtsuka T, Nakatsubo T, Koizumi H. (2006) The methane flux along topographical gradients on a glacier foreland in the High Arctic, Ny-Alesund, Svalbard. Polar bioscience 20: 131-139.

Åström EK, Sen A, Carroll ML, Carroll J (2020) Cold seeps in a warming Arctic: Insights for benthic ecology. Frontiers in Marine Science 7: 244. https://doi.org/10.3389/fmars.2020.00244

Bao T, Xu X, Jia G, Billesbach DP, Sullivan RC (2021) Much stronger tundra methane emissions during autumn freeze than spring thaw. Global Change Biology 27: 376-387. https://doi.org/10.1111/gcb.15421

Berndt C, Feseker T, Treude T, Krastel S, Liebetrau V, Niemann H, Bertics VJ, Dumke I, Dünnbier K, Ferré B, Graves C. (2014) Temporal constraints on hydrate-controlled methane seepage off Svalbard. Science 343: 284-7. https://doi.org/10.1126/science.1246298

Betlem P, Roy S, Birchall T, Hodson A, Noormets R, Römer M, Skogseth R, Senger K (2021) Modelling of the gas hydrate potential in Svalbard's fjords. Journal of Natural Gas Science and Engineering 94: 104127. https://doi.org/10.1016/j.jngse.2021.104127

Betlem P, Senger K, Hodson A (2019) 3D thermobaric modelling of the gas hydrate stability zone onshore central Spitsbergen, Arctic Norway. Marine and Petroleum Geology 100: 246-262. https://doi.org/10.1016/j.marpetgeo.2018.10.050

Birchall T, Jochmann M, Betlem P, Senger K, Hodson A, Olaussen S (2023) Permafrost Trapped Natural Gas in Svalbard, Norway. Frontiers in Earth Science 11: 1277027. https://doi.org/10.3389/feart.2023.1277027

Blake LI, Tveit A, Øvreås L, Head IM, Gray ND (2015) Response of methanogens in Arctic sediments to temperature and methanogenic substrate availability. PLoS One 10: e0129733. https://doi.org/10.1371/journal.pone.0129733

Braathen A, Bælum K, Christiansen HH, Dahl T, Eiken O, Elvebakk H, Hansen F, Hanssen TH, Jochmann M, Johansen TA, Johnsen H (2012) The Longyearbyen CO 2 Lab of Svalbard, Norway—initial assessment of the geological conditions for CO 2 sequestration. Norwegian Journal of Geology/Norsk Geologisk Forening 92(4).

Brantley SL, McDowell WH, Dietrich WE, White TS, Kumar P, Anderson SP, Chorover J, Lohse KA, Bales RC, Richter DD, Grant G. (2017) Designing a network of critical zone observatories to explore the living skin of the terrestrial Earth. Earth Surface Dynamics: 5:841-60. https://doi.org/10.5194/esurf-5-841-2017

Burns R, Wynn PM, Barker P, McNamara N, Oakley S, Ostle N, Stott AW, Tuffen H, Zhou Z, Tweed FS, Chesler A (2018) Direct isotopic evidence of biogenic methane production and efflux from beneath a temperate glacier. Scientific reports 8: 17118. https://doi.org/10.1038/s41598-018-35253-2

Cable S, Elberling B, Kroon A (2018) Holocene permafrost history and cryostratigraphy in the High-Arctic Adventdalen Valley, central Svalbard. Boreas 47: 423-442. https://doi.org/10.1111/bor.12286

Crémière A, Lepland A, Chand S, Sahy D, Condon DJ, Noble SR, Martma T, Thorsnes T, Sauer S, Brunstad H (2016) Timescales of methane seepage on the Norwegian margin following collapse of the Scandinavian Ice Sheet. Nature communications https://doi.org/10.1038/ncomms11509

Chen Q, Zhu R, Wang Q, Xu H (2014) Methane and nitrous oxide fluxes from four tundra ecotopes in Ny-Ålesund of the High Arctic. Journal of Environmental Sciences 26: 1403-1410. https://doi.org/10.1016/j.jes.2014.05.005

Christiansen HH (2005) Thermal regime of ice-wedge cracking in Adventdalen, Svalbard. Permafrost and Periglacial Processes 16:87-98. https://doi.org/10.1002/ppp.523

Christiansen JR, Röckmann T, Popa ME, Sapart CJ, Jørgensen CJ (2021) Carbon emissions from the edge of the Greenland ice sheet reveal subglacial processes of methane and carbon dioxide turnover. Journal of Geophysical Research: Biogeosciences, 126: e2021JG006308. https://doi.org/10.1029/2021JG006308

Damm E, Mackensen A, Budéus G, Faber E, Hanfland C (2005) Pathways of methane in seawater: Plume spreading in an Arctic shelf environment (SW-Spitsbergen). Continental Shelf Research 25: 1453-1472. https://doi.org/10.1016/j.csr.2005.03.003

Damm E, Ericson Y, Falck E (2021) Waterside convection and stratification control methane spreading in supersaturated Arctic fjords (Spitsbergen). Continental Shelf Research 224:104473. https://doi.org/10.1016/j.csr.2021.104473

Dean JF, Middelburg JJ, Röckmann T, Aerts R, Blauw LG, Egger M, Jetten MS, de Jong AE, Meisel OH, Rasigraf O, Slomp CP (2018) Methane feedbacks to the global climate system in a warmer world. Reviews of Geophysics 56:207-50. https://doi.org/10.1002/2017RG000559

Delpech LM, Tveit AT, Hodson AJ, Hand KP, Kalenitchenko D (2024) Chemolithoautotrophic bacteria flourish at dark water-ice interfaces of an emerged Arctic cold seep. The ISME Journal 18: wrae170. https://doi.org/10.1093/ismejo/wrae170

Demidov NE, Borisik AL, Verkulich SR, Wetterich S, Gunar AY, Demidov VE, Zheltenkova NV, Koshurnikov AV, Mikhailova VM, Nikulina AL, Novikov AL (2020) Geocryological and hydrogeological conditions of the western part of Nordenskiold Land (Spitsbergen Archipelago). Izvestiya, Atmospheric and Oceanic Physics 56:1376-400.

Demidov V, Demidov N, Verkulich S, Wetterich S. (2022) Distribution of pingos on Svalbard. Geomorphology 412:108326. https://doi.org/10.1016/j.geomorph.2022.108326

Donateo A, Famulari D, Giovannelli D, Mariani A, Mazzola M, Decesari S, Pappaccogli G (2024) Observations of methane net sinks in the Arctic tundra. EGUsphere 2024:1-31. https://doi.org/10.5194/egusphere-2024-1440

Diak M, Böttcher ME, Ehlert von Ahn CM, Hong WL, Kędra M, Kotwicki L, Koziorowska-Makuch K, Kuliński K, Lepland A, Makuch P, Sen A. (2023) Permafrost and groundwater interaction: current state and future perspective. Frontiers in Earth Science 11:1254309. https://doi.org/10.3389/feart.2023.1254309

Ernakovich JG, Barbato RA, Rich VI, Schädel C, Hewitt RE, Doherty SJ, Whalen ED, Abbott BW, Barta J, Biasi C, Chabot CL (2022) Microbiome assembly in thawing permafrost and its feedbacks to climate. Global Change Biology 28:5007-26. https://doi.org/10.1111/gcb.16231

Forwick M, Baeten NJ, Vorren TO (2009) Pockmarks in Spitsbergen fjords. Norwegian Journal of Geology/Norsk Geologisk Forening 89: 65 - 77.

Gilbert GL, O'Neill HB, Nemec W, Thiel C, Christiansen HH, Buylaert JP (2018) Late Quaternary sedimentation and permafrost development in a Svalbard fjord-valley, Norwegian high Arctic. Sedimentology 65:2531-58. https://doi.org/10.1111/sed.12476

Graef C, Hestnes AG, Svenning MM, Frenzel P (2011) The active methanotrophic community in a wetland from the High Arctic. Environmental microbiology reports 3: 466-472. https://doi.org/10.1111/j.1758-2229.2010.00237.x

Graves CA, Steinle L, Rehder G, Niemann H, Connelly DP, Lowry D, Fisher RE, Stott AW, Sahling H, James RH (2015) Fluxes and fate of dissolved methane released at the seafloor at the landward limit of the gas hydrate stability zone offshore western Svalbard. Journal of Geophysical Research: Oceans. 120:6185-201. https://doi.org/10.1002/2015JC011084

Haldorsen S, Heim M, Dale B, Landvik JY, van der Ploeg M, Leijnse A, Salvigsen O, Hagen JO, Banks D. (2010) Sensitivity to long-term climate change of subpermafrost groundwater systems in Svalbard. Quaternary Research 73:393-402. https://doi.org/10.1016/j.yqres.2009.11.002

Hodson AJ, Nowak A, Hornum MT, Senger K, Redeker K, Christiansen HH, Jessen S, Betlem P, Thornton SF, Turchyn AV, Olaussen S (2020) Sub-permafrost methane seepage from open-system pingos in Svalbard. The Cryosphere 14:3829-42. https://doi.org/10.5194/tc-14-3829-2020

Hodson AJ, Nowak A, Redeker KR, Holmlund ES, Christiansen HH, Turchyn AV (2019) Seasonal dynamics of methane and carbon dioxide evasion from an open system pingo: Lagoon pingo, Svalbard. Frontiers in Earth Science 7:30. https://doi.org/10.3389/feart.2019.00030

Hodson A, Kleber G, Johnson J, Lonardi M, Petroselli C, Dixon T, Bottrell S (2023) Effects of glacier retreat upon glacier-groundwater coupling and biogeochemistry in Central Svalbard. Journal of Hydrology 624:129894. https://doi.org/10.1016/j.jhydrol.2023.129894

Hornum MT, Hodson AJ, Jessen S, Bense V, Senger K (2020) Numerical modelling of permafrost spring discharge and open-system pingo formation induced by basal permafrost aggradation. The Cryosphere 14: 4627-51. https://doi.org/10.5194/tc-14-4627-2020

Høj L, Olsen RA, Torsvik VL (2008) Effects of temperature on the diversity and community structure of known methanogenic groups and other archaea in high Arctic peat. The ISME journal 2: 37-48. https://doi.org/10.1038/ismej.2007.84

Humlum O, Instanes A, Sollid JL (2003) Permafrost in Svalbard: a review of research history, climatic background and engineering challenges. Polar research 22:191-215. https://doi.org/10.3402/polar.v22i2.6455

Huq F, Smalley PC, Mørkved PT, Johansen I, Yarushina V, Johansen H (2017) The Longyearbyen CO2 Lab: Fluid communication in reservoir and caprock. International Journal of Greenhouse Gas Control 63:59-76. https://doi.org/10.1016/j.ijggc.2017.05.005

Johansen BE, Karlsen SR, Tømmervik H (2012) Vegetation mapping of Svalbard utilising Landsat TM/ETM+ data. Polar Record, 48(1), 47-63. https://doi.org/10.1017/S0032247411000647

Jones, E., 2019. The Biogeochemistry of the Active Layer and Shallow Permafrost in a High Arctic Fjord Valley, Svalbard (Doctoral dissertation, University of Sheffield), 178 p. https://etheses.whiterose.ac.uk/26304/

Jones EL, Hodson AJ, Redeker KR, Christiansen HH, Thornton SF, Rogers J (2023) Biogeochemistry of low-and high-centered ice-wedge polygons in wetlands in Svalbard. Permafrost and Periglacial Processes 34:359-69. https://doi.org/10.1002/ppp.2192

Jones EL, Hodson AJ, Thornton SF, Redeker KR, Rogers J, Wynn PM, Dixon TJ, Bottrell SH, O'Neill HB (2020) Biogeochemical processes in the active layer and permafrost of a high Arctic Fjord valley. Frontiers in Earth Science 8:342. https://doi.org/10.3389/feart.2020.00342

Kim JH, Ryu JS, Hong WL, Jang K, Joo YJ, Lemarchand D, Hur J, Park MH, Chen M, Kang MH, Park S (2022) Assessing the impact of freshwater discharge on the fluid chemistry in the Svalbard fjords. Science of the Total Environment 835:155516. https://doi.org/10.1016/j.scitotenv.2022.155516

Kleber GE, Hodson AJ, Magerl L, Mannerfelt ES, Bradbury HJ, Zhu Y, Trimmer M, Turchyn AV (2023) Groundwater springs formed during glacial retreat are a large source of methane in the high Arctic. Nature Geoscience 16:597-604. https://doi.org/10.1038/s41561-023-01210-6

Kleber GE, Magerl L, Turchyn AV, Redeker K, Thiele S, Liira M, Herodes K, Øvreås L, Hodson A (2024) Shallow and deep groundwater moderate methane dynamics in a high Arctic glacial catchment. Frontiers in Earth Science 12: 1340399. https://doi.org/10.3389/feart.2024.1340399

Kleber GE, Magerl L, Turchyn AV, Trimmer M, Zhu Y, Hodson A (In Press) Proglacial methane emissions driven by meltwater and groundwater flushing in a high Arctic glacial catchment. EGUsphere 2024:1-23. https://doi.org/10.5194/egusphere-2024-1273

Kolchev I, Marshall IP, Jones E, Yde JC, Nørnberg P, Mateos-Rivera A, Hodson AJ, Bak EN, Finster K (2022) Microbial iron reduction and greenhouse gas production in response to organic matter amendment and temperature increase of periglacial sediments, Bolterdalen, Svalbard. Arctic, Antarctic, and Alpine Research 54: 314-34. https://doi.org/10.1080/15230430.2022.2097757

Konya K, Sueyoshi T, Iwahana G, Morishita T, Uetake J, Wakita M (2024) CH4 emissions from runoff water of Alaskan mountain glaciers. Scientific Reports 14: 10558. https://doi.org/10.1038/s41598-024-56608-y

Kuhn MA, Varner RK, Bastviken D, Crill P, MacIntyre S, Turetsky M, Walter Anthony K, McGuire AD, Olefeldt D. (2021) BAWLD-CH_4: a comprehensive dataset of methane fluxes from boreal and arctic ecosystems. Earth Syst. Sci. Data 13: 5151–5189. https://doi.org/10.5194/essd-13-5151-2021.

Kutzbach L, Wagner D, Pfeiffer EM (2004) Effect of microrelief and vegetation on methane emission from wet polygonal tundra, Lena Delta, Northern Siberia. Biogeochemistry 69:341-62. https://doi.org/10.1023/B:BIOG.0000031053.81520.db

Lamarche-Gagnon G, Wadham JL, Sherwood Lollar B, Arndt S, Fietzek P, Beaton AD, Tedstone AJ, Telling J, Bagshaw EA, Hawkings JR, Kohler TJ (2019) Greenland melt drives continuous export of methane from the ice-sheet bed. Nature 565: 73-7. https://doi.org/10.1038/s41586-018-0800-0

Li J, Zhu ZY, Yang Z, Li W, Lv Y, Zhang Y (2023) Soil microorganisms and methane emissions in response to short-term warming field incubation in Svalbard. Frontiers in Microbiology 14: 1276065. https://doi.org/10.3389/fmicb.2023.1276065

Liira M, Noormets R, Sepp H, Kekišev O, Maddison M, Olaussen S (2019) Sediment geochemical study of hydrocarbon seeps in Isfjorden and Mohnbukta: a comparison between western and eastern Spitsbergen, Svalbard. Arktos 5:49-62. https://doi.org/10.1007/s41063-019-00067-7

Lindroth A, Pirk N, Jónsdóttir IS, Stiegler C, Klemedtsson L, Nilsson M (2022) Moist moss tundra on Kapp Linne, Svalbard is a net source of CO2 and CH4 to the atmosphere. Biogeosciences 19: 3921 – 3934. https://doi.org/10.5194/bg-19-3921-2022

Malard L, Avila-Jimenez M, Convey P, Larose C, Hodson A, Øvreås L, Schmale J, Anwar MZ, Pearce D (2019) Microbial activity monitoring by the Integrated Arctic Earth Observing System. In: Orr et al. (eds): SESS report 2018, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 48-81. https://doi.org/10.5281/zenodo.4778348

Mateos-Rivera A, Øvreås L, Wilson B, Yde JC, Finster KW (2018) Activity and diversity of methane-oxidizing bacteria along a Norwegian sub-Arctic glacier forefield. FEMS Microbiology Ecology 94: fiy059. https://doi.org/10.1093/femsec/fiy059

Mau S, Blees J, Helmke E, Niemann H, Damm E (2013) Vertical distribution of methane oxidation and methanotrophic response to elevated methane concentrations in stratified waters of the Arctic fjord Storfjorden (Svalbard, Norway). Biogeosciences 10: 6267-78. https://doi.org/10.5194/bg-10-6267-2013

Mau S, Römer M, Torres ME, Bussmann I, Pape T, Damm E, Geprägs P, Wintersteller P, Hsu CW, Loher M, Bohrmann G (2017) Widespread methane seepage along the continental margin off Svalbard-from Bjørnøya to Kongsfjorden. Scientific reports 7: 42997. https://doi.org/10.1038/srep42997

Metcalfe DB, Hermans TD, Ahlstrand J, Becker M, Berggren M, Björk RG, Björkman MP, Blok D, Chaudhary N, Chisholm C, Classen AT (2018) Patchy field sampling biases understanding of climate change impacts across the Arctic. Nature Ecology & Evolution 2: 1443-8. https://doi.org/10.1038/s41559-018-0612-5

Miner KR, Turetsky MR, Malina E, Bartsch A, Tamminen J, McGuire AD, Fix A, Sweeney C, Elder CD, Miller CE (2022) Permafrost carbon emissions in a changing Arctic. Nature Reviews Earth & Environment 3: 55-67. https://doi.org/10.1038/s43017-021-00230-3

Montelli A, Solovyeva M and Akhmanov G (2024) Extensive glacitectonism and rapid deglacial fluid expulsion in the northeastern Barents Sea. Communications Earth & Environment 5: 353. https://doi.org/10.1038/s43247-024-01512-6

Morimoto S, Aoki S, Nakazawa T, Yamanouchi T (2006) Temporal variations of the carbon isotopic ratio of atmospheric methane observed at Ny Ålesund, Svalbard from 1996 to 2004. Geophysical Research Letters 33: L01807. https://doi.org/10.1029/2005GL024648

Müller O, Bang-Andreasen T, White III RA, Elberling B, Taş N, Kneafsey T, Jansson JK, Øvreås L (2018) Disentangling the complexity of permafrost soil by using high resolution profiling of microbial community composition, key functions and respiration rates. Environmental microbiology 20: 4328-42. https://doi.org/10.1111/1462-2920.14348

Myhre CL, Hermansen O, Fiebig M, Lunder CR, Fjæraa AM, Svendby TM, Platt SM, Hansen GH, Schmidbauer JN, Krognes T (2016) Monitoring of greenhouse gases and aerosols at Svalbard and Birkenes NILU report, 31/2016. NILU, Kjeller. http://hdl.handle.net/11250/2452834

Nisbet EG, Manning MR, Dlugokencky EJ, Fisher RE, Lowry D, Michel SE, Myhre CL, Platt SM, Allen G, Bousquet P, Brownlow R. Very strong atmospheric methane growth in the 4 years 2014–2017 (2019) Implications for the Paris Agreement. Global Biogeochemical Cycles 33:318-42. https://doi.org/10.1029/2018GB006009

Nowak A, Hodgkins R, Nikulina A, Osuch M, Wawrzyniak T, Kavan J, Łepkowska E, Majerska M, Romashova K, Vasilevich I, Sobota I, Rachlewicz, G (2021) From land to fjords: The review of Svalbard hydrology from 1970 to 2019. In: Moreno-Ibáñez et al (eds) SESS report 2020, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 176-200.

https://doi.org/10.5281/zenodo.4294063

Ohm SE, Larsen L, Olaussen S, Senger K, Birchall T, Demchuk T, Hodson A, Johansen I, Titlestad GO, Karlsen DA, Braathen A (2019) Discovery of shale gas in organic-rich Jurassic successions, Adventdalen, Central Spitsbergen, Norway. Norsk Geologisk Tidsskrift 99:349. https://doi.org/10.17850/njg007

Olaussen S, Grundvåg SA, Senger K, Anell I, Betlem P, Birchall T, Braathen A, Dallmann W, Jochmann M, Johannessen EP, Lord G (2025) Svalbard composite tectono-sedimentary element, Barents Sea. Geological Society, London, Memoirs 57: M57-2021. https://doi.org/10.1144/M57-2021-36

Olaussen S, Senger K, Braathen A, Grundvåg SA, Mørk A (2019) You learn as long as you drill; research synthesis from the Longyearbyen CO2 Laboratory, Svalbard, Norway. Norwegian Journal of Geology 99: 157-87. https://dx.doi.org/10.17850/njg008

Panieri G, Bünz S, Fornari DJ, Escartin J, Serov P, Jansson P, Torres ME, Johnson JE, Hong W, Sauer S, Garcia R (2017) An integrated view of the methane system in the pockmarks at Vestnesa Ridge, 79 N. Marine Geology 390: 282-300. https://doi.org/10.1016/j.margeo.2017.06.006

Patil SK, Islam T, Tveit A, Hodson A, Øvreås L. (2024) Targeting methanotrophs and isolation of a novel psychrophilic Methylobacter species from a terrestrial Arctic alkaline methane seep in Lagoon Pingo, Central Spitsbergen (78° N). Antonie van Leeuwenhoek 117:60. https://doi.org/10.1007/s10482-024-01953-1

Pirk N, Mastepanov M, López-Blanco E, Christensen LH, Christiansen HH, Hansen BU, Lund M, Parmentier FJ, Skov K, Christensen TR. (2017) Toward a statistical description of methane emissions from arctic wetlands. Ambio 46:70-80. https://doi.org/10.1007/s13280-016-0893-3

Pirk N, Tamstorf MP, Lund M, Mastepanov M, Pedersen SH, Mylius MR, Parmentier FJ, Christiansen HH, Christensen TR. (2016) Snowpack fluxes of methane and carbon dioxide from high Arctic tundra. Journal of Geophysical Research: Biogeosciences 121:2886-900. https://doi.org/10.1002/2016JG003486.

Pirk N, Santos T, Gustafson C, Johansson AJ, Tufvesson F, Parmentier FJ, Mastepanov M, Christensen TR (2015) Methane emission bursts from permafrost environments during autumn freeze-in: New insights from ground-penetrating radar. Geophysical Research Letters 42: 6732-8. https://doi.org/10.1002/2015GL065034

Pisso I, Myhre CL, Platt SM, Eckhardt S, Hermansen O, Schmidbauer N, Mienert J, Vadakkepuliyambatta S, Bauguitte S, Pitt J, Allen G. (2016) Constraints on oceanic methane emissions west of Svalbard from atmospheric in situ measurements and Lagrangian transport modeling. Journal of Geophysical Research: Atmospheres 121:14-88. https://doi.org/10.1002/2016JD025590.

Platt SM, Hov Ø, Berg T, Breivik K, Eckhardt S, Eleftheriadis K, Evangeliou N, Fiebig M, Fisher R, Hansen G, Hansson HC (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

Platt SM, Svendby TM, Hermansen O, Lunder CR, Fiebig M, Fjæraa AM, Hansen GH, Schmidbauer N, Myhre CL, Stebel K (2023) Monitoring of greenhouse gases and aerosols at Svalbard and Birkenes in 2022. NILU report 24/2023. https://hdl.handle.net/11250/3107693

Portnov A, Vadakkepuliyambatta S, Mienert J, Hubbard A (2016) Ice-sheet-driven methane storage and release in the Arctic. Nature communications 7:10314. https://doi.org/10.1038/ncomms10314

Reigstad LJ, Jorgensen SL, Lauritzen SE, Schleper C, Urich T (2011) Sulfur-oxidizing chemolithotrophic proteobacteria dominate the microbiota in high arctic thermal springs on Svalbard. Astrobiology 11: 665-78. https://doi.org/10.1089/ast.2010.055

Rodes N, Betlem P, Senger K, Römer M, Hodson A, Liira M, Birchall T, Roy S, Noormets R, Smyrak-Sikora A, Olaussen S. (2023) Active gas seepage in western Spitsbergen fjords, Svalbard archipelago: spatial extent and geological controls. Frontiers in Earth Science 20:p1173477. https://doi.org/10.3389/feart.2023.1173477

Römer, M, Marcon Y, Pape T, Malnati J, Meurer C, Gutiérrez Flores P, Bazhenova E, Feddersen G, Marklein M, Betlem P, Rodes N (2024) Gas system within Svalbard's fjords, Cruise no. HE628, 04 September - 01 October 2023, Longyearbyen (Norway) - Stavanger (Norway). Cruise Report, Begutachtungspanel Forschungsschiffe, Bonn, 2024-01-01. https://doi.org/10.48433/cr_he628.

Rotem D, Weinstein Y, Christiansen HH, Sültenfuß J Hodson A (2024) Ra isotope perspective on the hydrology and continuity of permafrost in the high Arctic. Science of The Total Environment 950: 175412. https://doi.org/10.1016/j.scitotenv.2024.175412

Roy S, Senger K, Hovland M, Römer M, Braathen A (2019) Geological controls on shallow gas distribution and seafloor seepage in an Arctic fjord of Spitsbergen, Norway. Marine and Petroleum Geology 107: 237-54. https://doi.org/10.1016/j.marpetgeo.2019.05.021

Sahling H, Römer M, Pape T, Bergès B, dos Santos Fereirra C, Boelmann J, Geprägs P, Tomczyk M, Nowald N, Dimmler W, Schroedter L (2014) Gas emissions at the continental margin west of Svalbard: mapping, sampling, and quantification. Biogeosciences 11: 6029-46. https://doi.org/10.5194/bg-11-6029-2014

Sapper SE, Jørgensen CJ, Schroll M, Keppler F, Christiansen JR (2023) Methane emissions from subglacial meltwater of three alpine glaciers in Yukon, Canada. Arctic, Antarctic, and Alpine Research 55: 2284456. https://doi.org/10.1080/15230430.2023.2284456

Saunois M, Stavert AR, Poulter B, Bousquet P, Canadell JG, Jackson RB, Raymond PA, Dlugokencky EJ, Houweling S, Patra PK, Ciais P. The global methane budget 2000–2017. Earth System Science Data Discussions. 2019 Aug 19;2019:1-36. https://doi.org/10.5194/essd-12-1561-2020

Schuur EA, Abbott BW, Commane R, Ernakovich J, Euskirchen E, Hugelius G, Grosse G, Jones M, Koven C, Leshyk V, Lawrence D (2022) Permafrost and climate change: carbon cycle feedbacks from the warming Arctic. Annual Review of Environment and Resources 47: 343-71. https://doi.org/10.1146/annurev-environ-012220-011847

Senger K, Betlem P, Braathen A, Olaussen S, Sand G. (In Press) Longyearbyen CO2 lab project–from a vision of a CO2-neutral Svalbard to a geoscience data eldorado. Arctic Science. https://doi.org/10.1139/as-2024-0019

Senger K, Brugmans P, Grundvåg SA, Jochmann MM, Nøttvedt A, Olaussen S, Skotte A, Smyrak-Sikora A. Petroleum, coal and research drilling onshore Svalbard: a historical perspective. Norwegian Journal of Geology, 99:3. https://doi.org/10.17850/njg99-3-1

Senger K, Ammerlaan F, Betlem P, Dumais M-A, Eagles G, Foster W, Geissler WH, Grundvåg S-A, Hodson A, Horota R, Hurum J, Jones M, Kierulf HP, Majka J, Marsden L, Michalski K, Minakov A, Ogata K, Olaussen S, Osmundsen PT, Planke S, Ruppel A, Sartell A, Shephard GE, Śliwińska KK, Smeraglia L, Smyrak-Sikora A, Spiegel-Behnke C, Zuchuat V (2025) Geology of Svalbard: Deep-time and Deep-Earth. In: Runge et al (eds) SESS report 2024, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 52-83. https://doi.org/10.5281/zenodo.14425478

Serov P, Vadakkepuliyambatta S, Mienert J, Patton H, Portnov A, Silyakova A, Panieri G, Carroll ML, Carroll J, Andreassen K, Hubbard A (2017) Postglacial response of Arctic Ocean gas hydrates to climatic amelioration. Proceedings of the National Academy of Sciences 114: 6215-20. https://doi.org/10.1073/pnas.1619288114

Sevestre H, Benn DI, Hulton NR, Bælum K (2015) Thermal structure of Svalbard glaciers and implications for thermal switch models of glacier surging. Journal of Geophysical Research: Earth Surface 120:2220-2236. https://doi.org/10.1002/2015JF003517

Stanley EH, Casson NJ, Christel ST, Crawford JT, Loken LC, Oliver SK (2016) The ecology of methane in streams and rivers: patterns, controls, and global significance. Ecological monographs 86: 146-71. https://doi.org/10.1890/15-1027

Strand SM, Christiansen HH, Johansson M, Åkerman J, Humlum O (2021) Active layer thickening and controls on interannual variability in the Nordic Arctic compared to the circum-Arctic. Permafrost and Periglacial Processes 32: 47-58. https://doi.org/10.1002/ppp.2088

Thompson RL, Sasakawa M, Machida T, Aalto T, Worthy D, Lavric JV, Lund Myhre C, Stohl A (2017) Methane fluxes in the high northern latitudes for 2005–2013 estimated using a Bayesian atmospheric inversion. Atmospheric Chemistry and Physics 17: 3553-72. https://doi.org/10.5194/acp-17-3553-2017

Trubitsyn VE, Suzina NE, Rivkina EM, Shcherbakova VA (2023) A new methanogenic, hydrogenotrophic archaeon from Spitsbergen permafrost. Microbiology 92:119-128. https://doi.org/10.1134/S0026261722603256

Tveit A, Schwacke R, Svenning MM, Urich T (2013) Organic carbon transformations in high-Arctic peat soils: Key functions and microorganisms. ISME Journa 7: 299–311. https://doi.org/10.1038/ismej.2012.99

Tveit AT, Söllinger A, Rainer EM, Didriksen A, Hestnes AG, Motleleng L, Hellinger HJ, Rattei T, Svenning MM (2023) Thermal acclimation of methanotrophs from the genus Methylobacter. The ISME Journal 17: 502-13. https://doi.org/10.1038/s41396-023-01363-7

Tveit AT, Urich T, Frenzel P, Svenning MM (2015) Metabolic and trophic interactions modulate methane production by Arctic peat microbiota in response to warming. Proceedings of the National Academy of Sciences 112: E2507-16. https://doi.org/10.1073/pnas.1420797112

Wadham JL, Tranter M, Tulaczyk S, Sharp M (2008) Subglacial methanogenesis: a potential climatic amplifier? Global Biogeochemical Cycles 22: GB2021. https://doi.org/10.1029/2007GB002951

Wadham JL, Arndt S, Tulaczyk S, Stibal M, Tranter M, Telling J, Lis GP, Lawson E, Ridgwell A, Dubnick A, Sharp MJ (2012) Potential methane reservoirs beneath Antarctica. Nature 488: 633-7. https://doi.org/10.1038/nature11374

Walter Anthony KM, Anthony P, Hasson N, Edgar C, Sivan O, Eliani-Russak E, Bergman O, Minsley BJ, James SR, Pastick NJ, Kholodov A (2024) Upland Yedoma taliks are an unpredicted source of atmospheric methane. Nature Communications 15: 6056. https://doi.org/10.1038/s41467-024-50346-5

Walter Anthony K, Daanen R, Anthony P, Schneider von Deimling T, Ping CL, Chanton JP, Grosse G (2016) Methane emissions proportional to permafrost carbon thawed in Arctic lakes since the 1950s. Nature Geoscience 9: 679-82. https://doi.org/10.1038/ngeo2795

Wartiainen I, Hestnes AG, Svenning MM (2003) Methanotrophic diversity in high arctic wetlands on the islands of Svalbard (Norway)-denaturing gradient gel electrophoresis analysis of soil DNA and enrichment cultures. Canadian Journal of Microbiology 49: 602-12. https://doi.org/10.1139/w03-080

Workman E, Fisher RE, France JL, Linse K, Yang M, Bell T, Dong Y, Jones AE (2024) Methane emissions from seabed to atmosphere in polar oceans revealed by direct methane flux measurements. Journal of Geophysical Research: Atmospheres 129: e2023JD040632. https://doi.org/10.1029/2023JD040632

Whiticar MJ (1999) Carbon and hydrogen isotope systematics of bacterial formation and oxidation of methane. Chemical Geology 161: 291-314. https://doi.org/10.1016/S0009-2541(99)00092-3

Wittig S, Berchet A, Pison I, Saunois M, Thanwerdas J, Martinez A, Paris JD, Machida T, Sasakawa M, Worthy DE, Lan X (2023) Estimating methane emissions in the Arctic nations using surface observations from 2008 to 2019. Atmospheric Chemistry and Physics 23: 6457-85. https://doi.org/10.5194/acp-23-6457-2023

Yun J, Yang Y, Zhou X, Lee J, Choi J, Kim M, Gyeong H, Laffly D, Kang H (2023) Effects of deglaciation on the succession of methanotrophic communities in inland and tidewater glaciers in the high Arctic, Svalbard. Catena 231: 107267. https://doi.org/10.1016/j.catena.2023.107267

Zona D, Gioli B, Commane R, Lindaas J, Wofsy SC, Miller CE, Dinardo SJ, Dengel S, Sweeney C, Karion A, Chang RY (2016) Cold season emissions dominate the Arctic tundra methane budget. Proceedings of the National Academy of Sciences 113: 40-45. https://doi.org/10.1073/pnas.1516017113

Appendix 1

Table A1: Crude estimates of methane emission/sequestration potential in Svalbard. Note that only the first two rows are from peer-reviewed, published estimates. The remaining estimates are very uncertain and require more rigorous treatment that is beyond the scope of this report. Positive values are emissions.

Emission surface	Likely flux	Comments
Svalbard "Continental Platform"	< 0.2×10^{12} g CH_4 y^{-1}	Maximum contribution of Svalbard land mass and coastal waters to Arctic atmosphere from Pisso et al. (2016). Large uncertainty between 0 and 1×10^{12} g CH_4 y^{-1}
Glacial forefields	2.3×10^9 g CH_4 y^{-1} ($\pm 0.14 \times 10^9$ g CH_4 y^{-1})	Basic bottom-up estimate from extrapolation after surveying 10% of Svalbard land area (after Kleber et al. 2023). See data deposition https://doi.org/10.5281/zenodo.7709380 .
Pingo seeps	< 10^7 g CH_4 y^{-1}	Of 139 pingo mounds (Demidov et al. 2022), about 12 have ongoing discharge, 9 of which confirm high methane emission potential. See CLIMAGAS data (Appendix 1 Table A2). Here we assume a maximum of 1×10^6 g CH_4 y^{-1}, substantially higher than the only published flux, which only considered diffusion during summer (Hodson et al. 2017: ebullition measurements are lacking, but greatly exceed diffusion at this site: Hodson, unpub. data).
Wetlands	~ 6.9×10^8 g CH_4 y^{-1}	There is ca. 345 km^2 of "swamp and wet moss tundra" or "mires and wet marsh tundra" (mostly in Spitsbergen), which constitute wetlands of proven methanogenic potential (Category 10 and 11 in Johansen et al. 2012). The emission potential here assumes net fluxes of 2 g CH_4 m^{-2} y^{-1}, based upon median values from chamber measurements of 3 consecutive summer seasons (range: ca. 1–2 g CH_4 m^{-2} y^{-1}). We use the upper value because winter emissions are not accounted for.
Tundra (net methanotrophic surfaces)	> -5.3×10^8 g CH_4 y^{-1}	There are ca. 3700 km^2 of vegetated surfaces in Svalbard that are likely to promote net methanotrophy according to soil moisture and plant community descriptions (Category 12 to 15) of Johansen et al. (2012). Eddy covariance measurements over two entire years at a dry tundra site produced a strong sink (0.08–0.18 g CH_4 m^{-2} y^{-1}) and so here we use the upper limit of sequestration to represent the ca. 2900 km^2 of corresponding tundra vegetation (Category 13 and 14) defined by Johansen et al. (2012). No other methanotrophy is considered here.
Central West Spitsbergen Fjords	Not possible but net source likely	Isfjord, Van Mijenfjord, Van Kuelenfjord and Hornsund are all underlain by shale-prone geologies that release geogenic gas and with a combined surface area of ca. 3500 km^2. Workman et al.'s (2024) sea–air CH_4 fluxes in West Spitsbergen coastal waters include some Isfjorden measurements and lie in the range −0.22 to 1.50 mg CH_4 m^{-2} d^{-1}, with an average of 0.21 ± 0.13 mg CH_4 m^{-2} d^{-1} for waters < 200 m deep. However, extrapolating these values to fjord waters, without accounting for their strong seasonality is not possible. Furthermore, significant shallow-marine emissions from the same sub-sea geologies are likely from Eastern Svalbard and into the Barents Sea (whose entire emission flux is thought to be $4.5 \pm 1.6 \times 10^9$ g CH_4 $month^{-1}$ (summer only: Workman et al. 2024).
Lakes and ponds	Not possible, but minimum impact likely	The CLIMAGAS data set suggests large proglacial lakes are likely to be weak methane sources if they are connected to the same groundwaters that exploit glacier forefields. Small lakes are unknown. The combined lake cover in Svalbard is only 395 km^2 according to Chernov and Romashova (2023). Many lack through-taliks and are underlain by fine grained (former marine) sediments, implying limited migration from sub-permafrost groundwaters. Deeper lakes and organic-rich ponds deserve assessment.

Table A2: Individual studies with useful methane data from Svalbard. Blank cells indicate a lack of deposited data.

Dataset	Parameter	Period	Location	Data Accessibility	Source/Publication	Notes
Active Layer Methane	-Eddy Covariance measurements	2021–2023	Ny-Ålesund	https://metadata.iadc.cnr.it/geonetwork/srv/api/records/a4848f34-1063-4ee0-b0ed-b358ca30a651	Donateo et al. 2024	The longest running eddy covariance installation for CH_4. Manuscript under review at time of writing.
Active Layer Methane	-Chamber flux measurements	2014	Ny-Ålesund		Li et al. 2016	Discusses impact of sunlight on methane emissions in tundra ecosystems
Active Layer Methane	-Chamber CH_4 measurements	2015–2016	Kapp Linné	https://doi.org/10.5281/zenodo.5704509	Lindroth et al. 2021	Examines CH_4 fluxes in a moist moss tundra environment
Active Layer Methane	-CH_4 isotopes -Chamber CH_4 measurements	2015	Adventdalen	Data available upon request to norbert.pirk@nateko.lu.se	Pirk et al. 2016	Cold season methane flux measurements in a low-centred ice-wedge polygon environment Concurrent work conducted in Greenland
Active Layer Methane	-Chamber CH_4 measurements	2013–2015	Adventdalen		Pirk et al. 2017	Impact of snow cover and ground thermal conditions on methane emissions from a tundra ecosystem Concurrent work conducted in Greenland
Active Layer Methane	-Chamber CH_4 flux measurements	2008–2009	Ny-Ålesund		Chen et al. 2014	Investigates methane fluxes from 4 tundra ecotopes
Active Layer Methane	-Chamber CH_4 flux measurements	2008–2009	Ny-Ålesund		Zhu et al. 2012	Compares methane fluxes from the tundra in seabird and non-seabird colonies
Active Layer Methane	-Porewater water quality parameters -Methane concentrations -Methane isotopes	2015–2017	Adventdalen	https://doi.org/10.5285/4c90d954-3db2-4084-9fe9-e050c839a6fe	Jones, 2019	Pore water extractions from sediment cores in the active layer and upper permafrost
Atmospheric Methane	-CH_4 mole fractions	2017–2024	Zeppelin Observatory, Ny-Ålesund	https://hdl.handle.net/11676/gaD1iRYTx0BlRuLedkbDy1Pe	Lund Myhre et al. 2024	ICOS (Integrated Carbon Observation System) hourly atmospheric CH_4 molar fraction data
Atmospheric Methane	-CH_4 mole fraction -CH_4 isotope ratios	1996–2013	Ny-Ålesund		Morimoto et al. 2017	Analysis of weekly air samples

Dataset	Parameter	Period	Location	Data Accessibility	Source/Publication	Notes
Atmospheric Methane	-FTIR methane mixing ratios	1992–2023	Ny-Ålesund	https://www-air.larc.nasa.gov/missions/ndacc/data.html	NDACC, 2023	Continuous Ground-based Fourier Transform InfraRed (FTIR) spectrometry measurements facilitated by the Network for the Detection of Atmospheric Composition Change (NDACC)
Atmospheric Methane	-CH_4 mole fraction -CH_4 isotope ratios	2012–2019	Ny-Ålesund		Morimoto et al. 2021	Pan-Arctic greenhouse gas observations, with long-term, continuous observations based at Ny Ålesund
Atmospheric methane	-CH_4 air mole fractions	1983–2024	Zeppelin Observatory, Ny-Ålesund,	https://gml.noaa.gov/aftp/data/trace_gases/ch4/flask/surface/txt/ch4_zep_surface-flask_1_ccgg_event.txt	Lan et al. 2024 and NOAA Global Monitoring Laboratory	Discrete and monthly analysis of CH_4 mole fractions in glass flasks from the NOAA GML Carbon Cycle Cooperative Global Air Sampling Network
Atmospheric Methane	-CH_4 carbon isotopes	1998–2022	Zeppelin Observatory, Ny-Ålesund	https://gml.noaa.gov/aftp/data/trace_gases/ch4c13/flask/surface/txt/ch4c13_zep_surface-flask_7_sil_event.txt	Michel et al. 2023 and NOAA Global Monitoring Laboratory	Discrete analysis of methane carbon isotope compositions in glass flasks from the NOAA GML Carbon Cycle Cooperative Global Air Sampling Network
Gas Hydrates	-Modelled natural gas hydrate stability zone (GHSZ)		Onshore Central Spitsbergen	Article includes table citing the data integrated into the model	Betlem et al. 2019	3D thermobaric modelling of GHSZ
Groundwater Methane	-CH_4 concentrations -CH_4 isotopic composition -Water quality parameters	2015–2017	Adventdalen	https://doi.org/10.5285/3D82FD3F-884B-47B6-B11C-6C96D66B950D	Hodson, 2020	Analysis of groundwater springs discharging from open system pingos
Groundwater Methane	-Borehole groundwater gas composition -Spring/icing/lake water CH_4 analysis	Soviet period; 2016–2020	Western Spitsbergen		Demidov et al. 2020	Archived geocryological and hydrogeological data and results from Russian Scientific Arctic Expedition on Spitsbergen (RAE-S) studies

Dataset	Parameter	Period	Location	Data Accessibility	Source/Publication	Notes
Groundwater Methane	-Water geochemistry -16S rRNA sequences -CH_4 concentrations -CH_4 carbon isotopes	2021–2022	Vallåkrabreen	https://zenodo.org/records/10600361	Kleber et al. 2024	Geochemical analysis of groundwater and glacial river methane to determine methane source and pathway
Groundwater Methane	-CH_4 concentrations -Icing depth and area	2021–2022	Central Spitsbergen	https://doi.org/10.5281/zenodo.7709380	Hodson and Kleber, 2023	Part of the CLIMAGAS inventory (See Table 1)
Microbial Methane Processes	-Analysis of new methanogenic archaeal strain -16S rRNA sequences	2016	Barentsburg	https://www.ncbi.nlm.nih.gov/ (16S rRNA accession number OK037044; mcrA accession number OM927980; read libraries accession number SRA SRX12179610n; genome accession number GCA_019931065.1)	Trubitsyn et al. 2023	Discusses new strain of methanogenic archaea in Spitsbergen permafrost and assesses ideal growth conditions
Microbial Methane Processes	-16S rRNA gene sequences -CH_4 concentrations	2018	Barentsburg	The National Omics Data Encyclopedia Database, BioProject accession number OEP004357 and OEP004358	Li et al. 2023	Incubation study analysing how bacterial composition and CH_4 production potential vary with increasing temperatures
Microbial Methane Processes	-Methanotrophic microbial community analysis -Chamber CH_4 fluxes	2014–2018	Kongsfjordneset	**https://doi.org/jd4g** https://www.ncbi.nlm.nih.gov/sra (16S rRNA gene sequences, accession number BioProject PRJNA888098)	Newsham et al. 2022	Examines response of microbial community to changes in temperature and precipitation in patterned ground environments
Microbial Methane Processes	-Microbial identity and gene pool analysis	2009	Ny-Ålesund	https://www.ncbi.nlm.nih.gov/sra (accession number SRP014474)	Tveit et al. 2013	Analyses identity and gene pool of microbiota driving soil organic carbon degradation in active layer
Microbial Methane Processes	-Microbial community analysis -CH_4 production	2010	Knudsenheia	https://www.ncbi.nlm.nih.gov/sra (accession numbers SRX885604, SRX885607, SRX885609, SRX885611, and SRX885615–SRX885628)	Tveit et al. 2015	Anoxic microcosm study assessing impact of warming on microbial community structure

Dataset	Parameter	Period	Location	Data Accessibility	Source/Publication	Notes
Microbial Methane Processes	-Microbial community structure -16S rRNA gene sequencing -CH_4 fluxes	2019–2021	Lagoon Pingo, Adventdalen	https://www.ncbi.nlm.nih.gov/genbank/ (accession numbers: OQ832782, SAMN37693933, SAMN37693934, SAMN37693935, SAMN37693936, SAMN37693937, SAMN37693938, SAMN37693939, SAMN37693940, PRJNA1024098) https://www.jcm.riken.jp/cgi-bin/jcm/jcm_number?JCM=39463 DSMZ accession number 114308	Patil et al. 2024	Methanotroph study in active pingo system with methane seeps
Microbial Methane Processes	-CH_4 production rates -Microbe community structure analysis -16S rRNA sequences	2007	Solvatnet and Stuphallet	16S rRNA sequences deposited in GenBank database, accession numbers FR845726-FR845769	Blake et al. 2015	Microcosm study examining impact of temperature and substrate on methane production and methanogen community structure in wetland tundra sediments
Microbial Methane Processes	-Methanotroph diversity and community analysis -16S rRNA sequences -CH_4 oxidation rates	2007	Solvatnet	16S rRNA sequences deposited in DBJ/EMBL/GenBank nucleotide databases, accession numbers HQ534070–HQ534099	Graef et al. 2011	Examines the diversity of methanotroph communities in wetland tundra soil
Microbial Methane Processes	-Methane concentrations -Methane oxidation rates -16S rRNA sequences	2020	Norskebanken and Hinlopen Trough	https://ebas.nilu.no/ (RV Konprins Haakon) NCBI BioProject database (accession number PRJNA1118678)	de Groot et al. 2024 and NILU	Investigates methane dynamics and microbial community structure in cold seeps north of Svalbard
Sea-air Fluxes	-CH_4 mixing ratios (land, ship, and aircraft measurements)	2014	Offshore Western Svalbard; Zeppelin Observatory, Ny-Ålesund	https://ebas.nilu.no/ (RV Helmer Hanson and Zeppelin Observatory data)	Pisso et al. 2016 and NILU	Measured methane fluxes from various platforms to create a transport model and better confine regional methane budget

Dataset	Parameter	Period	Location	Data Accessibility	Source/Publication	Notes
Seafloor Seeps	-Hydrocarbon gas geochemistry -CH_4 concentration -CH_4 isotopes	2014–2015	Isfjordan and Mohnbukta	https://static-content.springer.com/esm/art%3A10.1007%2Fs41063-019-00067-7/MediaObjects/41063_2019_67_MOESM1_ESM.pdf	Liira et al. 2019	Geochemical analysis of hydrocarbon gas from pockmarks and surrounding seafloor in western and eastern Svalbard
Seafloor Seeps	-Dissolved CH_4 concentrations -Hydrographic data	2015–2017	Adventdalen and Tempelfjordan	Data will be made available upon request to Ellen.Damm@awi.de	Damm et al. 2021	Time-series analysis of methane distribution within water column
Seafloor Seeps	-Acoustic flare detection -Dissolved CH_4 concentration -CH_4 isotopes	2015	Western Svalbard		Mau et al. 2017	Identification of gas discharge sites and analysis of dissolved methane in collected water samples Includes estimates of sea–air fluxes
Seafloor Seeps	-Flare detection via hydroacoustic anomalies (EK60) -Dissolved CH_4 analysis	2012	Western Svalbard Shelf	https://doi.org/10.1594/PANGAEA.833998	Sahling et al. 2014	Mapping of methane seeps and quantification of methane released into water column
Seafloor Seeps	-Acoustic flare detection	2018–2021	Northern Norwegian Barents Sea	https://static-content.springer.com/esm/art%3A10.1038%2Fs41467-023-37514-9/MediaObjects/41467_2023_37514_MOESM3_ESM.xlsx	Serov et al. 2023	Multibeam gas flare mapping to link petroleum systems to natural methane seeps
Seafloor Seeps	-Seismic data	2016	Storfjordrenna	https://doi.org/10.18710/YWQZYV	Waage, 2019	Examines gas seepage from seafloor Gas Hydrate Pingos; investigates connection between sub-seafloor geological structures and methane migration

Resources Cited

Betlem P (2021) Modelled gas hydrate stability zone extents for Svalbard's fjord and near-shore settings. https://doi.org/10.5281/zenodo.5091765

Betlem, P., K. Senger, and Hodson A (2019) 3D thermobaric modelling of the gas hydrate stability zone onshore central Spitsbergen, Arctic Norway. Marine and Petroleum Geology 100: 246–262. https://doi.org/10.1016/j.marpetgeo.2018.10.050

Blake LI, Tveit A, Øvreås L, Head IM and Gray ND (2015) Response of methanogens in arctic sediments to temperature and methanogenic substrate availability. PLoS ONE, 10: e0129733, https://doi.org/10.1371/journal.pone.0129733

Chen Q, Zhu R, Wang Q and Xu H (2014) Methane and nitrous oxide fluxes from four tundra ecotopes in Ny-Ålesund of the High Arctic. Journal of Environmental Sciences (China) 26: 1403–1410. https://doi.org/10.1016/j.jes.2014.05.005

Chernov RA and Romashova KV (2023) Large Periglacial Lakes on the Spitsbergen (Svalbard): State in 2008–2012 and Dynamics in 1991–2022. Lëd i Sneg Ice and Snow) 63: 525-539. In Russian

Damm E, Ericson Y and Falck E (2021) Waterside convection and stratification control methane spreading in supersaturated Arctic fjords (Spitsbergen). Continental Shelf Research 224: 104473. https://doi.org/10.1016/j.csr.2021.104473

Demidov NE, Borisik AL, Verkulich SR et al. (2020) Geocryological and Hydrogeological Conditions of the Western Part of Nordenskiöld Land (Spitsbergen Archipelago). Izvestiya, Atmospheric and Oceanic Physics 56: 1376–1400. https://doi.org/10.1134/S000143382011002X

Donateo A, Famulari D, Giovannelli D, Mariani A, Mazzola M, Decesari S, Pappaccogli G (2024) Observations of methane net sinks in the Arctic tundra. EGUsphere 2024:1-31. https://doi.org/10.5194/egusphere-2024-1440

Graef CA, Hestnes G, Svenning MM and Frenzel P (2011) The active methanotrophic community in a wetland from the High Arctic. Environmental Microbiology Reports 3: 466–472. https://doi.org/10.1111/j.1758-2229.2010.00237.x

de Groot TR, Kalenitchenko D, Moser M, Argentino C, Panieri G, Lindgren M, Dølven KO, Ferré B, Svenning MM and Niemann H (2024) Methanotroph activity and connectivity between two seep systems north off Svalbard. Frontiers in Earth Science 12: 1287226. https://doi.org/10.3389/feart.2024.1287226

Hodson A (2020) Detailed water quality parameters, including methane concentrations and isotopic composition, for groundwater springs discharging from open system pingos in Adventdalen, Svalbard (2014-2017). UK Polar Data Centre, Natural Environment Research Council, UK Research & Innovation. https://doi.org/10.5285/3d82fd3f-884b-47b6-b11c-6c96d66b950d

Hodson A and Kleber G (2023) Enhanced methane emissions driven by glacial retreat in the high Arctic. https://doi.org/10.5281/zenodo.7709380

Jones E (2019) Permafrost and active layer biogeochemical data from Adventdalen (2015-2017). UK Polar Data Centre, Natural Environment Research Council, UK Research & Innovation. https://doi.org/10.5285/4c90d954-3db2-4084-9fe9-e050c839a6fe

Kleber GE, Magerl L, Turchyn AV, Redeker K, Thiele S, Liira M, Herodes K, Øvreås L, and Hodson A (2024) Shallow and deep groundwater moderate methane dynamics in a high Arctic glacial catchment. Frontiers in Earth Science 12: 1340399. https://doi.org/10.3389/feart.2024.1340399

Kleber G, Redeker K, Turchyn A and Hodson A (2024) Biogeochemistry of Svalbard Glacial and Periglacial Groundwater Springs. https://doi.org/10.5281/zenodo.13736679

Lan X, Mund JW, Crotwell AM, Thoning KW, Moglia E, Madronich M, Baugh K, Petron G, Crotwell MJ, Neff D, Wolter S, Mefford T and DeVogel S (2024) Atmospheric Methane Dry Air Mole Fractions from the NOAA GML Carbon Cycle Cooperative Global Air Sampling Network, 1983-2023, Version: 2024-07-30. https://doi.org/10.15138/VNCZ-M766

Li F, Zhu R, Bao T, Wang Q, and Xu H (2016) Sunlight stimulates methane uptake and nitrous oxide emission from the High Arctic tundra. Science of the Total Environment 572: 1150–1160. https://doi.org/10.1016/j.scitotenv.2016.08.026

Li J, Zhu Z-Y, Yang Z, Li W, Lv Y and Zhang Y (2023) Soil microorganisms and methane emissions in response to short-term warming field incubation in Svalbard. Frontiers in Microbiology 14: 1276065. https://doi.org/10.3389/fmicb.2023.1276065

Liira M, Noormets R, Sepp H, Kekišev O, Maddison M and Olaussen S (2019) Sediment geochemical study of hydrocarbon seeps in Isfjorden and Mohnbukta: a comparison between western and eastern Spitsbergen, Svalbard. Arktos 5: 49–62. https://doi.org/10.1007/s41063-019-00067-7

Lindroth A, Pirk N, Jónsdóttir I, Stiegler C, Klemedtsson L, and Nilsson MB (2021) Kapp Linné Lindroth. Zeonodo https://doi.org/10.5281/zenodo.5704509

Lund Myhre C, Platt SM, Hermansen O and Lunder C (2024) ICOS ATC CH4 Release, Zeppelin (15.0), 2017-07-27-2024-03-31: ICOS Data Portal. https://meta.icos-cp.eu/objects/wb29RCuGilQ3jB6_7Vsrzq8H

Mau S, Römer, M, Torres ME, Bussmann I, Pape T, Damm E, Geprägs P, Wintersteller P, Hsu CW, Loher M and Bohrmann G (2017) Widespread methane seepage along the continental margin off Svalbard-from Bjørnøya to Kongsfjorden. Scientific Reports 7: 42997. https://doi.org/10.1038/srep42997

Michel SE, Clark J R, Vaughn BH, Crotwell M, Madronich M, Moglia E, Neff D, and Mund J (2023) Stable Isotopic Composition of Atmospheric Methane (13C) from the NOAA GML Carbon Cycle Cooperative Global Air Sampling Network, 1998-2022: University of Colorado, Institute of Arctic and Alpine Research (INSTAAR). https://doi.org/10.15138/9p89-1x02

Morimoto S, Goto D, Murayama S, Fujita R, Tohjima Y, Ishidoya S, Machida T, Inai Y, Patra PK, Maksyutov S. and Ito A (2021) Spatio-temporal variations of the atmospheric greenhouse gases and their sources and sinks in the Arctic region. Polar Science 27: 100553.

Morimoto S, Fujita R, Aoki S, Goto D, Nakazawa T (2017) Long-term variations of the mole fraction and carbon isotope ratio of atmospheric methane observed at Ny-Ålesund, Svalbard from 1996 to 2013. Tellus B: Chemical and Physical Meteorology 1: 1380497 https://doi.org/10.1080/16000889.2017.1380497

NDACC, 2023, (Network for the Detection of Atmospheric Composition Change): NDACC Public Data Access. https://ndacc.larc.nasa.gov/

Newsham KK, Danielsen BK, Biersma EM, Elberling B, Hillyard G, Kumari P, Priemé A, Woo C, Yamamoto N. (2022) Rapid response to experimental warming of a microbial community inhabiting high Arctic patterned ground soil. Biology 14: 1819

Patil SK, Islam T, Tveit A, Hodson A, Øvreås L. (2024) Targeting methanotrophs and isolation of a novel psychrophilic Methylobacter species from a terrestrial Arctic alkaline methane seep in Lagoon Pingo, Central Spitsbergen (78° N). Antonie van Leeuwenhoek 117: 60. https://doi.org/10.1007/s10482-024-01953-1

Pirk N, Mastepanov M, López-Blanco E, Christensen LH, Christiansen HH, Hansen BU, Lund M, Parmentier FJ, Skov K, Christensen TR. (2017) Toward a statistical description of methane emissions from arctic wetlands. Ambio 46: 70-80. https://doi.org/10.1007/s13280-016-0893-3

Pirk N, Tamstorf MP, Lund M, Mastepanov M, Pedersen SH, Mylius MR, Parmentier FJ, Christiansen HH, Christensen TR. (2016) Snowpack fluxes of methane and carbon dioxide from high Arctic tundra. Journal of Geophysical Research: Biogeosciences 121: 2886-900. https://doi.org/10.1002/2016JG003486

Pisso I, Myhre CL, Platt SM, Eckhardt S, Hermansen O, Schmidbauer N, Mienert J, Vadakkepuliyambatta S, Bauguitte S, Pitt J, Allen G. (2016) Constraints on oceanic methane emissions west of Svalbard from atmospheric in situ measurements and Lagrangian transport modeling. Journal of Geophysical Research: Atmospheres 121: 14-88. https://doi.org/10.1002/2016JD025590

Rodes N, Betlem P, Senger K, Römer M, Hodson A, Liira M, Birchall T, Roy S, Noormets R, Smyrak-Sikora A, Olaussen S. (2023) Active gas seepage in western Spitsbergen fjords, Svalbard archipelago: spatial extent and geological controls. Frontiers in Earth Science 20: 1173477. https://doi.org/10.3389/feart.2023.1173477

Sahling, H. et al. 2014, (Supplement 1) Table of hydroacoustic anomalies (flares) extracted from EK 60 echosounder records. https://doi.org/10.1594/PANGAEA.833998

Senger K, Betlem P, Braathen A, Olaussen S, Sand G. (In Press) Longyearbyen CO2 lab project–from a vision of a CO2-neutral Svalbard to a geoscience data eldorado. Arctic Science. https://doi.org/10.1139/as-2024-0019

Serov P, Mattingsdal R, Winsborrow M, Patton H, Andreassen K. (2023) Widespread natural methane and oil leakage from sub-marine Arctic reservoirs. Nature Communications 30: 1782. https://doi.org/10.1038/s41467-023-37514-9

Trubitsyn VE, Suzina NE, Rivkina EM, Shcherbakova VA (2023) A new methanogenic, hydrogenotrophic archaeon from Spitsbergen permafrost. Microbiology 92: 119-128. https://doi.org/10.1134/S0026261722603256

Tveit A, Schwacke R, Svenning MM, Urich T (2013) Organic carbon transformations in high-Arctic peat soils: Key functions and microorganisms. ISME Journal 7: 299–311. https://doi.org/10.1038/ismej.2012.99

Tveit AT, Urich T, Frenzel P, Svenning MM (2015) Metabolic and trophic interactions modulate methane production by Arctic peat microbiota in response to warming. Proceedings of the National Academy of Sciences 112: E2507-16. https://doi.org/10.1073/pnas.1420797112

UNIS CO2 Laboratory (2024) Longyearbyen CO2 Lab - Geochemistry, gas and isotope data: UNISCO2Lab. https://doi.org/10.5281/zenodo.10813248

Waage M (2019) Replication Data for: Geological controls on fluid flow and gas hydrate pingo development on the Barents Sea margin. DataverseNO, https://doi.org/10.18710/YWQZYV

Wittig S, Berchet A, Pison I, Saunois M, Thanwerdas J, Martinez A, Paris JD, Machida T, Sasakawa M, Worthy DE, Lan X. (2023) Estimating methane emissions in the Arctic nations using surface observations from 2008 to 2019. Atmospheric Chemistry and Physics 23: 6457-85. https://doi.org/10.5194/acp-23-6457-2023

Workman EM, Yang T, Bell Y, et al. (2024) Sea-air methane fluxes measured using an eddy-covariance technique on RRS James Clark Ross from January 2019 to March 2021. NERC EDS UK Polar Data Centre. https://doi.org/10.5285/c9ed4746-f104-4117-ba60-174c5275e2fe.

Zhu R, Chen Q, Ding W, Xu H (2012) Impact of seabird activity on nitrous oxide and methane fluxes from High Arctic tundra in Svalbard, Norway. Journal of Geophysical Research: Biogeosciences 117: G4. https://doi.org/10.1029/2012JG002130

The Atlantification process in Svalbard: a broad view from the SIOS Marine Infrastructure network (ARiS)

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1. Introduction

The Arctic marine systems represent some of the most unique and critical components of the Earth's ecological and climatic framework. The Arctic Ocean and adjacent seas are characterised by extreme seasonal variability and have vast areas of sea ice that significantly influence global weather patterns and ocean currents. The biodiversity in these marine environments is specially adapted to freezing temperatures, limited sunlight in the winter months, and high nutrient abundance during the summer melting period (CAFF 2013). The Arctic marine systems are threatened by climate change to an unprecedented extent. The Arctic, and particularly the Svalbard Archipelago, is affected by the phenomenon known as "Atlantification", a process associated with the increasing influence of Atlantic Water (AW) in the Arctic seas and fjords (Polyakov et al. 2017; Skogseth et al. 2020; Årthun et al. 2021; De Rovere et al. 2022; Vivier et al. 2023). The fjords are highly affected by Atlantification, because of specific atmospheric–oceanic–topographic interaction processes that control the intrusion of AW into the fjords of West Svalbard (Cottier et al. 2007; Nilsen et al. 2016). Together with rising air temperatures, the inflow of warm AW accelerates the loss of sea ice and glaciers (Luckman et al. 2015; Muckenhuber et al. 2016; Holmes et al. 2019). The inflow of AW and declining ice cover not only affects local ecosystems (Payne and Roesler 2019; Hopwood et al. 2020; Jones et al. 2021; Weydmann-Zwolicka et al. 2021), but also has far-reaching consequences for global sea levels and climate (Ingvaldsen et al. 2021; Tsubouchi et al. 2021; Polyakov et al. 2023). A highly valuable way to detect, observe and understand even small changes in the ocean and regional seas is through long-term observatories, i.e., marine infrastructures that ensure the collection of sufficiently long data series with adequate temporal resolution to resolve ocean processes from daily to multi-year scale. Svalbard's unique location, combined with its relatively easily accessible infrastructure, makes it an ideal location for studying the ongoing changes and their impacts on the Arctic environment. The Svalbard SIOS Marine infrastructure is of central importance for monitoring short- and long-term marine processes in the fjords and in the coastal areas around Svalbard. The marine observatories in the Svalbard Archipelago are strategically located (Figure 1) to obtain continuous observations of sea temperature, salinity, current, and biogeochemical properties to understand the complex interactions between the ocean, ice, and atmosphere in this rapidly changing region on seasonal, interannual, and decadal time scales. Research studies conducted through the Svalbard Marine Observatories contribute to global climate modelling, improve the prediction of sea level rise and feedback caused by long-term climatic changes, and provide information for conservation strategies for endangered Arctic species. In addition, the data collected will support international efforts to mitigate the effects of climate change and ensure sustainable management of Arctic resources by providing scientific evidence of environmental change and background information on the need for action by policy makers.

2. Data analysis and overview

This SESS Report chapter focuses on time series obtained from fixed observing systems anchored in fjords, on the shelf and slopes around the Svalbard archipelago. Here, we present a combined spatial and temporal analysis of the long-term oceanographic data series coming from the SIOS Marine Infrastructure network including seasonal, interannual, and decadal variations detected at each observatory. The chapter emphasises signal variability related to the intrusion and northward propagation of AW. Data integration and time series analysis is supported by and is relevant to several

national and international projects/initiatives, such as the Arctic PASSION and the A-DBO[1], NorEMSO[2], RAW[3], opKROP[4], and ATTRACTION.

2.1. Methods

Here we present the most comprehensive overview of long-term mooring data from Svalbard waters to date, with standardised analysis on both published and unpublished data. Locations of the moorings are marked as coloured dots in Figure 1 (see also Table 1). We use conservative temperature (T, °C) and absolute salinity (S_A, g/kg). Daily and monthly means were calculated from the original data (e.g., temporal resolution up to 1 h). Multi-year averages (with linear trends) were calculated from monthly mean data. The "climatological" monthly average (for time series longer than 5 years) was also calculated, considering all the data collected within the same months for the entire time series. Note that here we use the term "climatological" even though it does not refer to a period of at least 30 years. For the available datasets, monthly means, monthly "climatological" mean, long-term means, and linear trends were calculated from the T and S_A. The proportions of AW and Transformed Atlantic Water (TAW) were determined in each time series as the days of the year when these water masses were present (reported in Figures 2b, 3b). AW is defined as S_A>35.07 g/kg, T > 3°C for all time series except those recorded in the northernmost part of Svalbard (A-TWAIN and Rijpfjorden), where T > 2°C and potential density (σ_θ) in the range 27.7-27.97 kg/m^3 was used. TAW is defined as S_A > 34.87 g/kg and T > 1°C, according to Sundfjord et al. (2017), Tverberg et al. (2019), Skogseth et al. (2020), De Rovere et al. (2022), and Renner et al. (2023). For time series at S1 (1000 m depth) we defined AW with T ≥ -0.5°C. To avoid seasonal effects of surface warming and freshening in the A-TWAIN, Rjipfjorden, Kongsfjorden Mouth and Mid, and Isfjorden time series, T and S_A were interpolated to discrete depths and then depth-averaged starting from 50 m.

2.1.1. Hornsund fjord (HS)

Year-round T and S_A data are available from shallow (10-25 m) coastal waters in Hornsund fjord. The instruments have been deployed 0.5 m above bottom. T data starts from June 2014 and S_A data from June 2017 onward (excluding part of years 2021-2022). The deployment location has not been fixed and varies somewhat from year to year (approx. location of HS in Figure 1). Most of the measurements are from the northern side of the fjord near the fjord opening, but between January 2021 and July 2022, T is only available from the southern side. For the periods when observations from both sides are available (Jun 2016–May 2017 for T, Jun 2018–Jan 2021 and Sep 2022–May 2023 for both T and S_A), the data show practically no variability between locations, and therefore it was decided to combine all data available from Hornsund into one timeseries.

2.1.2. NorEMSO (The Norwegian node for the European Multidisciplinary Seafloor and water column Observatory) Observatory at South Cape (SC)

An observatory known as the K-Lander (Dølven et al. 2022) has been deployed on the continental shelf southeast Sørkapp, the South Cape of Spitsbergen (76.1070°N,15.9680°E, SC in Figure 1), at around 380 m water depth from 14 April 2022 to 20 April 2023 with the main aim to monitor the release of a major submarine methane eruption (Serov et al. 2017). The K-Lander, a trawl-proof observatory with a diameter of 3.6 m and a height of 1.6 m, measured T, S_A, pH and oxygen at about 1 m above the seafloor. Conductivity–temperature–depth (CTD) casts were conducted immediately before deployment and recovery to ensure quality control.

2.1.3. Deep observatory offshore southwest Svalbard (S1)

The oceanographic mooring S1, located at 76° N and 14° E (S1 in Figure 1), at 1040 m depth on the continental slope west of Svalbard, has

1 https://arcticpassion.eu/adbo/
2 https://www.uib.no/en/noremso
3 https://raw-grieg.igf.edu.pl/
4 https://www.mare-incognitum.no/opkrop/

been operating since mid-June 2014. Yearly time series data of T and S_A are obtained after annual maintenance. Data are processed and quality checked by comparing them to calibrated CTD profiles collected before and after each yearly mooring deployment and uploaded to the Italian Arctic Data Centre. The time resolution of the time series is 60 minutes. The data presented here covers the period from 9 June 2014 to 22 June 2023.

2.1.4. Isfjorden moorings

Three different oceanographic moorings were positioned in the mouth and entrance area of Isfjorden over the years to make robust analyses of variability and trends in the AW circulating in the trough and fjord system (Skogseth et al. 2020). The first was placed on the southern slope of the Isfjorden Trough outside the fjord mouth (Isfjorden Mouth in Figure 1). The second was placed inside of the entrance of the fjord also on the southern side (Isfjorden in Figure 1). The third was positioned on the northern slope (Isfjorden North in Figure 1), opposite to the Isfjorden Mouth mooring. Yearly T and S_A from evenly distributed depths have been recorded since September 2005 until present and are still being recorded at the Isfjorden Mouth and Isfjorden moorings, with the Isfjorden Mouth mooring being the longest in operation. The resolution of the time series is 20-60 minutes. Data are published following FAIR principles (Wilkison et al. 2016) at the Norwegian Polar Institute Data Centre (NPDC), available from the SIOS Data Management System.

2.1.5. Prins Karls Forland observatory (PKF)

The K-Lander was deployed around 78.6 °N, 10.14 °E (PK Forland in Figure 1) from June 2015 to May 2016 (Dølven et al. 2022) and from October 2016 to July 2017 to monitor methane release and the influence of oceanic parameters. The instruments were sent for maintenance and calibration between the two deployments. CTD casts were conducted immediately before deployment and recoveries to ensure quality control and to correct any drifts in the time series.

2.1.6. Kongsfjorden moorings

UiT/SAMS observatory at the mouth of Kongsfjorden Svalbard (KF Mouth)

The oceanographic mooring KF Mouth is located at approx. 78.96 °N 11.8 °E in Kongsfjorden, in a water depth of ~225 metres and has been active since September 2002 (Kongsfjorden Mouth in Figure 1). In 2002 and 2003, the mooring was located about 10 km west of its current location at 79.05 °N 11.28 °E. Year-long T and S_A data from evenly distributed depths are obtained after annual maintenance.

IndARC mooring in mid Kongsfjorden (KF Mid)

IndARC (Indian Arctic) mooring was first deployed in the central part of Kongsfjorden at 78.94 °N and 12.01 °E in July 2014 at a bottom depth of ~198 m (Kongsfjorden Mid in Figure 1), with minimal variations in sensor locations/depths and measuring data from ~20 m below the water surface. The mooring has been deployed and recovered annually in the first three deployments. In the last two mooring deployments, it was recovered after two years of data recording. T and S_A have been recorded at five to six evenly distributed depths at an hourly resolution. CTD casts were carried out near the mooring site for quality control.

MDI mooring in inner Kongsfjorden (KF Inner)

MDI (mooring *Dirigibile Italia*) was deployed in September 2010 at 78.914 °N and 12.246 °E (Kongsfjorden, KF Inner in Figure 1) at a depth of 104 m. The mooring is 73 m long, and T and S_A have been recorded almost continuously since 2010 at 85 and 30-35 m (nominal depths). Data is downloaded during periodical maintenance, quality controlled with the spike test and gradient test according to the procedures proposed by SeaDataNet and the Global Ocean Observing System and uploaded to the Italian Arctic Data Centre.

2.1.7. Rijpfjorden mooring (RF)

The Rijpfjorden mooring (Figure 1) was established in summer 2006. The mooring is in the northern part of the fjord at a depth of 230 m, at 80.28 °N, 22.28 °E. The instrumentation used in Rijpfjorden is consistent with that used in Kongsfjorden (KF Mouth). T and S_A data cover the water column for the entire period apart from 2008–2009, when heavy ice conditions made deployment impossible.

2.1.8. Northeast Svalbard moorings: A-TWAIN

A mooring array deployed northeast of Svalbard over the upper part of the continental slope (north of Kvitøya, A-TWAIN in Figure 1) towards the Nansen Basin is part of the project "Long-term variability and trends in the AW inflow region" (A-TWAIN) (Lundesgaard et al. 2021, 2022; Renner et al. 2018, 2023). Measurements started in 2012 at two moorings, positioned over the 200 m isobath (A200) and 800 m isobath (A800). In this chapter we refer to the longest time series, A200, which runs from September 2012 to November 2019 and from November 2021 to October 2022.

2.2. Results: time series from marine observatories

2.2.1. Monthly climatology

The monthly climatological data obtained from the time series at the SIOS Marine Infrastructure (Figure 1) offer a valuable perspective for comparing local thermohaline variability at each location. They also allow valuable insights of the spatial propagation of the warm and salty AW west of Spitsbergen, towards the Arctic Ocean north of Spitsbergen and into individual fjord systems on the way. We acknowledge that the climatology can be highly influenced by the chosen infrastructure location, and that some of the marine infrastructures do not cover the whole water column. However, we have found a set of marine time series that can clearly show the Atlantification of the Svalbard region during the last two decades, and in addition, can provide precious data to investigate the AW propagation and its interaction processes with the continental slope–shelf–fjord system. In summer, the climatological maximum T in Kongsfjorden is found in October (Figure 1) and therefore delayed by one month compared to (depth-average data) Isfjorden, and two months compared to (surface data) Hornsund. Maximum T is found in October/November in Rijpfjorden and at the A-TWAIN mooring northeast of Svalbard and depth-averaged T at A-TWAIN is 1°C lower compared to Isfjorden and Kongsfjorden. The climatological minimum T is found in March/April for all shelf/fjord systems along the West Spitsbergen Shelf (WSS), while the S1 and A-TWAIN moorings have their minimum T in June (Renner et al. 2018; Bensi et al. 2019). At the S1 and A-TWAIN moorings, the seasonal signal in both T and S_A is dominated by the seasonal cycle in advected AW, with maximum influence in October/November when the West Spitsbergen Current (WSC) and Svalbard Branch (SB, Figure 1) are in their strongest phase and T and S_A signals are highest north of Svalbard (Lundesgaard et al. 2022). The seasonal cycle in S_A at the Isfjorden Mouth is more influenced by the fresher Spitsbergen Polar Current (SPC), especially during fall. In winter and spring (January–May) the interplay between the SPC and the Spitsbergen Through Current (STC) determines the interannual S_A variations. However, the maximum S_A at Isfjorden Mouth is found in March due to the strong STC during winter (Skogseth et al. 2020), driven by the strong and frequent winter storms across Svalbard (Cottier et al. 2007; Nilsen et al. 2016). According to Nilsen et al. (2016), the maximum S_A signal is advected northwards by the STC to the Kongsfjorden mouth, passing the PK Forland observatory (Figure 1), with a reduced S_A one month later, in April. The Kongsfjorden Inner seems to be less affected by the SPC since S_A stays close to the same level after the maximum in April but with a local maximum in September due to the increased exchange of AW between the shelf and Kongsfjorden (Cottier et al. 2007; De Rovere et al. 2022). In contrast, at the deep site S1 south of Svalbard, the greatest impact of AW intrusions occurs during the winter season (December–January) as a result of vertical mixing caused by the passage of internal waves along the western margin of Svalbard (Bensi et al. 2019).

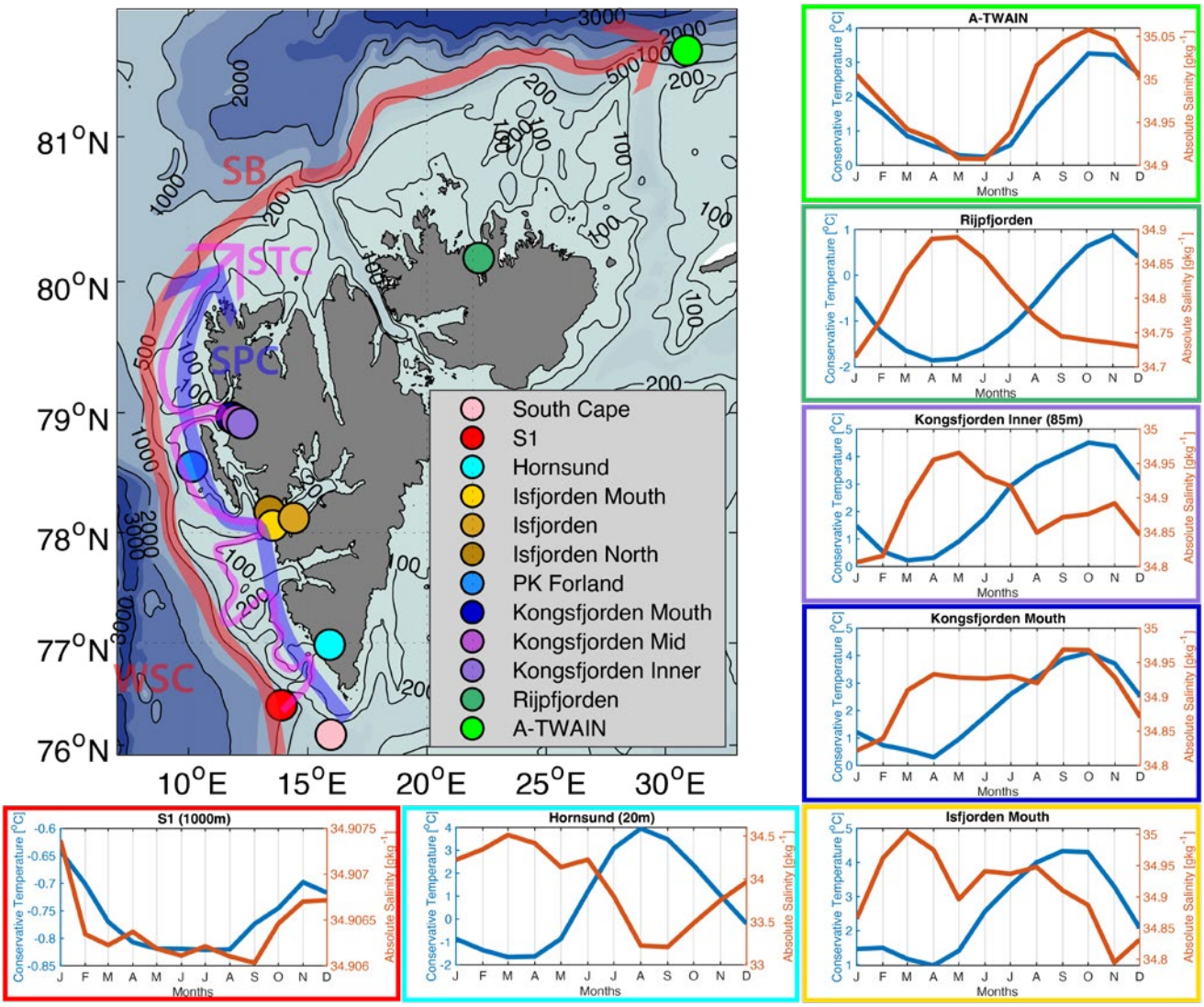

Figure 1: The position of all SIOS Marine Infrastructures described and analysed in this report with illustration of the dominating current systems influencing the West Spitsbergen Shelf, the fjord systems in Svalbard and the shelf north of Svalbard. Monthly climatology of Conservative Temperature and Absolute Salinity are presented for marine infrastructure with a time series longer than five years. Climatology is calculated from depth-averaged time series starting from 50 m and deeper if no specific depth is indicated in the title. Note that the scales differ. WSC: West Spitsbergen Current; STC: Spitsbergen Through Current; SPC: Spitsbergen Polar Current; SB: Svalbard Branch.

2.2.2. Multi-year variability

We analysed the time series of monthly mean data from the offshore marine systems (Figure 2) merged with the model output from Copernicus Arctic Ocean Physics Reanalysis (CMEMS, Arctic Ocean Physics Reanalysis, product ID ARCTIC_MULTIYEAR_PHY_002_003, monthly average[5]) to get an overview of what the fixed observatories are recording with respect to the upstream signals. The long-term thermohaline variability, expressed by the CMEMS time series at 200 m depth, shows both the seasonal signal and the long-term variability. The latter reveals a slight increase (+ 0.8°C) in T from 2002 to 2022, while S_A shows two phases: an increasing phase until around 2012–2013 and a subsequent decrease, more pronounced after 2018. This freshening phase could be related to a delayed effect of the freshwater anomaly of the subpolar regions of the North Atlantic, whose signal is shifted to the high latitudes by the subpolar gyre (Holliday et al. 2020, Figures 2 and 3). The annual and seasonal variations appear to be quite consistent across the four observing systems. The

5 https://doi.org/10.48670/moi-00007

decrease in S_A observed in the CMEMS output is also observed in A-TWAIN and S1, showing that this AW freshening signal propagates both northwards and into the deep ocean. Within the time series in Figures 2a,b, two overlapping periods are considered for which overall means and standard deviations (std) are calculated. During the longer overlapping period, Jul 2014–Nov 2019, mean and std for T (and S_A) are: CMEMS 4.908±0.495 (35.261±0.024), A-TWAIN 1.791±1.257 (34.968±0.095), S1 -0.770±0.081 (35.074±0.001). During the shorter period, Dec 2021–Sept 22, they are: CMEMS 4.573±0.523 (35.218±0.017), A-TWAIN 1.111±0.817 (34.900±0.039), and S1 -0.732±0.065 (35.074±0.000). Larger std values at A-TWAIN reflect a greater thermohaline variability in northernmost Svalbard. The anomalies associated with the monthly climatology (Figure 2c,d) show multi-year cycles of AW inflow in the CMEMS data. The longest persistently positive T anomaly is found between 2015 and 2019. It also appears coherently in the A-TWAIN time series until 2018. A persistently positive T anomaly at S1 is observed after 2020. During the longer overlapping period, Jul 2014–Nov 2019, linear trends for the anomalies are calculated (Figures 2c,d) but only statistically significant trends are reported in T for A-TWAIN (-0.8°C) and S_A for both CMEMS (-0.05 g/kg) and A-TWAIN (-0.2 g/kg).

All hydrographic time series from the continental shelf and inside fjord systems are presented in Figure 3. Figure 3a shows a latitudinal T gradient, with the northernmost fjord, Ripfjorden, being coldest. It also shows the lowest S_A (Figure 3b). However, the southernmost fjord, Hornsund, has a lower maximum T during summer compared to Isfjorden and Kongsfjorden, due to having the closest proximity to the northwestern Barents Sea and Storfjorden, which historically consist of

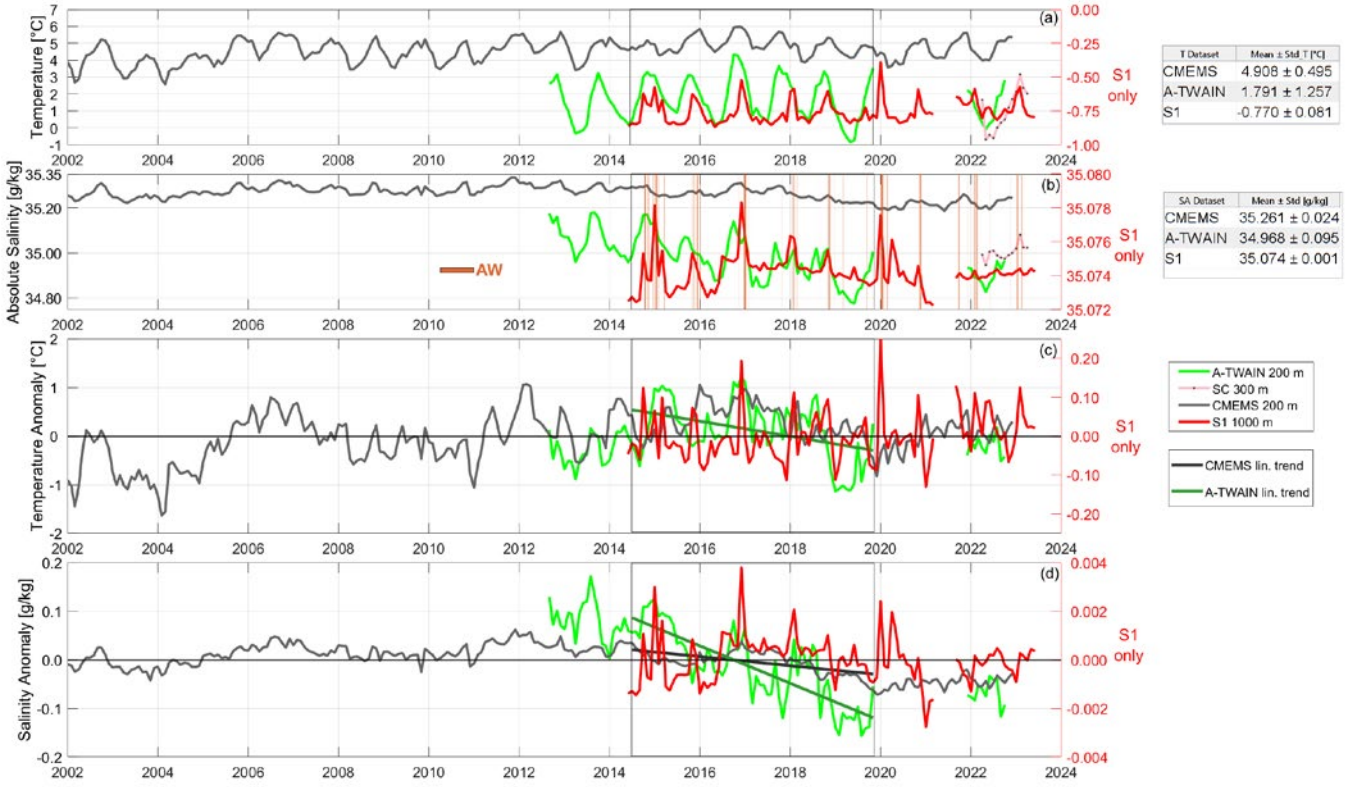

Figure 2: Conservative Temperature **(a)** and Absolute Salinity **(b)** time series (monthly mean) from the offshore marine observatories (S1, SC, A-TWAIN) at depths indicated in the legend, compared with CMEMS outputs at around 76°N 14°E and 200 m depth (AW core). A-TWAIN data are depth-averaged time series starting from 50 m. The vertical red lines (b) indicates AW intrusions at S1, using the definition described in section 2.1 and based on daily mean time series. Mean values and std for the overlapping period Jul 2014–Nov 2019 are reported in the tables. **(c, d)**: deviation from the climatological mean (anomaly) for the time series longer than five years. Linear trends (statistically significant with $p<0.05$) are shown for the overlapping period Jul 2014–Nov 2019. Note that the y-axis on the right (red) has a different scale to reproduce the variability at S1.

Arctic Water types. There is no apparent trend in T and S_A over the two decades (Figure 3a, b), but the anomalies (Figure 3c, d) reveal cycles of warmer/saltier periods (2006–2008, 2012–2018) and colder/fresher periods (2002–2006, 2008–2012, 2020–present). The flooding of AW on the WSS and into the fjord systems are indicated by the AW and TAW detection in Figure 3b and the period 2012–2018 shows their exceptionally high occurrences. This is what we call Atlantification (i.e., increasing influence of AW in Arctic regions). Cottier et al. (2007) explained the first incident of Atlantification on the WSS during winter 2006 through regional air–ocean interaction mechanisms (i.e., periods of sustained northerly winds along the shelf that generate upwelling, which has the potential to transport AW across the shelf and into the fjords). Moreover, Nilsen et al. (2016) showed

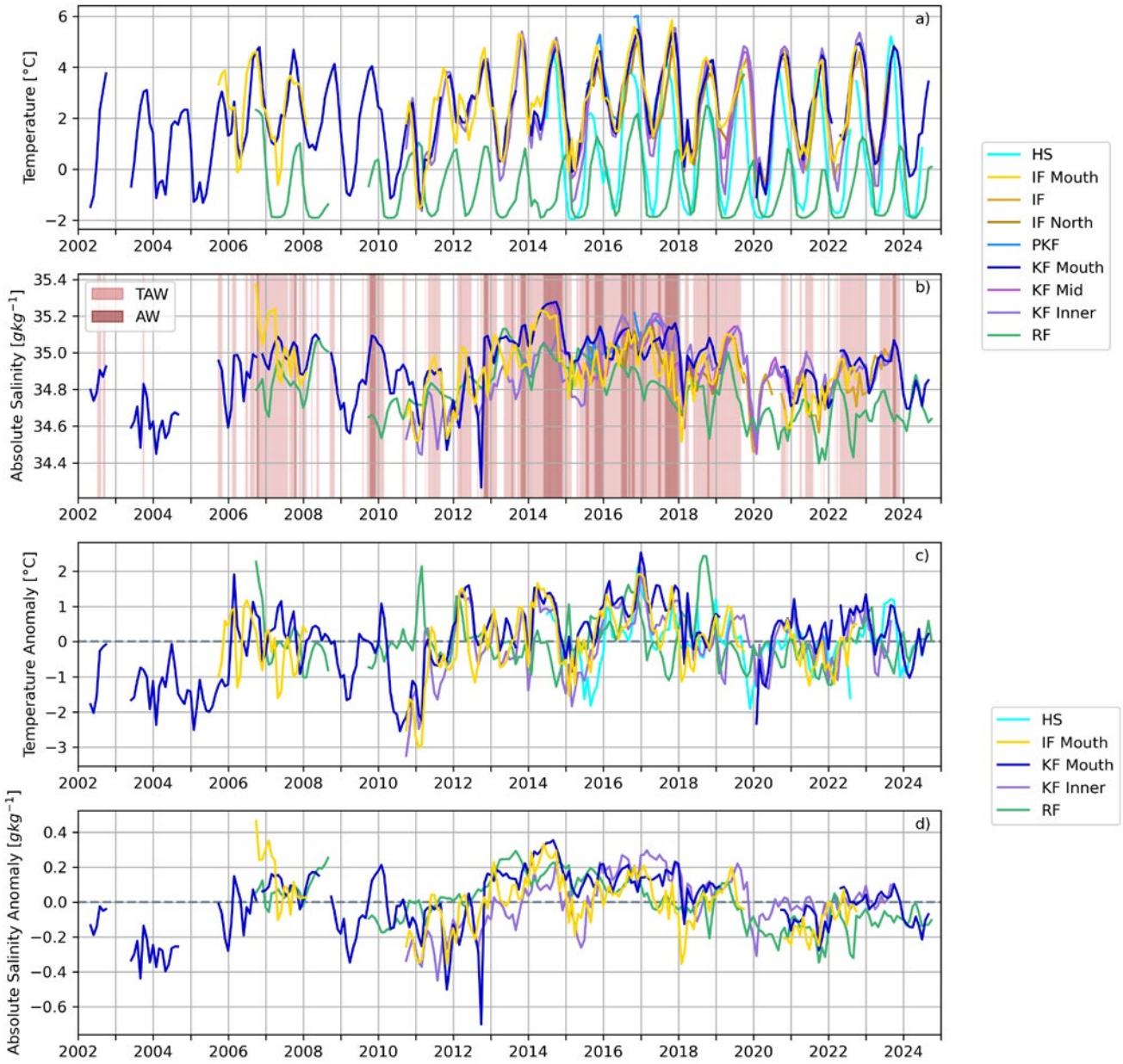

Figure 3: Time series of monthly mean Conservative Temperature **(a)** and Absolute Salinity **(b)** from the marine infrastructures (with similar colour code as in Figure 1) on the continental shelf and fjord systems west and north of Svalbard. These are depth-averaged time series starting from 50 m if no specific depth is indicated in Figure 1. The light red shading **(b)** indicates when AW and TAW are present west of Spitsbergen, using the definition described in section 2.1 and based on daily mean time series. The Isfjorden Mouth time series was used to classify water masses since it has the best coverage of salinity sensors in the water column, and the Kongsfjorden Mouth time series is used whenever the former had a gap. (c, d): deviation from the climatological mean (anomaly) for the time series longer than five years (Figure 1). Abbreviations: HS – Hornsund, IF – Isfjorden, PKF – Prins Karls Forland, KF – Kongsfjorden, RF – Rijpfjorden.

that the Isfjorden system is the Svalbard fjord most exposed to the WSC and hence to the AW source. There, the topography of the Isfjorden Trough favours the entrance of the AW transported by the STC (Figure 1). The T and S_A anomaly time series (Figures 3c, d) show an approximate 6-year cycle of AW and TAW inflow (Figure 3b and Walczowski et al. 2012) in the fjord systems as well as short-term Atlantification pulses occurring during wintertime and reported in literature (Cottier et al. 2007; Nilsen et al. 2016; Skogseth et al. 2020). T and S_A anomalies show a good correspondence between Isfjorden and Kongsfjorden. The freshening phase since 2018 (Figure 3b), as also observed in the offshore marine systems (Figure 2b), and the predominantly negative S_A anomalies in 2020–2021 (Figure 3d), are probably related to the freshening of the north Atlantic and the Nordic Seas that began in 2012 (Mork et al. 2019; Holliday et al. 2020) and transported to high latitudes. This would be consistent with the estimated delay of 4-6 years for the S_A signal to propagate to Svalbard from the north Atlantic (Holliday et al. 2020). The freshening signal after 2018 is also observed in the northwestern Barents Sea (Kolås et al. 2024).

3. Contributions to interdisciplinarity

The Atlantification of Svalbard waters has wide-reaching effects, with implications for multiple disciplines. The large heat content of Atlantic water affects both atmosphere and cryosphere, melting sea ice, tidewater glaciers, and heating the air above. The positive feedback of loss of ice reducing albedo and thus increasing radiative warming (Arctic amplification) is a phenomenon that is particularly evident in western fjords of Svalbard, where air temperatures are rising twice as fast as in other regions. Atlantic water carries nutrients that potentially affect phytoplankton blooms; it also transports marine species from the south, altering the local marine species communities and predator–prey relationships. Increasing interdisciplinary collaboration also has the potential to reveal drivers of Atlantification. Combining the long hydrographic time series with data from local weather stations is useful to clarify the driving mechanisms for the pulses/cycles of AW inflow and predict marine heat waves and the advection of aerosols. While we present purely physical parameters (temperature and salinity) here, mooring infrastructures increasingly carry biological and chemical sensors that contribute to multidisciplinary studies of marine ecosystems over long periods.

4. Unanswered questions

What is the dominant time scale of Atlantification?

The North Atlantic exhibits a pronounced atmosphere and ocean decadal variability (Årthun et al. 2021). Arctic Atlantification is reflected in both long-term and multi-year variability. Recent studies also show that this process appears to have accelerated in the 2000s. The issue is controversial, however, and some palaeoceanographic studies point to signs of Atlantification as early as the beginning of the 20th century (Tesi et al. 2021; Polyakov et al. 2023).

Is the Atlantification permanent and irreversible?

This is not yet completely understood. There is certainly multi-year variability in the system, but the data collected to date show a long-term trend that is linked to the global warming process and cannot be ignored.

5. Recommendations for the future

- MAINTAIN long-term deep-sea observation systems south and north of Spitsbergen to record the variability of the Atlantic Water inflow.
- PLAN AND PROMOTE opportunistic and systematic Conductivity–Temperature–Depth (CTD) measurements in key areas and near marine infrastructure and standard monitoring transects to ensure data quality (comparisons), possibly in collaboration with the Atlantic–Arctic Distributed Biological Observatory (A-DBO) network.
- HARMONIZE marine infrastructures by promoting the installation of oxygen sensors (harmonising marine observatories) to monitor deep-water ventilation or, as an indirect measure, to monitor changes in the ecosystem (e.g., biological carbon pump) linked to the Atlantification.
- EVALUATE the optimisation of marine infrastructures for specific purposes, e.g., monitoring the Atlantification process, and encouraging the international scientific community to opt for common systems, other than standard repeat transects, instead of competing systems near each other.
- INVESTIGATE the sequestration of carbon to ocean depths associated with the seasonal migration of polar zooplankton because of Atlantification.

6. Data availability

Table 1: Data availability and location of metadata from the marine systems used in the ARiS Chapter

Location (lat/lon)	Dataset/Code	Parameter/ depth (m)	Period	Dataset provider	Metadata access (URL)
SouthSvalbard 76°6.42' N 015°58.02' E	NorEMSO-South Cape (lander)/SC	T/S@380	2022-23	UiT	https://doi.org/10.18710/XIBMHR
SW Svalbard 76°24.01' N 013°54.00' E	S1 mooring/S1	T/S@1040	2014-23 Gap Mar-Sep 2021	OGS, CNR-ISP	https://doi.org/10.71761/2298c267-0e42-4bb8-8196-d2076fdf6d8e
Hornsund fjord 76°59.00' N 015°55.00'E	LONGHORN mooring/HS	T/S@10-25	2014-24(T) 2017-24(T&S)	IG PAS	https://dataportal.igf.edu.pl/dataset/temp_sal_one_hour_averaged_mooring_data
Western Svalbard 78°33.66'N 010°08.52'E	Prins Karls Forland (lander)/ PKF	T/S@90	2015-17	UiT	https://doi.org/10.18710/IIMSEK
Kongsfjorden 78°54.84' N 012°14.76' E	MDI mooring/KF inner	T/S@90	2010-23	CNR-ISP	https://metadata.iadc.cnr.it/geonetwork/srv/eng/catalog.search#/metadata/aa793636-94bb-4c57-8480-1cb0e5af6296
		T@35	2010-23		https://metadata.iadc.cnr.it/geonetwork/srv/eng/catalog.search#/metadata/60ed7e7b-e355-4348-9a22-4888cd088fa1
		T/S@30	2016-23		https://metadata.iadc.cnr.it/geonetwork/srv/eng/catalog.search#/metadata/1044a3a5-6b4f-4834-a718-a47dd2d4e6e5

Location (lat/lon)	Dataset/Code	Parameter/ depth (m)	Period	Dataset provider	Metadata access (URL)
Kongsfjorden 78°58'N 011°48'E (main) 79°03'N 011°18'E (some early years)	KF mooring/ KF Mouth	T/S@3-250	2002-24	UiT, SAMS, UNIS, NPI	https://dx.doi.org/10.5281/zenodo.14016309
Kongsfjorden 78°56.40'N 012°0.60' E	IndARC/KF mid	T/S@17-182	2014-21	National Centre for Polar and Ocean Research, India	https://npdc.ncpor.res.in/npdc/search_mf_data.action?search=location&expedition_type=Arctic&parameter=MF-1131211289&userType=user
Isfjorden 78° 03.64' N 013°31.44' E	Mouth South/IF Mouth	T/S@20-200* *Varies annually	2005-07 2010-19 2020-22	UNIS	https://data.npolar.no/dataset?pageSize=50&q=Isfjorden%20mooring
Isfjorden 78°10.95' N 013°23.63' E	Mouth North/IF North	T/S@20-225* *Varies annually	2015-19		https://data.npolar.no/dataset?pageSize=50&q=Isfjorden%20mooring
Isfjorden 78°07.52' N 014°25.16' E	Entrance South/ IF	T/S@20-160* *Varies annually	2007-08* *Gap Jan-Sep 2008 2019-23* *Gap Jun-Sep 2020	UNIS	https://data.npolar.no/dataset?pageSize=50&q=Isfjorden%20mooring
Shelf break north of Svalbard 81°24.2′N 031°13.2′E	A-TWAIN arrays/ A-TWAIN	T/S@44-137	2012–13	NPI/IOPAN/ IMR/UiT	https://data.npolar.no/dataset/73d0ea3a-fd21-4eab-8eb9-1e033fefcd8e
			2013-15		https://data.npolar.no/dataset/c972dd9c-562b-4c6c-9b4b-44ad0c0f4707
			2015-17		https://data.npolar.no/dataset/ceb74f92-bb58-44f0-b492-c75667ddc86d
			2017-19*		https://data.npolar.no/dataset/e7041026-9d91-4924-a186-48ba2d93b487
			2021*-22*		https://data.npolar.no/dataset/86ec6869-76c2-46f2-a8f2-8dfae84930e5
Rijpfjorden 80° 17.71'N 022° 17.94'E	Rijpfjorden mooring/RF	T@8-230 T/S@20-230	2006-24	UiT/SAMS/ UNIS	https://dx.doi.org/10.5281/zenodo.14018468

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8. References

Årthun M, Wills RCJ, Johnson HL, Chafik L, Langehaug HR (2021) Mechanisms of Decadal North Atlantic Climate Variability and Implications for the Recent Cold Anomaly. Journal of Climate 34(9):3421–3439. https://doi.org/10.1175/JCLI-D-20-0464.1

Bensi M, Kovačević V, Langone L, Aliani S, Ursella L, Goszczko I et al (2019) Deep Flow Variability Offshore South-West Svalbard (Fram Strait). Water 11(4):683 https://doi.org/10.3390/w11040683

CAFF (2013) Arctic Biodiversity Assessment. Status and trends in Arctic biodiversity. Conservation of Arctic Flora and Fauna, Akureyri. http://hdl.handle.net/11374/223

Cottier F, Nilsen F, Inall ME, Gerland S, Tverberg V, Svendsen H (2007) Wintertime warming of an Arctic shelf in response to large-scale atmospheric circulation. Geophys Res Lett 34(10):L10607. https://doi.org/10.1029/2007GL029948

Cottier F, Skogseth R, Divya D, De Rovere F, Vogedes D, Daase M, Berge J (2022) Temperature and salinity time series in Svalbard fjords – Integrated Marin Observatory Partnership (iMOP II). In: Feldner J et al (eds) SESS report 2021, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 26–36. https://doi.org/10.5281/zenodo.5751717

De Rovere F, Langone L, Schroeder K, Miserocchi S, Giglio F, Aliani S, Chiggiato J (2022) Water Masses Variability in Inner Kongsfjorden (Svalbard) during 2010–2020. Front Mar Sci 9. https://doi.org/10.3389/fmars.2022.741075

Dølven KO, Ferré B, Silyakova A, Jansson P, Linke P, Moser M (2022) Autonomous methane seep site monitoring offshore western Svalbard: hourly to seasonal variability and associated oceanographic parameters. Ocean Sci 18(1):233–254. https://doi.org/10.5194/os-18-233-2022

Holliday NP, Bersch M, Berx B, Chafik L, Cunningham S,

6 https://researchinsvalbard.no/

Florindo-López C et al (2020) Ocean circulation causes the largest freshening event for 120 years in eastern subpolar North Atlantic. Nat Commun 11:585. https://doi.org/10.1038/s41467-020-14474-y

Holmes FA, Kirchner N, Kuttenkeuler J, Krützfeldt J, Noormets R (2019) Relating ocean temperatures to frontal ablation rates at Svalbard tidewater glaciers: Insights from glacier proximal datasets. Sci Rep 9:9442. https://doi.org/10.1038/s41598-019-45077-3

Hopwood MJ, Carroll D, Dunse T, Hodson A, Holding JM, Iriarte JL et al (2020) Review article: How does glacier discharge affect marine biogeochemistry and primary production in the Arctic? The Cryosphere 14:1347–1383. https://doi.org/10.5194/tc-14-1347-2020

Ingvaldsen RB, Assmann KM, Primicerio R, Fossheim M, Polyakov IV, Dolgov AV (2021) Physical manifestations and ecological implications of Arctic Atlantification. Nat Rev Earth Environ 2:874–889. https://doi.org/10.1038/s43017-021-00228-x

Jones EM, Chierici M, Menze S, Fransson A, Ingvaldsen RB, Lødemel HH (2021) Ocean acidification state variability of the Atlantic Arctic Ocean around northern Svalbard. Progress in Oceanography 199. https://doi.org/10.1016/j.pocean.2021.102708

Kolås EH, Baumann TM, Skogseth R, Koenig Z, Fer I (2024) Circulation and hydrography in the northwestern Barents Sea: Insights from recent observations and historical data (1950–2022). Journal of Geophysical Research: Oceans 129(8):2023JC020211. https://doi.org/10.1029/2023JC020211

Luckman A. Benn DI, Cottier F, Bevan S, Nilsen F, Inall M (2015) Calving rates at tidewater glaciers vary strongly with ocean temperature. Nat Commun 6:8566. https://doi.org/10.1038/ncomms9566

Lundesgaard Ø, Sundfjord A, Renner AHH (2021) Drivers of interannual sea ice concentration variability in the Atlantic Water inflow region north of Svalbard. Journal of Geophysical Research: Oceans 126(4):e2020JC016522. https://doi.org/10.1029/2020JC016522

Lundesgaard Ø, Sundfjord A, Lind S, Nilsen F, Renner AHH (2022). Import of Atlantic Water and sea ice controls the ocean environment in the northern Barents Sea. Ocean Sci 18(5):1389–1418. https://doi.org/10.5194/os-18-1389-2022

Mork KA, Skagseth Ø, Søiland H (2019) Recent Warming and Freshening of the Norwegian Sea Observed by Argo Data. J Climate 32:3695-3705. https://doi.org/10.1175/JCLI-D-18-0591.1

Muckenhuber S, Nilsen F, Korosov A, Sandven S (2016) Sea ice cover in Isfjorden and Hornsund, Svalbard (2000–2014) from remote sensing data. The Cryosphere 10(1):149–158. https://doi.org/10.5194/tc-10-149-2016

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 Oceanogr 46:1209–1230. https://doi.org/10.1175/JPO-D-15-0058.1

Payne CM, Roesler CS (2019) Characterizing the influence of Atlantic water intrusion on water mass formation and phytoplankton distribution in Kongsfjorden, Svalbard. Continental Shelf Research 191. https://doi.org/10.1016/j.csr.2019.104005

Polyakov IV, Pnyuskov AV, Alkire MB, Ashik IM, Baumann TM, Carmack EC et al (2017) Greater role for Atlantic inflows on sea-ice loss in the Eurasian Basin of the Arctic Ocean. Science 356(6335):285–291. https://doi.org/10.1126/science.aai8204

Polyakov IV, Ingvaldsen RB, Pnyushkov AV, Bhatt US, Francis JA, Janout M, Kwok R, Skagseth Ø (2023) Fluctuating Atlantic inflows modulate Arctic atlantification. Science 381(6661):972–979. https://doi.org/10.1126/science.adh5158

Renner AHH, Sundfjord A, Janout MA, Ingvaldsen RB, Beszczynska-Möller A, Pickart RS, Pérez-Hernández MD (2018) Variability and redistribution of heat in the Atlantic Water boundary current north of Svalbard. Journal of Geophysical Research: Oceans 123(9):6373–6391. https://doi.org/10.1029/2018JC013814

Renner AHH, Bailey A, Reigstad M, Sundfjord A, Chierici M, Jones EM (2023) Hydrography, inorganic nutrients and chlorophyll a linked to sea ice cover in the Atlantic Water inflow region north of Svalbard. Prog Oceanogr 219. https://doi.org/10.1016/j.pocean.2023.103162

Serov P, Vadakkepuliyambatta S, Meinert J, Hubbard A (2017) Postglacial response of Arctic Ocean gas hydrates to climatic amelioration. Proceedings of the National Academy of Sciences of the United States of America 114(24):6215–6220. https://doi.org/10.1073/pnas.1619288114

Sundfjord A, Albretsen J, Kasajima Y, Skogseth R, Kohler J, Nuth C et al (2017) Effects of glacier runoff and wind on surface layer dynamics and Atlantic Water exchange in Kongsfjorden, Svalbard; a model study, Estuar Coast Shelf Sci 187:260–272. https://doi.org/10.1016/j.ecss.2017.01.015

Skogseth R, Olivier LLA, Nilsen F, Falck E, Fraser N, Tverberg V et al (2020) Variability and decadal trends in the Isfjorden (Svalbard) ocean climate and circulation—an indicator for climate change in the European Arctic. Prog Oceanogr 187. https://doi.org/10.1016/j.pocean.2020.102394

Tesi T, Muschitiello F, Mollenhauer G, Miserocchi S, Langone L, Ceccarelli C et al (2021) Rapid Atlantification along the Fram Strait at the beginning of the 20th century. Sci Adv 7(48):abj2946. https://doi.org/10.1126/sciadv.abj2946

Tsubouchi T, Våge K, Hansen B, Larsen KMH, Østerhus S, Johnson C, Jónsson S, Valdimarsson H (2021) Increased ocean heat transport into the Nordic Seas and Arctic Ocean over the period 1993–2016. Nat Clim Chang 11:21–26. https://doi.org/10.1038/s41558-020-00941-3

Tverberg V, Skogseth R, Cottier F, Sundfjord A, Walczowski W, Inall ME, Falck E, Pavlova O, Nilsen F (2019) The Kongsfjorden Transect: Seasonal and Inter-annual Variability in Hydrography. In: Hop H, Wiencke C (eds) The Ecosystem of Kongsfjorden, Svalbard. Advances in Polar Ecology, vol 2, pp 49–104. Springer, Cham. https://doi.org/10.1007/978-3-

319-46425-1_3

Vivier F, Lourenço A, Michel E, Skogseth R, Rousset C, Lansard B et al (2023) Summer hydrography and circulation in Storfjorden, Svalbard, following a record low winter sea-ice extent in the Barents Sea. Journal of Geophysical Research: Oceans 128(2):e2022JC018648. https://doi.org/10.1029/2022JC018648

Walczowski W, Piechura J, Goszczko I, Wieczorek P (2012) Changes in Atlantic water properties: an important factor in the European Arctic marine climate. ICES Journal of Marine Science 69(5):864–869. https://doi.org/10.1093/icesjms/fss068

Weydmann-Zwolicka A, Prątnicka P, Łącka M, Majaneva S, Cottier F, Berge J (2021) Zooplankton and sediment fluxes in two contrasting fjords reveal Atlantification of the Arctic. Science of The Total Environment 773. https://doi.org/10.1016/j.scitotenv.2021.145599

Wilkinso M, Dumontier M, Aalbersberg I et al. (2016) The FAIR Guiding Principles for scientific data management and stewardship. Sci Data 3, 160018. https://doi.org/10.1038/sdata.2016.18

Microbial communities as sentinels of environmental changes in Svalbard (MicroSIOS)

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1. Introduction

Microbial communities are major drivers in all Earth's ecosystems, playing a pivotal role in energy flows and biogeochemical cycles. Being sensitive to environmental conditions and external processes, microorganisms are considered excellent sentinels of possible changes taking place in the Arctic, an area particularly sensitive to alterations in ecological dynamics due to climate change. This makes them valuable for providing substantial information which can be correlated with other variables, thus offering a more comprehensive understanding of global changes and trends (Caruso et al. 2016). As stated by Malard et al. (2019), a comprehensive census of microbial biodiversity and functional patterns is needed in the Svalbard region to better understand the role of these communities and the possible use of microbial variables (abundance, diversity, metabolism, antibiotic resistance) as a sentinel of environmental change.

Although several studies describing microbial biodiversity have been conducted in Svalbard, very little is known about how such biodiversity might shed light on antibiotic resistance or pathogen abundance. The general lack of insight into microbial spatial distribution patterns and how microbial communities response to environmental change, is further exacerbated by the fact that the data are often expressed in different forms or obtained by different methods. This represents a serious gap, as the specific conditions in the Arctic (its geographic location, low temperature, presence of ice and snow cover, and extended periods of darkness) favours accumulation of airborne particles, creating a reservoir for compounds transported by the atmosphere. Moreover, due to intense glacier melting and permafrost thawing, particles that have been stored for centuries are now being re-introduced to the environment. In addition to pollutants, these particles can contain pathogenic bacteria or viruses that can pose a threat to ecosystems (Pearson et al. 2019; Perini et al. 2019). Despite low abundance of pathogenic microorganisms in aquatic environments, the cryosphere could preserve them in a dormant state, and the melting of ice matrices caused by global warming could lead to their release, thus posing a potential danger of epidemics that could rapidly cause health problems, economic losses, and societal damage (Lowther et al. 2012; Hofmeister et al. 2021). In addition, the expansion of human settlements could also contribute to the spread of human-associated pathogens (Gitay et al. 2002). The presence of antibiotic-resistant microorganisms and antibiotic-resistance genes (ARGs) was demonstrated in frozen environments in the Arctic and elsewhere (Rafiq et al. 2019; Busi et al. 2023; Vishnupriya et al. 2024). Climate change processes determine the mobilisation and accumulation of chemical contaminants in the Arctic (AMAP 2018) and the release of dormant-but-viable microorganisms entrapped therein for millennia (Yarzábal et al. 2021).

In an attempt to address the issues described above, this review applies a systematic approach, compiling scattered data and providing a temporally and spatially explicit knowledge framework to better delineate and define future priorities. The review explores the currently available studies that have assessed microbial diversity in the Svalbard archipelago using culture-dependent methods (e.g., cultivation followed by isolation and screening) or a culture-independent approach (e.g., DNA sequencing). The chapter showcases the state of the art on major microbial taxa in the different matrices investigated in Svalbard by providing a snapshot on biodiversity. It highlights the under-investigated matrices and the most promising approaches for studying them. Moreover, microbial diversity is critically discussed in relation to important topics such as antibiotic resistance (AR), the spread of chemical pollution and pathogens, and climate change.

The Research in Svalbard Portal (RiS[1]) is a useful tool for gaining an overview of past and current research, fieldwork and monitoring activities in Svalbard. In total 46 of the projects present in RIS (of which eight are currently active) relate to

1 https://researchinsvalbard.no/

microbial diversity, but only two concern eastern Svalbard. Sixteen projects in the RiS catalogue study the effects of climate change on microbial communities, of which five are currently active, while one is related to the study of pathogenic microbial communities in glacial ice. Additionally, four projects concern microbial AR, and one project is focused on the potential microbiological risks of virulence factor and ARGs under global climate change. Prior to the literature search for this review, different search strings were tested to query Scopus and Web of Science as appropriate databases in scientific fields.

2. Microbial diversity across the Svalbard environments

To gain an overview about studies on microbial diversity, the literature search included three substrings connected using Boolean operators (AND and OR) and the wildcard "*", by imposing Article title, Abstract, and Keywords as search fields. The substrings used were broad enough to collect a large amount of literature, while also allowing us to refine the results in line with the objective of the research (James et al. 2016). After comparison of different combinations of keywords, the string ("Svalbard" AND "bacterial" AND "diversity") was used. Therefore, more focused literature search was carried out on the main themes of the review, i.e., AR, spread of bacterial pathogens, pollution and climate change. The use of strings makes it possible to do a standardised search, by establishing precise criteria to extract information from the databases in a more rigorous way. The search may have missed a few articles if the exact terms were not present in the article title, abstract and keywords, but we are confident that the reference literature is sufficiently comprehensive. Sections 2.1–2.5 present the microbial taxa found in different matrices in Svalbard, summarising the current state of art on the topic, highlighting the underexplored issues, and thus suggesting the direction for research in the future.

The microbial diversity in Svalbard has been explored over years with different approaches and techniques, spanning from the detection of bacterial abundance and viability status (by DAPI staining and LIVE/DEAD cell counting) to the study of metabolic profiles (by carbon substrate utilisation profiles and microbial enzymatic activity measurements) and taxonomic structure (taxonomic identification of bacterial strains, molecular techniques including Denaturing Gradient Gel Electrophoresis, pyrosequencing, next generation sequencing techniques (e.g., metabarcoding, metatrancriptomics, metagenome assemblies, shotgun sequencing). Among the approaches used, cultivation frequently provides taxonomic identification up to the genus level, alongside data on physiological and biotechnological properties. In contrast, metabarcoding using next-generation sequencing generates a vast number of sequences, offering a more comprehensive view of total microbial communities, in this text reported at higher phylogenetic rank due to the large amount of data. Studies using the more recent metabarcoding techniques are mainly based on amplicon sequencing, while a few papers adopted the whole metagenome approach (see Table A1 in digital appendix[2]). Among studies referring to the microorganisms inhabiting the Svalbard habitats, studies on fungal, microalgal and viral assemblages are available. Originally, this chapter aimed to include all microorganisms; however, in view of the copious amounts of data to discuss, and for the sake of synthesis and greater clarity, the chapter will mainly refer to bacterial and archaeal communities. Different environmental compartments were investigated for microbial diversity on Svalbard (Figure 1), but studies were conducted mainly in Spitsbergen, the largest island of the Svalbard archipelago. A detailed overview of available studies is provided in Table A1 in digital appendix.

2 https://doi.org/10.5281/zenodo.14455795

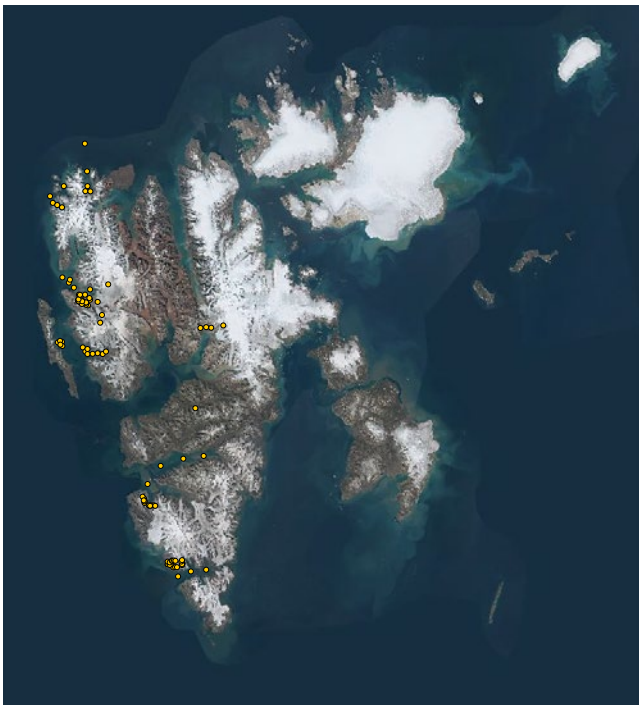

Figure 1: Locations of microbial diversity studies conducted in Svalbard.

2.1. Glaciers: snow, ice, cryoconite

Research on glaciers revealed a hitherto unknown microbial diversity, with indicator species that are potential sentinels for the exchange of bacteria between glaciers and downstream seawater; this transport may have altered the fjord water composition and impacted the marine ecosystems (Garcia-Lopez et al. 2019). Glaciers currently represent habitats hosting unknown and novel taxa.

SNOW – The characterization of bacteria in the snow cover is a challenge for researchers interested in improving knowledge to decipher the role of microorganisms in biogeochemical cycles and the chemical reactions occurring in Arctic snow (Dayal et al. 2023; Amato et al. 2007), or their correlations with meteorological events. Currently, isolating bacteria from snow is still very difficult due to low abundances and the peculiar growth conditions required, which are hard to replicate in laboratory conditions. In Ny-Ålesund and in the accumulation area of the Kongsvegen glacier, a total of ten distinct bacterial strains were recovered by cultivation (identified as *Chelatococcus*, *Brevundimonas*, *Bacillus*, *Micromonospora*, *Moraxella*, Undetermined *Sphingomonadaceae*, *Paenibacillus* and *Agromyces)*, but most of them were obtained after proper enrichment procedure instead of direct plating of melted snow on agar media (Amato et al. 2007). However, the application of next generation sequencing techniques allowed us to overcome the issue and has provided a more comprehensive overview of snow microbial diversity. In a recent study on seven glaciers in Svalbard, metabarcoding revealed that *Gammaproteobacteria* were predominant in snow bacterial communities, followed by *Betaproteobacteria*, *Alphaproteobacteria*, *Actinobacteria*, *Bacilli*, *Sphingomonas*, *Flavobacteria*, and *Cyanobacteria*. The role of these isolates in snow chemistry is crucial, probably linked to their capacity to break down organic compounds commonly found in Arctic snow (e.g., propionate, acetate, and formate) and to their physiological properties (spore-forming ability, pigmentation, and capacity to grow in low-nutrient media). This enables them to thrive during snowmelt and to contribute to the carbon balance and other geochemical cycles.

ICE – Glaciobiological studies in the Svalbard area are few and mainly focused on cryoconite biology (Amato et al. 2007; Edwards et al. 2011). The available studies on ice samples mainly employed traditional methods to define the total cell abundance in firn-cores (Midtre Lovénbreen glacier, Svalbard; Singh et al. 2015 a,b). Bacteria play diverse metabolic roles in the carbon (C), nitrogen (N), and phosphorus (P) cycles (Edwards et al. 2011) and have a significant impact on the biogeochemistry of their environments. As evidenced for snow, the studies reported a low culturability of bacteria from samples in laboratory conditions. The bacterial isolates were mainly affiliated to *Bacillus*, *Pseudomonas* and *Sphingomonas* spp. A total of 59 phylotypes (distributed among *Proteobacteria*, *Bacteroidetes*, *Actinobacteria*, *Firmicutes*, *Acidobacteria*, *Deinococcus-Thermus*, *Chloroflexi*, *Planctomycetes*, *Cyanobacteria* and candidate division TM7) were detected in ice core samples from the Austre Lovénbreen glacier by applying a mixed approach, coupling clone libraries and bacterial isolation (Zeng et al. 2013). In total, nineteen *Pseudoalteromonas* and *Psychrobacter*

strains were isolated. Overall, there was a strong correlation between the ice cores and marine environments, indicating a wide distribution of some bacterial taxa in both terrestrial and marine ecosystems.

CRYOCONITE – Cryoconite holes are peculiar habitats occurring on glaciers, formed as a result of aeolian transport of dust and debris to the glacier surface, and offering optimal conditions for the proliferation of microbial life. The reduction of albedo due to the presence of dust induces melting and the formation of cylindrical melt-holes containing dark granular sediment and clear meltwater. The consequent increase of solar radiation absorption by the cryoconite granules favours the establishment of high rates of microbial primary production and respiration (Edwards et al. 2013). To date, studies on prokaryotic diversity in cryoconite ecosystems have concerned the glacier areas of Austre and Vestre Brøggerbreen and Midtre Lovénbreen (Ny-Ålesund) (Edwards et al. 2011, 2013, 2014), the Foxfonna ice cap in Svalbard (Gokul et al. 2016), the Hans and Werenskiold Glacier (Hornsund) (Grzesiak et al. 2015), Longyearbreen (Zarsky et al. 2013), three valley glaciers Nordenskiöldbreen, Hørbyebreen and Ebbabreen (Vonnahme et al. 2016, on prokaryotic cyanobacteria). The interest in cryoconite systems lies in the correlations between the microbial community structure and the functionality of these habitats, in addition to the interactions between the aeolian transfer of biota from ice-marginal habitats and the potential for cryoconite microbes to inoculate proglacial habitats, currently poorly explored. Several studies support the establishment of distinct functional microbial communities in the cryoconites, with distinctive niches for bacterial taxa. These observations were obtained by using terminal restriction fragment length polymorphism (T-RFLP) and 454-pyrosequencing techniques, which identified *Proteobacteria*, *Cyanobacteria* and *Bacteroidetes* as dominant taxa (Edwards et al. 2011, 2013, 2014). *Cyanobacteria*, together with *Actinobacteria* members, were subsequently suggested as respective keystone taxa and ecosystem engineers of cryoconite ecosystems colonising ice caps (Gokul et al. 2016). The only scientific data on culturable bacterial communities are provided by Singh et al. (2014), who highlighted a strong ecological adaptive potential of isolates (mainly *Pseudomonas*, *Polaromonas*, *Micrococcus*, *Subtercola*, *Agreia*, *Leifsonia*, *Cryobacterium*, and *Flavobacterium* members) in terms of carbon utilisation, production of fatty acids and cryoenzymes.

More often, the studies are geared toward multiple interrelated matrices, allowing predictive assessments about the interactions between different environmental compartments (Piquet et al. 2010). In line with this, Thomas et al. (2020), reported an abundance of *Betaproteobacteria* in glacier snow, ice and meltwaters, while *Alphaproteobacteria* and *Verrucomicrobiae* predominated the fjord water. Interestingly, distinct bacterial communities were described in melting waters, with clear signatures of the glacier ecosystem, and fjord water, with a most pronounced representation of marine taxa. These findings highlighted the occurrence of unknown taxa in the melting waters, pointing out their role as conducive hotspots for unknown microbiota resulting from the amplicon sequencing (V3–V4 region of the 16S rRNA) (Keuschnig et al. 2023). The same technique combined with cultivation approach was applied by Perini et al. (2019) on the study of fungal and bacterial communities of three glaciers by exploring glacial ice and associated meltwater and lake-derived tapwater in Kongsfjorden. Interestingly, the fungal communities of the three glaciers were spatially heterogeneous, while a high sharing level was detected in the bacterial communities with *Flavobacterium* as the most frequently isolated genus and *Actinobacteria* and *Proteobacteria* as the most abundant taxa detected by amplicon sequencing. Some studies were focused on the search for specific bacterial taxa possibly involved in biogeochemical cycles, such as ammonia-oxidising Archaea, contributing to the immobilisation of NH_4^+ and the production of surplus NO_3^- detected in aggregation of surface debris particles on melting glaciers (Zarsky et al. 2013). It has been proven that the surface of the valley glacier Aldegondabreen hosts a diverse microbial community dominated by *Cyanobacteria*, *Proteobacteria*, *Bacteroidetes*, and

Actinobacteria, while ammonia-oxidising Archaea were first detected in the aggregates on an Arctic glacier supplied with carbon and nutrients from different sources across its surface, including colonies of seabirds. The study of microbial community composition was interestingly related to other biotic compartments, by correlating the bacterial and archaeal assemblages with the role of algal populations in some Svalbard glaciers (Vestre and Austre Brøggerbreen, Midtre and Austre Lovénbreen, Pedersenbreen, and Feiringbreen), including a miscellany samples (clean, red, and green snow, biofilm, clean and dirty ice, and cryoconite samples) (Lutz et al. 2017). Bacteria were mainly represented by *Proteobacteria*, *Bacteriodetes* and *Cyanobacteria*, with the predominance of *Bacteriodetes* in snow and transition habitats and lower abundances in dirty ice and cryoconite holes. Contrastingly, the Archaea showed low diversity, with a community structure composed by *Nitrosophaerales* and *Methanobacteriales* members, detected in snow, ice and cryoconite samples.

2.2. Soil and permafrost

- TUNDRA SOILS – Soil microbial communities play a fundamental role in major global biogeochemical cycles, particularly in polar regions. The role of soil heterotrophic bacteria mainly lies in stabilising and decomposing organic matter in soil, which affects the global carbon cycling. The microbially driven mineralisation of organic matter is anticipated to be a key feedback mechanism affecting the global climate system (Schuur et al. 2015). Warmer Arctic winters, predicted by climate models, could result in decreasing local snow cover and modify the frequency of freeze–thaw cycles. These changes, together with soil structure, may influence the activities and environmental functions of the microbiota (Kotas et al. 2018; Lim et al. 2018; Wutkowska et al. 2019). Overall, the most abundant bacterial phyla in Svalbard tundra soils are *Proteobacteria*, *Actinobacteria*, *Acidobacteria*, *Planctomycetes*, *Cyanobacteria*, *Chloroflexi*, *Bacteroidetes*, *Cyanobacteria* and *Verrucomicrobia* (Wang et al. 2016; Lim et al. 2018, 2020; Kerfahi et al. 2019; Almela et al. 2023). Warming could slowly influence the bacterial community composition in Arctic soil, highlighting the importance of water availability in determining microbial responses to warming (Lim et al. 2018). The proportions of *Proteobacteria* and *Bacteroidetes* can change, depending on soil organic matter and total organic carbon contents, being higher in the organic layer than in the mineral soil layer. Conversely, the proportion of *Acidobacteria* can be higher in mineral soil than in the organic layer (Lee et al. 2013).
- BIOCRUST – Ice-free soils in polar and sub-polar regions can be covered by biocrusts (biological soil crusts, with a thickness of about 5 mm), deriving from the association between prokaryotes and eukaryotes living on the uppermost soil surface. In partially vegetated Arctic areas, biocrusts are crucial habitats because they support the establishment and development of vascular plants and small animal communities, as well as the carbon (C) and nutrient cycles (N and P). Still, knowledge about the composition of the biocrust microbial community in polar areas, including Svalbard, remains scant and fragmentary. Overall, taxonomic assignment revealed the dominance of *Acidobacteria*, *Actinobacteria*, and *Chloroflexi* in Svalbard biocrusts (Pushkareva et al. 2022). Nitrogen-fixing cyanobacteria *Nostocales*, *Synechococcales*, and *Oscillatoriales* dominate cyanobacteria communities (Pushkareva et al. 2015). Together with them, *Actinobacteria* also can fix nitrogen, a particularly vital function in polar biocrusts where nitrogen is scarce. *Actinobacteria* are oligotrophs with a role in the carbon, nitrogen, and sulphur cycles, and have the ability to produce extracellular polymeric substances that support their survival in extreme environments and may promote biocrust formation (Weber et al. 2022).
- POLAR DESERTS (ROCKS) – Rocks can represent hotspots for microbial diversity, as the physical and chemical features of lithic substrates can affect microbial colonisation. The assessment of the microbiome of rocks showed that *Thaumarchaeota*, *Proteobacteria*, and *Ascomycota* are the most abundant archaeal, bacterial and fungal taxa, respectively (McCann

et al. 2016; Choe et al. 2021). The compositions of both bacterial and fungal communities can vary across different rock types (e.g., sandstone, basalt, or granite) depending on the geochemical characteristics of the rocks (i.e., Mg and Ca for bacteria, and Fe for fungi and bacteria) (Choe et al. 2018). Among Bacteria, *Actinobacteria*, *Chloroflexi*, *Bacteroidetes* and *Acidobacteria* can be predominant (McCann et al. 2016). Fungal communities can consist of *Eurotiomycetes*, *Lecanoromycetes*, *Dothideomycetes* and *Leotiomycetes*. Overall, the survival of rock-dwelling microbes in diverse environments relies on essential traits such as oligotrophy, stress resistance, and a wide variety of growth forms.

- GLACIAL FOREFIELDS/FORELAND – Glacial forefields represent unique natural laboratories to study microbial community succession, soil formation, and polar ecosystem evolution and functioning. Microbial communities have been recognised as pioneering inhabitants of glacier forefields, being involved in the soil development during glacier retreat. In Svalbard, soil microbial co-occurrence network was found to change along the temporal succession of glacier retreat. Species tended to have closer integration and more interaction with each other in more stressed environments. Results from chronosequence approaches suggest that soil ecosystem development is highly influenced by locally heterogeneous factors, and integration between members of soil biota and microbial consortia, playing important roles in niche adaptation and survival (Schütte et al. 2009; Dong et al. 2022; Luláková et al. 2023). The microbial community structure, ecological functions, and stress adaptation strategies in glacial forefields in Svalbard have scarcely been explored. At the initial stage of soil development of the glacial forefields in Svalbard, Bacteria generally are more abundant than Archaea and Fungi (Venkatachalam et al. 2021; Dong et al. 2016, 2022; Tian et al. 2023). *Proteobacteria* and *Actinobacteria* are generally dominant bacterial phyla in glacial environments, followed by *Bacteroidota*, *Acidobacteriota*, *Bdellovibrionota*, *Firmicutes*, and *Myxococcota* (Górniak et al. 2017; Wojcik et al. 2018; Venkatachalam et al. 2021, 2024; Dong et al. 2022; Tian et al. 2023). Among Bacteria, *Cyanobacteria* are important colonisers of recently deglaciated proglacial soil in Svalbard (Kaštovská et al. 2005, 2007; Pessi et al. 2019). Early, primary communities are composed of chemolitotrophic phylotypes related either to potentially novel lineages or lineages predominantly restricted to cold (polar and alpine) biotopes, suggesting that the initial colonisation of proglacial soil is accomplished by cyanobacteria transported from nearby glacial environments. Late, more stable communities include more widely distributed phylotypes, becoming established only after the microenvironment has been modified by the pioneering taxa (Pessi et al. 2019). As revealed by metagenome-assembled genomes (Tian et al. 2023; Venkatachalam et al. 2024), bacteria in glacial environments have developed multiple physiological adaptations to survive a combination of stress factors (e.g., low temperature, frequent freeze–thaw, high UV irradiation, and oligotrophy). In addition, dissimilatory nitrate reduction and denitrification were identified as the main nitrogen metabolic pathways in glacial forefields in the Arctic region of Svalbard. The presence of the diazotrophic communities across the glacier forefields was also reported at Midtre Lovénbreen, with key organisms including *Nostoc*, *Geobacter*, *Polaromonas* and *Frankia* (Nash et al. 2018). Metabolic pathway reconstruction also suggested versatility for sulphide and thiosulphate oxidation, H_2 and CO utilisation, and CO_2 fixation, highlighting the importance of microbes in elemental cycling in glacial forefields.
- PERMAFROST AND ACTIVE LAYER SOILS – Thirty-seven percent of the northern hemisphere is covered in permafrost, which holds large amounts of ancient carbon locked in the form of soil organic matter (Strauss et al. 2015). The Arctic's present warming is a cause for concern for the climate because it may release an unknown amount of carbon into the atmosphere through processes known as the "permafrost carbon feedback" (Schuur et al. 2015). Microbiological studies

have focused on both the uppermost layer of permafrost, known as the active layer, which experiences periodic cycles of freezing and thawing, and the underlying permafrost layer, which stays frozen all year round (Dobiński 2020). Microbial communities in permafrost play key roles in carbon cycle processes (organic matter decomposition, hydrolysis, acetogenesis, methanogenesis and methanotrophy) (Yang et al. 2024). Permafrost areas are warming at a global scale, and the increased microbial activity causes previously protected organic matter to decompose more quickly and releases greenhouse gasses (such carbon dioxide and methane). The thawing of Arctic permafrost has significantly increased by 1.0 to 1.5 days/year (Grünberg et al. 2024), as highlighted by the growing active layer thickness in the soil. Studies were performed to identify potential connections between microbial community structure and metabolic activity, permafrost thawing and greenhouse gas fluxes, to better predict climate change effects that include microbial processes in Svalbard. The active layer of the permafrost in Svalbard has been generally found to have a higher microbial diversity, biomass, and activity than in the permafrost layer. Nitrogen cycle processes are crucial in the active layer. Variations occur at seasonal level with the enrichment of certain taxa specific for a season, as well as stability or dynamic nature of bacterial communities between seasons (Schostag et al. 2015; Loganathachetti et al. 2022). According to Loganathachetti et al. (2022), the conditions prevailing during winter and summer can shape the bacterial community in the active layer, with stable diversity in both periods and variations mostly affected by total nitrogen content. At phylum level, *Proteobacteria*, *Acidobacteriota*, *Verrucomicrobiota*, *Chlorofexi*, and *Actinobacteriota*, followed by *Bacteroidota* and *Gemmatimonadota*, can occur in both winter and summer seasons. *Bacteroidota* and *Verrucomicrobiota* were more abundant in winter samples, whereas *Gemmatimonadota* and *Acidobacteriota* were present in high abundance in summer. *Nitrospirota*, FCPU426, *Patescibacteria* and *Fibrobacterota* were detected at very low abundance across all active layer samples (Loganathachetti et al. 2022). A further study carried out by Schostag et al. (2015) on a temporal scale based on PCR amplicons of 16S rRNA genes (DNA) and reverse transcribed transcripts (cDNA) revealed that overall, the dominant phyla were *Proteobacteria*, *Actinobacteria*, *Verrucomicrobia*, *Acidobacteria* and *Gemmatimonadetes*. At the cDNA level, the dominant potentially active phyla were *Proteobacteria*, *Acidobacteria*, *Actinobacteria*, *Verrucomicrobia*, and *Cyanobacteria*. These latter showed a pronounced seasonal variation with lower abundance in winter than in summer. A more in-depth analysis highlighted that the abundance of *Alphaproteobacteria*, *Gammaproteobacteria* and *Acidobacteria* can decrease with soil depth, whereas *Betaproteobacteria* and *Gemmatimonadetes* increase (Müller et al. 2018). These community shifts can be ascribed to C turnover within different soil horizons, as well as to a combination of several factors, including oxygen availability and redox effects. Interestingly, a spatial and temporal variability of CO_2 was observed in the fine-scale variations (every 3 cm) of microbial communities throughout permafrost cores (Müller et al. 2018). Xue et al. (2020) found that the bacterial community composition in soil horizons shifted markedly with depth, i.e., the dominant phyla switched from *Acidobacteria* and *Proteobacteria* in the active layer to *Actinobacteria*, *Bacteroidetes*, *Chloroflexi* and *Proteobacteria* in permafrost layers. When one is predicting metabolic functionality from metagenomic data, aerobic respiration and soil organic matter decomposition are key metabolic traits, in addition to the enrichment in genes involved in regulation of ammonium, sulphur and phosphate metabolism. This suggests that high resolution microbial community permafrost profiles may be useful to understand how the different microbes function in this globally important and changing Arctic environment. Limited information exists regarding the abundance and distribution of microorganisms associated with Fe cycling in Arctic permafrost. Among genera known to contain strains

associated with Fe reduction/oxidation there are *Geobacter* and *Rhodoferax*, *Desulfosporosinus*, *Anaeromyxobacter*, *Paenibacillus* and *Pelosinus* (Kolchev et al. 2022).

2.3. Marine environment

SEAWATER – Bacterial communities play a vital role in the marine food web; these communities include diverse populations of autotrophic and heterotrophic lineages that govern various biogeochemical processes. Changes in the bacterial community composition can directly impact the biogeochemical dynamics of marine systems. This is particularly evident in the fjord system, where rising temperature enhances efflux of meltwater from the glaciers, with strong environmental gradients in the water column due to the input of sediment and organic matter to the fjords. Any shift in community composition leads to a change in enzymatic function and would directly influence the biogeochemical processes, including those involving specific elements, e.g., iron and sulphur (Caruso et al., 2020). Advances in molecular sequencing techniques have strongly contributed to the knowledge in this research field. Sequencing revealed that the bacterial communities commonly retrieved from Svalbard waters (including fjord water, meltwater and glacier water) were mainly comprised of *Proteobacteria* (Alpha- and Gamma-), *Bacteroidetes*, *Cyanobacteria*, *Verrucomicrobiae*, *Actinobacteria*, *Acidimicrobiia* and *Oxyphotobacteria* (Cardman et al. 2014; Han et al. 2022; Kosek et al. 2019; Sułowicz et al. 2020; Venkatachalam et al. 2023; Kim et al. 2024). While groups such as Proteobacteria and *Bacteroidetes* are widespread in aquatic environments due to their wide metabolic capacity, members of *Verrucomicrobiota* and *Actinobacteriota* are respectively involved in the degradation of polysaccharides and organic pollutants, suggesting their role in the breakdown of organic compounds resulting from glacier runoff processes. The distribution of bacterial taxa could change locally, on the base of the geographical position, or also along the water column depending on the depth. Han et al. (2022) underlined the influence of water mass balance on the bacterial community composition with a distribution in which *Alphaproteobacteria* and *Actinobacteria* gradually decreased from surface water (in this case relatively cold and fresh) to subsurface water (warmer and with higher salinity) via intermediate water, while *Verrucomicrobiae* and *Acidimicrobiia* were less abundant in surface water than in intermediate and subsurface water.

Clear seasonal shifts in the microbial community composition at order level were detected in the Isfjorden system, with *Verrucomicrobiae* predominating in August, and *Gammaproteobacteria* represented by *Oceanospirillales* and *Alteromonadales* in June, and *Cellvibrionales* in August. Similarly, *Flavobacteriales* in June were represented by the genera *Polaribacter*, *Formosa* and NS5 marine group, while in August *Ulvibacter* spp. were more abundant (Delpech et al. 2021). At the glacier–seawater interface of the Blomstrandbreen glacier, new insights on the diversity of the microbial community were also obtained using an Unmanned Autonomous Vehicle (AUV) by Papale et al. (2023), who identified three main sub-regions differently affected by the haline gradient (close to the glacier) or terrigenous inputs of coastal origin. Across the sampled transects, different patterns of microbial abundance and metabolism were observed, highlighting the influence of ice melting and Atlantic water on microbial growth and functions. The archaeal community in the water was investigated less than the bacterial assemblage, but some specific groups, namely *Thermoplasmatota*, *Thaumarchaeota*, *Nanoarchaeota* and *Halobacterota* were observed to predominate in the surface waters of Kongsfjorden (Zeng et al. 2009; Liu et al. 2018; Jain and Krishnan 2021). Substantial effort also went into studying specific bacterial fractions in seawater, such as diazotroph bacteria. Biological nitrogen fixation is a key source of fixed nitrogen in oligotrophic marine environments, playing a crucial role in supporting primary production and sustaining the nitrogen balance. The majority of the *nifH* gene sequences obtained by Jabir et al. (2023) belong to phylum *Proteobacteria* (88.9%), *Cyanobacteria*, *Verrucomicrobiae*, and *Euryarchaeota*, suggesting predominance of non-cyanobacterial diazotrophs in Kongsfjorden. The culturable bacterial diversity was less studied, mainly explored in Kongsfjorden,

where the community composition and function were studied in different months and related to the changes in the water masses. Among the heterotrophic bacteria, *Firmicutes*, *Actinobacteria*, *Proteobacteria*, and *Bacteroidetes* were the predominant taxa retrieved, with representation of the genera *Leeuwenhoekiella aequorea*, *Sphingopyxis baekryungensis*, *Erythrobacter citreus*, *Agrococcus baldri*, *Psychrobacter nivimaris*, and *Bacillus subtilis* (Sinha et al. 2017a, b).

MARINE SEDIMENTS – Sediments in the Arctic host diverse microbial communities playing a pivotal role in the remineralisation of organic matter and associated biogeochemical cycles (Canion et al. 2013; Tait et al. 2014; Vipindas et al. 2020; Flieder et al. 2021; Vishnupriya et al. 2023; Miksch et al. 2021, 2024). This finding is in line with data reported by Teske et al. (2011) who compared the organic matter degradation capability of microbial communities in seawater and sediment by measuring the extracellular enzymatic hydrolysis rates of 10 substrates, and demonstrated broader enzymatic capabilities of microbial populations inhabiting sediments. Even if the benthic bacterial community structure is seasonally stable (Miksch et al. 2021), they can respond to the seasonally changing input of fresh organic matter (Miksch et al. 2024). Similarly, studies have demonstrated the potential of culturable bacteria representing phyla *Actinobacteria*, *Bacteroidetes*, and *Proteobacteria* to produce cold-active enzymes like amylase, lipase, caseinase, urease, gelatinase, and DNase as well as complex polysaccharide degrading enzymes like alginase, pectinase amylase and xylanase isolated from Kongsfjorden (Prasad et al. 2014; Jain and Krishnan 2017). *Proteobacteria* and *Bacteroidetes*, together with *Epsilonbacteraeota*, *Alphaproteobacteria* and *Fusobacteriia* dominate the overall bacterial community (Ravenschlag et al. 2001; Tian et al. 2009; Conte et al. 2018; Zeng et al. 2017; Thomas et al. 2021). The occurrence of *Verrucomicrobia*, *Actinobacteria*, *Chloroflexi* and *Lentisphaerae* was also highlighted, suggesting a strong sensitivity of microbiomes to changes in location depth, temperature and salinity. The influence of the glacial activity in the inner fjord was also pointed out, by suggesting a need for validation over long-term timescales in the future (Fang et al. 2019). According to Conte et al. (2018), the bacterial community structure can be likely influenced by the glacial activity in the inner Kongsfjorden, with the occurrence of distinctive phylotypes belonging to *Gemmatimonadates*, *Nitrospirae*, *Acidobacteria*, and *Chloroflexi*. Archaeal sequences are generally less represented (below 1% of total sequences) and mostly related to *Thaumarchaeota* (Zeng et al. 2017). Flieder et al. (2021) investigated the metabolic potential of uncultured *Acidobacteriota* lineages, together with their diversity and distributions. Metagenome-assembled genomes (MAGs) from *Acidobacteriota* occurring in marine fjord sediments of Svalbard revealed their ability to dissimilate various inorganic sulphur compounds, thus being involved in sulphur cycling.

2.4. Freshwater environments

The river–lake systems in the Arctic are peculiar environments strongly affected by the sources of water supply, which involve the transport of chemical compounds and microorganisms originating from the airborne pool, glaciers, sea aerosols and permafrost thaw (Kosek et al. 2019). Early studies in freshwater systems were focused on the estimation of bacterial abundance, in correlation with mixotrophy and microbial plankton dynamics (Laybourn-Parry and Marshall 2003). Overall, these environments are characterised by low bioavailability of the nutrients needed for bacterial growth, which is often altered by seasonal changes, thus requiring the development of various ecological tactics to survive. Even though such environments are considered oligotrophic, in some cases a very diverse bacterial community was detected. Shifts in the taxonomic composition of the bacterial community were recorded in the Revelva system (southern Spitsbergen) in relation to the biogeochemical changes that occur seasonally with the switching water sources. Interestingly, such communities could host both typically freshwater and marine microorganisms, mainly affiliated with specific taxa with roles in mineralization processes or associated with zooplankton (Ntougias et al. 2016). Despite the recognised dominance

of *Proteobacteria*, *Actinobacteria*, *Bacteroidetes*, *Planctomycetes* and *Firmicutes* (Ntougias et al. 2016; Kosek et al. 2019), the occurrence of some taxa rarely detected in polar environments was reported, namely the *Microgenomates*, retrieved in Fuglebekken Lake and Revvatnet lake (southern Svalbard); *Microgenomates* have been suggested to be involved in biogeochemical cycles in polar habitats (Ntougias et al. 2016). The rapid increase in temperature in the Arctic will strongly affect these river systems, as more precipitation in the form of rain events and more meltwater from thawing permafrost and glaciers will increase the water supply.

2.5. Atmosphere

The atmosphere is still one of the least understood of the global microbial ecosystems and this is particularly true for the Arctic, due to the remote location, extreme and highly variable conditions and particularly the technical challenges involved in acquiring representative samples at appropriate spatial and temporal scales. What is clear is that microorganisms have huge potential as key indicators due to their sheer numbers and response times. There is probably a core microbiome, composed of core Arctic members and cosmopolitan species and we know that they are active in climate processes and can potentially play important functional roles. The basic research challenges are high levels of microbial variability (across spatial and temporal scales), low biomass, multiple and diverse drivers and low match quality (much of the DNA sequence information is from hitherto unidentified species). Work to date in this area, specifically in Svalbard, is still relatively limited, although there has been a marked increase in interest recently, partly due to the molecular revolution and particularly as technical challenges are being overcome. The biodiversity patterns in Arctic air were investigated using molecular techniques in the Canadian High Arctic (Harding et al. 2011), and in Svalbard (Cuthbertson et al. 2017). Single-particle fluorescence spectroscopy and electron microscopy have been used to identify and quantify primary biological aerosol particles (PBAP) at Zeppelin Observatory, revealing that PBAP concentrations peak in summer. Moreover, they are strongly correlated with regional environmental factors (such as temperature and surface albedo), suggesting that the aerosol microphysical properties and cloud residual properties should be studied to cover the full aerosol life cycle (Pereira Freitas et al. 2023, 2024).

3. Bacterial antibiotic resistance and spread of pathogenic bacteria

The most appropriate string was set as (("Svalbard" AND ("bacteri*" OR "fung*" OR "microalg*") AND "antibiotic" AND ("resistance" OR "tolerance"))), leading to a total of 22 and 16 items from Scopus and the Web of Science, respectively. The issue of the presence and spread of AR in the Arctic regions has acquired alarming connotations in recent decades in the light of climate change and global warming. AMR is spreading rapidly and poses a serious global threat to human health and it has been described by the World Health Organization (WHO) as one of the top global public health and development threats. This situation might be due to the rapid spread of resistance genes through mutation or horizontal gene transfer within microbial populations, or even across different species, and to the overuse and misuse of antibiotics by humans (Holmes et al. 2016; Christaki et al. 2020; Samreen et al. 2021). The occurrence of multidrug-resistant bacteria is also a major threat in healthcare settings, especially for immunocompromised individuals. Despite the profound importance of the question for human health, the potential environmental reservoirs of AR in the Arctic are still poorly understood (Allen et al. 2010). It has been shown that AR occurs not only in polluted environments, but also in pristine cold environments. This could be due to some AR microorganisms that are able to survive under freeze–thaw stress conditions being released through the accelerated melting

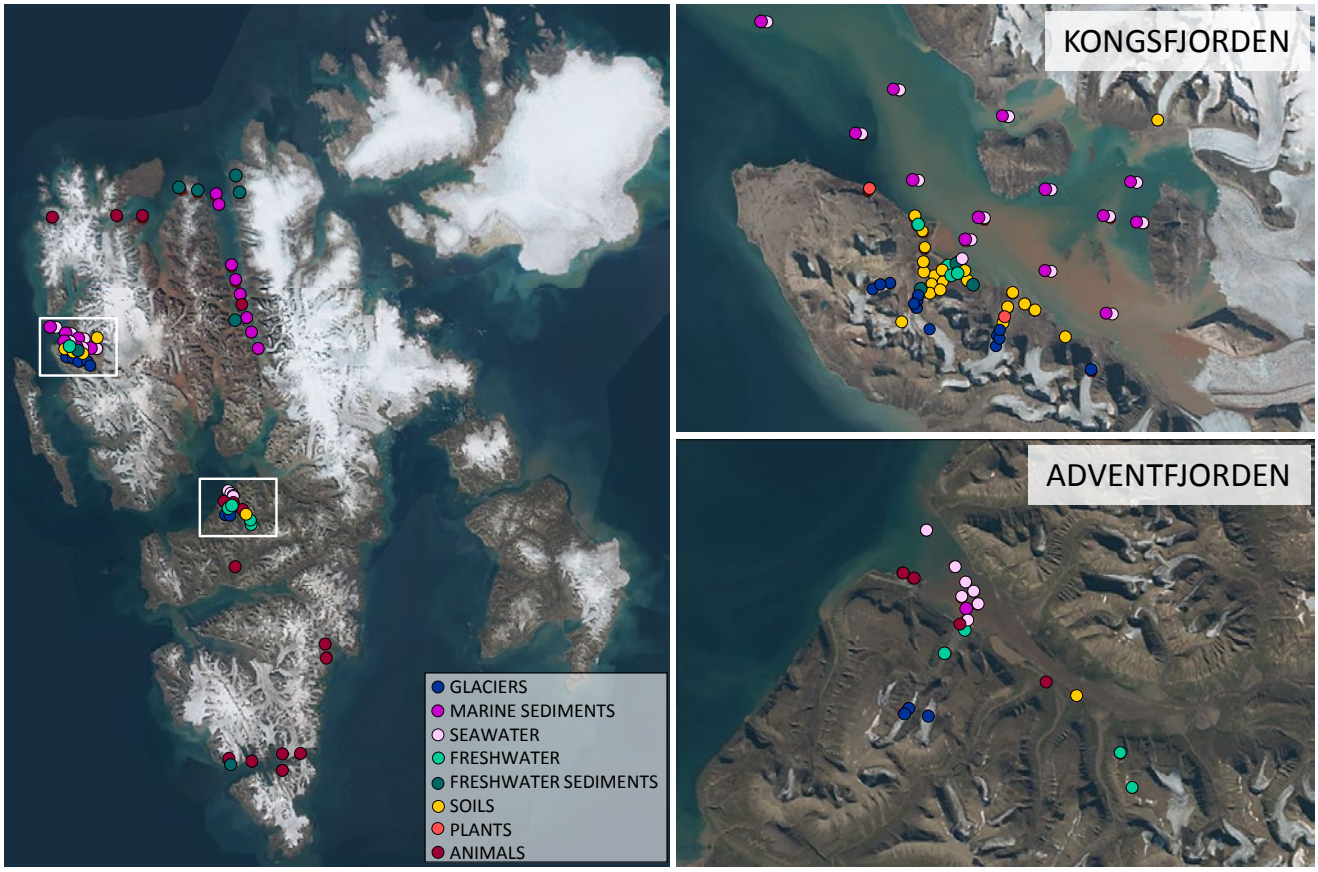

Figure 2: Maps showing locations and environmental compartments where bacterial antibiotic resistance has been detected in Svalbard.

process, and incursion of warm water currents bringing prokaryotes of tropical origin to the Arctic region. The role of migratory birds and wildlife is also important in the AMR spreading processes. A concerted effort is currently required to deepen investigations on the spread of AR in non-agricultural and non-clinical environments (Allen et al. 2010). Coordinated global efforts to combat antibiotic resistance—through better stewardship, research into new treatments, and improved infection prevention—are necessary to avoid a "post-antibiotic era" where many common infections and medical procedures become high-risk due to a lack of effective treatments. In this context, the definition of breakpoints for polar microorganisms (i.e., systems for categorising microorganisms as susceptible or intermediate (S and I) or resistant (R)) to agents approved for use in the treatment of infectious diseases, is strongly suggested.

Currently available studies on AR in the Svalbard area are split between research conducted through a culture-based approach, through innovative sequencing techniques, and studies that use a combined approach, as detailed below. Several studies are also available on the search for antibiotic-resistant bacteria (ARB) and/or ARGs in faecal samples from Arctic animals to determine if and to what extent these may be carriers for AR dispersal.

Figure 2 shows AR occurrence in microorganisms collected from different parts of Svalbard and in different environmental compartments. The process of retrieval and harmonisation of reported data carried out for this chapter was difficult due to the differences in the methods used in the studies and the non-harmonised presentation of results. Different antibiotics at different concentrations have been used for antibiotic susceptibility tests performed on bacterial strains isolated from several matrices. Most of the studies to isolate ARB or search for ARGs have focused on soils or sediments, followed by water and cryomatrices. Antibiotic-resistance is a common trait in

bacterial strains isolated from Kongsfjorden and Krossfjorden sediments; resistance to ceftazidime (45% of the total), followed by trimethoprim and sulphamethizole (27 and 24%, respectively), has been reported (Vishnupriya et al. 2024). Antibiotic residuals present in sediments may directly influence the structure of natural microbial communities, often causing a reduction in microbial biodiversity or functional stability (Grenni et al. 2018). The susceptibility/resistance of about 235 bacterial isolates from different matrices was tested overall on a total of 60 antibiotics from different categories combined (see Table A2 in digital appendix; Konieczna et al. 2011; Ambrožič Avguštin et al. 2013; Mechirackal Balan et al. 2018; Neethu et al. 2015; Singh et al. 2014, 2017; Hatha et al. 2015; Mogrovejo et al. 2020b; Kalinowska et al. 2021; Kang et al. 2022). Of the wide range of bacterial taxa screened, the most numerous tested strains were affiliated with the genera *Arthrobacter* and *Pseudomonas*, followed by *Cryobacterium* and *Enterococcus*.

Pseudomonas spp. of various origins are known for their wide antimicrobial resistance pattern, also due to the presence of protective capsules which reduce the concentration of antimicrobials reaching the cells, and of efflux pumps contributing to the development of a multidrug resistance phenotype (Mogrovejo et al., 2020b). The antibiotics for which a large number of resistant bacteria have been detected are oxacillin, ampicillin, erythromycin, cephixime, clidamycine, and cephmedazole (Figure 3). A recent study on the topic reported the antibiotic resistance pattern of bacterial strains isolated from different fjords in Svalbard

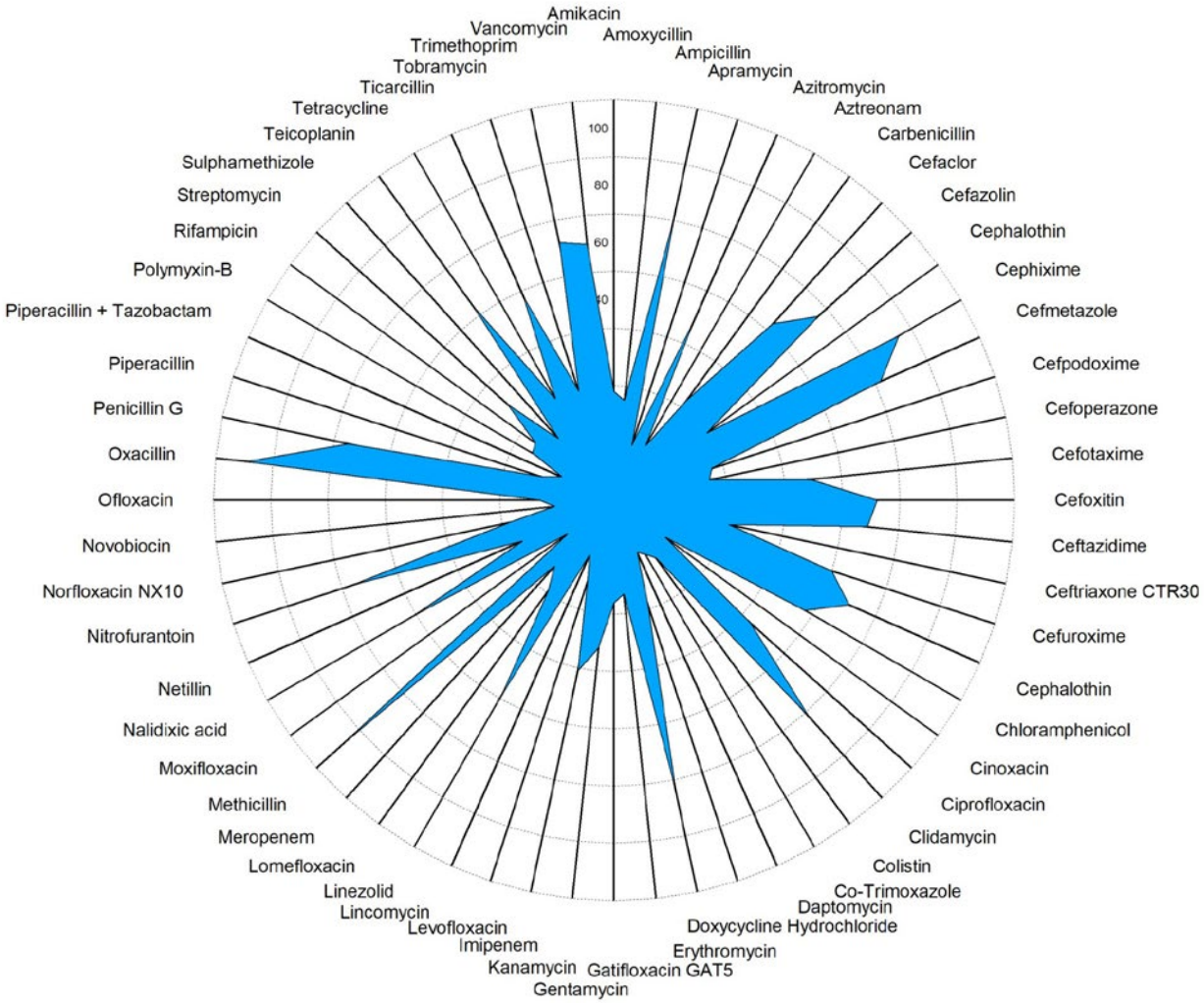

Figure 3: Bacterial antibiotic resistance: number of bacteria found to be resistant to specific tested antibiotics.

(Caruso et al. 2024). On a panel of 66 isolates phenotypically characterised as *Pseudomonas* spp., *P. putrefaciens*, *Vibrio* spp. and *Flavobacterium* spp., resistance to enrofloxacin and tetracycline was detected, while most of the strains were sensitive to ampicillin, clindamycin and gentamycin. In terms of geographical distribution of AR-bacteria in Svalbard, the highest abundance of tetracycline-resistant strains was observed in the central area, particularly in Adventfjorden (100% of the total isolates), followed by Dicksonfjorden (80%) and Sassenfjorden (60%), while multi-resistance to all of the tested antibiotics was detected in the bacterial strains isolated from the Hornsund sediments (data not inserted in the Table A2). In recent decades, with the availability of advanced molecular technologies, some studies detected ARGs in the genomes of culturable bacteria and class 1 integron-integrase gene (*intI*1) in the metagenome of samples taken from cryoconite and ice (Makowska et al. 2020). Integrons consist of an integrase gene capable of capturing gene cassettes coding mostly for antibiotic resistance in clinically relevant bacteria, but also for other functions (transport proteins, esterases, phosphatases, transposases, and proteins of unknown function) (Stalder et al. 2012). Among the classes of integrons, class 1 is the most ubiquitous in human-associated bacteria and is responsible for the spread of AR and virulence, and also plays a crucial role in bacterial adaptation to cold environmental conditions (Cambray et al. 2010). In cryoconite samples collected from Longyearbreen, and yielding a total of 69 bacterial isolates, Makowska et al. (2020) reported that 16 were glycopeptide-resistant, followed by 10 tetracycline-, 4 fluoroquinolone-, and 39 β-lactam-resistant. Moreover, 22 strains were positive for the *intI*1 integron-integrase gene. The presence of class 1 integron-integrase gene was also detected in the metagenomes, with genes conferring resistance to β-lactams, fluoroquinolones and chloramphenicol. Similar results were reported by Xue et al. (2020) in Svalbard permafrost soil samples, and by Zhang et al. (2022) in seawater and sediments collected from Kongsfjorden. In the Zhang study, peptide and multidrug resistance genes were most abundant in seawater, while rifamycin and beta-lactam resistance genes were the two most abundant ARG types in the sediment samples. A similar approach was applied to samples of ice, water and sediments collected in the most populated area of Svalbard, Longyearbyen (Makowska-Zawierucha et al. 2022). The average frequency of the integron-positive heterotrophic isolates ranged from 2.4% in sediment to 11.2% in water of the Adventfjorden seashore, while no class 2 or 3 integrons were detected. Of a total of 837 strains including heterotrophic and sulfamethoxazole-resistant bacteria, 48 showed the presence of class 1 integrons (in decrescent range from wastewater outflow, water and sediment of the Longyearelva, Larsbreen ice core and sediment of the Adventfjorden). Conversely, water samples collected from Adventfjorden and Isfjorden did not contain bacteria with *intI*1 gene. Among *intI*1-positive isolates a high percentage were multidrug resistant strains, all of which showed resistance to sulfamethoxazole, and a high percentage resistant to tobramycin and chloramphenicol. The highest relative abundances of the *intI*1 genes were observed in the wastewater outflow (88.0%), and the lowest ones in the water of Isfjorden (2.4%), while the occurrence of *intI*1 (7.1%) in the metagenome of ice samples collected from Longyearbreen was higher than in those from Larsbreen (4.1%). These observations suggest different interplays between natural and human forcings in shaping the polar aquatic resistome and emphasise the possible pathway for spread of integrons from glacial environments to proglacial river and municipal sewage to the marine environment, representing a serious threat for animal and human health (Makowska-Zawierucha et al. 2022). The role of anthropogenic inputs in the spread of AR was underlined by analysis of soil clusters in the Kongsfjorden, where high-throughput quantitative PCR detected 131 ARGs, predominantly associated with aminoglycosides (33%), multidrug defence systems (e.g., efflux pump systems; 30%), Macrolide-Lincosamide-Streptogramin B (MLSBs, 16%), and β-lactams (8%) (McCann et al. 2019). The most abundant ARGs in all samples were *aac(3)-VI*, typically related to gentamicin and sisomicin resistance (Rather et al. 1993), and the *acr*A and bla_{FOX} genes, often associated with β-lactam resistance in *E. coli* and *Klebsiella* (Ma et al. 1995). Interestingly, the study

conducted by McCann et al. (2019) detected also the bla_{NDM-1} gene cluster (coding for Delhi metallo-β-lactamase-1 protein, first reported in India in 2008), found for the first time in the High Arctic samples collected in 2013, less than three years after the first detection of bla_{NDM-1} in surface seeps in urban India (Walsh et al. 2011). This finding draws attention to the implications for human health of global and rapid spread of ARGs around the world, and highlights the need for long-term monitoring programmes.

An interesting study was focused on the search of specific genes and integrons in plasmidomes from Svalbard. Plasmids are bacterial genetic elements that can move within genomes or between bacterial cells, and thus play an important role in the dissemination of ARGs between and across the species. Virulence genes and ARGs were dominant in glacial ice, thus confirming the hypothesis of glacial ice as a repository of potentially pathogenic strains (Makowska-Zawierucha et al. 2024). Recent data obtained from molecular techniques show how these modern approaches can be applied successfully to estimate human influence, possible consequences of climate change phenomena, and enable predictive assessments in the context of evolutionary processes.

Studies carried out to investigate the role of animals as carriers of AR bacteria and ARG in the Svalbard area are limited to some species, i.e., the Arctic tern (*Sterna paradisaea*) (Prakash et al. 2022), little auks (*Alle alle*), glaucous gulls (*Larus hyperboreus*) (Literak et al. 2014), wild reindeer (*Rangifer tarandus platyrhyn*chus) (Sunde et al. 2021), and polar bear (*Ursus maritimus*) (Glad et al. 2010). All studies retrieved AR strains and noted presence of genes encoding for resistance to several antibiotics, i.e., ampicillin, sulfonamides, streptomycin and trimethoprim. In cloacal swabs from little auks and faeces of glaucous gulls a novel variant of ACT AmpC beta-lactamase gene was found (Literak et al. 2014). These investigations highlighted the role of both migratory and non-migratory animals in the dissemination of multidrug resistant bacteria.

The string ("Svalbard" AND "microorganisms" AND "pathogen*") retrieved a total of 11 and 6 items from Scopus and the Web of Science on microbial pathogens in the Svalbard region. Very few data are available in literature regarding the occurrence and distribution of pathogen species in Svalbard. Particularly, bacterial phenotypes commonly associated with pathogenicity, such as haemolytic activity, have rarely been reported. To fill this knowledge gap, Mogrovejo-Arias et al. (2020a) examined for potentially pathogenic bacteria samples from different matrices of Spitsbergen in summer 2017. A total of 78 genetically diverse isolates affiliated with 37 different genera were obtained and their haemolytic activity was assessed. Most of the isolates (55/78) were retrieved from soil and sediments, while few isolates were detected in seawater (12/78), snow (6/78), melt water (4/78), and pond water (1/78). The strains belonged to the phyla *Actinobacteria* and *Firmicutes* (32 and 28 isolates, respectively), followed by *Proteobacteria* (15), and *Bacteroidetes* (3). The most abundant genera were *Arthrobacter* (*Actinobacteria*), *Bacillus* (*Firmicutes*) *Pseudomonas* (*Proteobacteria*), *Pedobacter*, *Flavobacterium*, and *Algoriphagus* (*Bacteroidetes*). Haemolytic activity (alpha-and beta haemolysis) was observed in 32 out of 78 isolates. Possession of genes conferring haemolytic capability was interpreted as a competitive advantage favouring nutrient acquisition, but the presence of haemolytic bacteria in Arctic environments highlights the possible risks associated with these microorganisms in relation to climate warming. Warming temperatures in polar areas will likely favour the expansion of human settlements and, consequently, human-associated pathogens (Gitay et al. 2002; Revich et al. 2012). This finding underlines the increasing potential risks associated with the spread of virulent bacteria to new habitats (Harding et al. 2011), lack of natural barriers such as permafrost and glaciers (Park et al. 2011; Underwood 2014), increased animal migrations (Allen et al. 2010) and human pressure (Vayssier-Taussat et al. 2014; Edwards 2015).

While on the topic of potential pathogens in Arctic environments, some valuable scientific contributions on fungal species deserve brief mention. Searching for pathogenic fungi, Perini

et al. (2019) isolated a total of 320 species from pristine Arctic locations in Greenland and Svalbard. Fungal isolates were screened for the expression of properties generally associated with pathogenic species, such as the ability to grow at 37°C and haemolytic activity, and for their susceptibility to antifungal compounds. Emerging pathogens were identified as *Aureobasidium melanogenum*, *Naganishia albida*, and *Rhodotorula mucillaginosa*. All were able to grow at 37°C and showed beta-haemolytic activity; resistance to azoles and echinocandins as antifungal agents was observed. Isolates of *N. albida* and *Penicillium* spp. were scarcely susceptible to voriconazole, while *Glaciozyma watsonii* and *Glaciozyma*-related taxa to fluconazole. The results of this study stressed how the identification of virulence-associated phenotypes in Arctic fungi could assume critical importance, especially in light of climate change and the increased spread of opportunistic mycoses related to these antimycotic-resistant fungal species. Habitat was found to significantly affect the fungal assemblages at a local scale, with occurrence of 19 fungal guilds (e.g., lichenized, ectomycorrhizal) and 6 growth forms (e.g., yeast, thallus photosynthetic). Thirty-one potentially pathogenic fungal species were also isolated. In relation to climate change and increasing pollution levels in the Arctic, the prevalence and diversity of fungi that colonise live organisms are expected to increase. Pathogenic yeasts were detected in the cloaca and throat of the little auk (*A. alle*), a keystone seabird species in the Arctic ecosystem, in a breeding colony in Magdalenefjorden in 2009 (Dynowska et al. 2013). Twelve species of yeast from eight genera were found in 12% of the samples. *Dipodascus* was the most prevalent genus. The presence of yeast was related to the age of the birds, with adults more colonised by yeasts than the nestlings. The relatively low prevalence and diversity of yeast in little auks suggest that these birds are random carriers of fungi, with minor health impacts.

Also insects and the pathogens they may carry can proliferate due to temperature increase. Adult lice from Arctic foxes from Nunavut and Svalbard were analysed by PCR targeting the mitochondrial cytochrome c oxidase subunit 1 gene (cox1) (Buhler et al. 2023). Total similarity between Canadian and Svalbard samples was observed, suggesting genetic exchange between ectoparasites on Scandinavian and North American Arctic fox populations. PCR targeting the *glt*A gene for *Bartonella* spp. amplified DNA from an unknown gammaproteobacterium from two pooled louse samples collected from Svalbard foxes. The amplified sequences were 100% identical to each other but showed 78% similarity to *Proteus mirabilis* from GenBank (CP053614), suggesting that lice on Arctic foxes may carry unique and previously undescribed microorganisms.

4. Chemical pollution in Svalbard and its effects on microbial communities

The Svalbard archipelago is experiencing the impacts of an increased anthropogenic pressure (AMAP 2011; Pouch and Zaborska 2015, 2021). In the fast-changing Arctic, the effects of climate change add to those of pollution by increasing discharges, providing additional transport pathways, and enhancing the potential ecological consequences.

The main sources, distribution and fate of inorganic contaminants have recently been reviewed (Rudnicka-Kepa and Zaborska 2021). The main categories of pollutants detected in Svalbard include legacy compounds, e.g., heavy metals (Pb, As, Cd, Hg), radionuclides (^{137}Cs, Pu), polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), dioxins deriving mostly from the combustion of petroleum compounds (Lin et al. 2022); as well as emerging pollutants, e.g., pharmaceutical residues and personal care products (PPCPs) (Pouch et al., 2017). Recently, microplastics were identified as a rapidly emerging pollutant in

this vulnerable region (Bergmann et al. 2022).

Most pollutants arrive in Svalbard after long-range transport: atmospheric circulation, marine currents, sea ice transport (Macdonald et al. 2005). The contaminant concentrations are often higher at fjord entrances, suggesting important role of oceanic transport (Bazzano et al. 2014). In the marine environment they accumulate in Arctic biota and then are transported along food web components (Hop et al. 2001). The bioaccumulation and transfer of organic pollutants in the Arctic macro-benthic food web has recently been documented (Pouch et al. 2023; Sokolowski et al. 2024).

Svalbard also receives pollutants from local sources, e.g. past and present coal mining (Van den Heuvel-Greve et al. 2016; Granberg et al. 2017). Other human activities that increase Svalbard pollution are local settlements, harbours and increasing tourism. Large cruise ships have been identified as an important source of pollution in Kongsfjorden (Eckhardt et al. 2013). Moreover, Adventfjorden still receives untreated sewage (Kalinowska et al. 2020). Tourist activity can thus be an important source of pharmaceutical and PPCP residues as well as caffeine. Pharmaceutical residues were found to be introduced mainly by untreated sewage in Kongsfjorden (Choi et al. 2020) and Isfjorden (Korkmaz et al. 2022). Many pharmaceuticals in Kongsfjorden (carbamazepine, diclofenac, caffeine, paracetamol, ciprofloxacin and tetracycline) have been found to effectively accumulate in tissues of biota while some others (e.g. citalopram) have indicated biomagnification potential (Sokolowski et al. 2024). Antibiotic residues have recently been found in Kongsfjorden sediments (with ciprofloxacin mean concentrations of 365 ± 289 ng/g of dry matter, Rauseo et al. 2024).

Pollutants can affect the taxonomic and functional diversity of microbial communities (Cappello et al. 2023). At the abandoned coal waste piles that can be found especially in Bjørndalen and close to Longyearbyen, highly soluble iron and heavy metals stimulate the growth of algae-dominated microbial mats with a typical acid mine drainage microflora consisting of iron-oxidising bacteria (*Acidithiobacillus ferrivorans*, *Actinobacteria* and *Acidobacteria*). This contrasts with another community that is not structured into microbial mats, populating large deposits of secondary minerals, where *Saccharibacteria* and *Gallionellaceae* dominated (Garcia-Moyano et al. 2015). Microbial variables (abundance, diversity, metabolism) are responsive to pollutants, and microbes can serve as potential sentinels of contamination (Garcia-Lopez et al. 2022). Microorganisms can enhance the degradation of organic pollutants present in the environment. Microbial biodegradation refers to the process where microorganisms use specific enzymes to break down organic substances (also pollutants) to obtain energy. Biodegradation of pollutants depends on environmental conditions, e.g., temperature, pH, sunlight, and oxygen presence. Due to unfavourable conditions the biodegradation process is less effective in the Arctic. The presence of heavy metals at levels toxic for microorganisms can limit the biodegradation process; to deal with this problem some microorganisms developed resistance to metals (Díaz et al. 2004; Olaniran et al. 2013).

5. Microbial communities under climate change scenarios

Temperatures are rising in the Arctic more than twice as rapidly as in the rest of the world. Svalbard is therefore exposed to severe effects of climate changes (e.g., reduction of glacier thickness, glacier retreat, thawing permafrost, rain on snow events and extreme weather conditions). In addition, large-scale changes that include increased variability of the strength and directions of global air and ocean circulation can impact microorganism transport pathways. Two major monitoring programmes are carried out in Svalbard. MOSJ (Environmental Monitoring of Svalbard and Jan Mayen) is part of the Norwegian Government's environmental monitoring. It concerns climate, pollution, fishery

and biota. Several animal groups are taken into consideration – birds, mammals, fish and zooplankton – but not microbial communities. The Arctic Monitoring and Assessment Programme conducted by the Arctic Council assesses the status of the Arctic region with respect to pollution and climate change issues; however, like MOSJ, it does not deal with microbial communities.

The ongoing glacial retreat and permafrost thaw has many implications of importance to human society such as exacerbating climate change. The effect of climate change in Svalbard and its correlations with microbial communities is treated from multiple perspectives, but still largely understudied. Some bacterial clades with significant positive or negative correlations with temperature or salinity are suggested to be used to monitor the effects of changes in climate. Sinha et al. (2017b) were first to report the occurrence of the cultivable *Halomonas titanicae* strain in Kongsfjorden water. The higher abundance of this isolate in the August/September season, is possibly due to the higher intrusion of Atlantic water into Kongsfjorden. Another important issue is the risk related to melting and the consequent release of potentially dangerous bacterial species. As an example (mentioned above), Mogrovejo-Arias et al. (2020a) reported the presence of haemolytic bacteria in several Svalbard habitats, underlining the risks associated with these microorganisms in the event of habitat melting/destruction, ecosystem transition, and re-colonisation. Previous studies on Arctic environments outside Svalbard have shown that melting permafrost was cause of an anthrax outbreak in Siberia (Ezhova et al. 2021). Similarly, it has been reported that ancient nematodes (Shatilovich et al. 2023) and viruses (Legendre et al. 2015) from permafrost are viable. Due to climate change, the migration patterns of species change. Several species that have been localised in more temperate areas are now migrating towards regions that were previously colder. These species can potentially also bring along their pathogens. This means that we have new pools of organisms and genes that will diversify and establish new relationships in the years to come. The thawing Arctic region is at risk of giving rise to a new virus or bacterial pandemic, and scientific collaboration to monitor these pathogens should be prioritised. The COVID-19 pandemic powerfully demonstrated the importance of international scientific cooperation in addressing a serious threat to both human health and modern society as we know it.

The available data emphasise the risks that melting of glaciers and permafrost might lead to emergence of a new superbug under a climate change scenario in Svalbard. Melting permafrost affects microbial diversity and functions. Studies have shown that increasing temperatures and melting permafrost are related to higher diversity and activity of methanogens (Høj et al. 2008; Mackelprang et al., 2011; de Groot et al., 2024). However, the extent of this impact on the total metabolic potential of the microbiota is largely understudied.

6. Contributions to interdisciplinarity

A holistic approach integrating microbial research into topics related to biosphere, cryosphere, atmosphere and hydrosphere is strongly recommended. Establishing a long-term microbial monitoring station would be extremely important. By analysing community changes in the past, we can predict and gain information on possible effects and changes in the future. Therefore, time series are important, especially in the Arctic where the consequences of climate change will become manifest sooner. Data on chemical pollution could help elucidate ecotoxicological effects on microbial communities, crucial knowledge for effective environmental management and conservation strategies. Similarly, the microbiological parameters could be used as indicators of environmental changes, stressful conditions, and ecological dynamics. Microbiology influences and is influenced by parameters in many other spheres of the Earth System. This is clear from the many links between

this chapter and other chapters in this issue of the SESS report.

AAA-Source (Becagli et al. 2025) – Aerosols could be vehicles for sporigenic and pathogen species, thus spreading potentially dangerous species. Bacterial cells present in the atmosphere act as effective nucleation sites, becoming incorporated into ice and snow crystals as they form. Bacteria could thus be studied for their influence on meteorological events.

ARiS (Bensi et al. 2025) – Collaboration with scientists studying hydrology is strongly encouraged, as this would facilitate accurate interpretation of microbial dynamics in relation to water mass properties and assessment of how microbial communities are modulated in response to ongoing changes (e.g., Atlantification). The water mass balance shapes the hydrography of Arctic fjords and affects the adaptability of microorganisms.

SvalSurge (Harcourt et al. 2025) – Microbial communities in glaciers could include indicator species – potential sentinels for the exchange of bacteria between glaciers and downstream seawaters, and the effects on the fjord and marine ecosystems. Mass balance of Svalbard glaciers could be used as predictive tool for the release of sporigenic and/or antibiotic-resistant microorganisms.

SvalGaSess (Hodson et al. 2025) – The ecological dynamics of methane could be correlated with microbial taxa involved in the methane cycle. Microbial communities in permafrost play key roles in carbon cycle processes including methanogenesis and methanotrophy.

SvalGeol (Senger et al. 2025) – Geochemical variables could influence or be influenced by microbial communities.

AWARE (Spolaor et al. 2025) – The occurrence of warm events could determine the occurrence of shifts in terrestrial and aquatic microbial communities, by inducing changes in the ecosystems. Moreover, release of sporigenic and pathogenic microorganisms may be induced by global warming and melting processes.

STAFIEN (Coulson et al. 2025) – Terrestrial invertebrate microbiomes could be studied as potential indicators of ecosystem health or perturbation.

6.1. Unanswered questions

- What is the level of biodiversity loss in the Arctic? Is it comparable to that in temperate environments? And can current monitoring systems provide this information?
- Is it possible to devise ecology restoration strategies to apply in the Arctic (e.g., bioremediation of pollutants)?
- How can we define the role of microbial diversity in carbon cycle processes and gas release in the global warming scenario?
- How crucial is the role of cryospheric melting in the release of old pathogens?
- How do microbial communities change in relation to variability of Svalbard water masses and circulation patterns following climate change, and how do these communities respond to the increasing pollution recently detected in this area?
- How do microbial community structure and metabolism vary among different Svalbard regions? Is there a specific regional response?
- How might interactions between microbial communities and invasive species alter ecosystem processes in Svalbard, and what are the potential long-term effects on biodiversity?
- To what extent do seasonal changes in temperature and light cycles affect microbial activity in Svalbard, and how might these seasonal patterns alter with ongoing climate change?
- How effective are current microbial monitoring techniques in capturing transient or rare microbial species in the Arctic, and what advancements in technology or methodology could improve our understanding of microbial diversity and function?

6.2. Recommendations for the future

- **Microbial proxies**. Define a clear set of microbial variables to test for suitability as potential sentinels of environmental changes in Svalbard (for suggestions, see Table 1). Interaction between scientific research, stakeholders and local communities plays a critical role to protect Svalbard environments, therefore the involvement of local communities is critical to develop policy guidelines and governance plans to prevent risks from natural and anthropogenic forcings acting in Svalbard.
- **Long-term monitoring programmes and remediation measures**. Complement existing infrastructures (on land and at sea) with technology systems to expand the long-term data series into microbial ecology field. Long-term monitoring of the structural and functional diversity of microbial communities is currently lacking. This prevents us from obtaining a comprehensive picture of the current state of Arctic environments and proposing provisional models for microbial dynamics in a future climate warming scenario. Proper wastewater treatment must be set up to prevent the spread of pollutants and antibiotic resistance via wastewater effluents.
- **Implementation**. Promote a spatially well-distributed long-term microbial survey over Spitsbergen, as previously suggested (Malard 2019). Expand studies to give broader geographical and temporal coverage. Obtain additional samples in key areas; encourage studies in eastern Svalbard. Define key hotspot regions for climate change observations. Use high-throughput sequencing technologies, single-cell genomics, and stable isotope probing to better understand microbial adaptation and function in extreme environments.
- **Interdisciplinarity.** Integrate analysis of environmental and microbial community variables, as previously suggested (Søreide et al. 2021). Efforts should be made to elucidate how microbial communities interact with nutrient cycles and greenhouse gas fluxes, and this information should be integrated into large-scale climate models to better predict future environmental changes in the Arctic. Both culture-dependent and culture-independent methods are recommended to evaluate microbial diversity, since each one can be affected by biases. Intercalibration of analytical protocols is necessary to get comparable data.
- **Harmonisation and Standardisation.** Draft a handbook of best practices for standardised procedures and harmonise the presentation of results on microbial variables (medium-term objective) to overcome the problem of fragmentary and non-homogeneous data. Define breakpoints for the Arctic: breakpoints are used in systems for categorising microorganisms as susceptible or intermediate (S and I) and resistant (R) to agents approved for use in the treatment of infectious diseases. No breakpoint tables for Minimum Inhibitory Concentration or Zone Diameters have been established for Arctic species, making it difficult to define their resistance.

Table 1: Suite of potential prokaryotic indicators proposed to assess the Good Environmental Status (GES) (modified from Caruso et al. 2016b).

Parameter	Application	Provided information	Indicator type (*)
Prokaryotic abundance	Basic assessment of environmental status and of organic enrichment	Estimation of prokaryotic biomass from the balance between production and removal; parameter related to water trophism	S
Abundance of pathogenic bacteria	Faecal pollution monitoring	Level of anthropogenic pressures and risks to public and ecosystem health	P
Enzymatic activities on organic polymers (e.g., leucine aminopeptidase, alkaline phosphatase, beta-glucosidase)	Basic assessment of environmental status and of organic enrichment	Markers of the prokaryotic physiological diversity and efficiency in organic matter decomposition. Indices of nutrient limitation	S
Prokaryotic production (PP)	Basic assessment of environmental status and of organic enrichment	Prokaryotic biomass production	S
Community respiration (R)	Basic assessment of environmental status	Shows organic matter mineralisation rates that are related to ocean acidification and CO_2 emission. Indicates whether aquatic systems act as CO_2 sink or source	S
Heavy-metal tolerant bacteria	Assessment of environmental contamination	Markers of heavy metal contamination, correlation with the development of bacterial antibiotic resistance	P
Hydrocarbon-degrading bacteria	Oil spills	Markers of hydrocarbon contamination	P
Carbon substrate utilisation profiles	Metabolic diversity	Information on the rate of utilisation of organic compounds	S/P
Live/Dead	Physiological status of bacteria	Information on the degree of viability of prokaryotes in the environment	S/P
ESBL-carrying and Carbapenem resistant *Enterobactereceae*	Pollution with clinically important pathogens	Public health implications	P
Presence of intI1 integron-integrase gene mercury-resistance operon	Anthropogenic disturbance	Public health implications	P
Chlorophyll monitoring	Proxy of phytoplankton biomass	Assessment of the trophic condition of ecosystem	S
Multiple Antibiotic Resistance (MAR) indexing	Detection of resistance pattern, diversity and complexity of antibiotic resistance	Ratio between the number of antibiotics to which the isolate is resistant and the number of antibiotics to which the isolate was exposed	S/P
Airborne microbial communities	Diversity of airborne microbial communities, constituted by core Arctic members and cosmopolitan species	Effects and functional roles in climate processes	S/P
Prokaryotic diversity	α and β diversity	Assessment of diversity and richness values of microbial communities	S/P

*S, Indicators of ecosystem "status"; P, indicators of anthropogenic “pressures”

7. Data availability

Due to the large number of available data, information is provided as digital appendix[3], in tables A1 and A2.

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9. References

Allen HK, Donato J, Wang HH, Cloud-Hansen KA, Davis J, Handelsman J (2010) Call of the wild: antibiotic resistance genes in natural environment. Nat Rev Microbiol 8:251–259. https://doi.org/10.1038/nrmicro2312

Almela P, Rico E, Velazquez D, Verleyen E, Quesada A (2023) Soil moisture drives differences in the diversity and trophic complexity of high Arctic tundra soils. Fems Microbiol Ecol 99:fiad050. https://doi.org/10.1093/femsec/fiad050

AMAP (2011) Combined Effects of Selected Pollutants and Climate Change in the Arctic Environment. Arctic Monitoring and Assessment Programme (AMAP), Oslo. 108 pp https://www.amap.no/documents/download/978/inline

AMAP (2018) AMAP Assessment 2018: Biological Effects of Contaminants on Arctic Wildlife and Fish. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. vii+84pp https://www.amap.no/documents/download/3080/inline

Amato P, Hennebelle R, Magand O, Sancelme M, Delort AM, Barbante C, Boutron C, Ferrari C (2007) Bacterial characterization of the snow cover at Spitzberg, Svalbard. FEMS Microbiol Ecol 59(2):255–264. https://doi.org/10.1111/j.1574-6941.2006.00198.x

Ambrožič Avguštin J, Žgur Bertok D, Kostanjšek R, Avguštin G (2013) Isolation and characterization of a novel violacein-like pigment producing psychrotrophic bacterial species *Janthinobacterium svalbardensis* sp. nov. Antonie Van Leeuwenhoek 103(4):763–769. https://doi.org/10.1007/s10482-012-9858-0

Bazzano A, Rivaro P, Soggia F, Ardini F, Grotti M (2014) Anthropogenic and natural sources of particulate trace elements in the coastal marine environment of Kongsfjorden, Svalbard, Marine Chemistry 163:28–35. https://doi.org/10.1016/j.marchem.2014.04.001

Becagli S, Barbaro E, Eckhardt S, Gilardoni S, Krejci R, Mazzola M, Park K-T, Severi M, Traversi R, Yttri KE, Zieger P (2025) Assessing anthropogenic and natural aerosol sources in the Arctic: A baseline to detect changes due to climate change. In: Runge et al (eds) SESS report 2024, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 228-245. https://doi.org/10.5281/zenodo.14425953

Bensi M, Nilsen F, Ferré B, Skogseth R, Moskalik M, Korhonen M, Vogedes D, Kovacevic V, Paladini F, Ingrosso G, Langone L, Giordano P, Inali M, Mano B, Sundfjord A, Bailey A, Foss Ø, Daase M, Castro de la Guardia L, David DT, Renner A, Dumont E, Glowacki O, Ogg F, Olsen H, Dølven KO, Jones E (2025) The Atlantification process in Svalbard: a broad view from the SIOS Marine Infrastructure network. In: Runge et al (eds) SESS report 2024, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 138-151. https://doi.org/10.5281/zenodo.14425673

Bergmann M, Collard F, Fabres J, Gabrielsen GW, Provencher JF, Rochman CM, van Sebille E, Tekman MB (2022) Plastic pollution in the Arctic. Nature Rev Earth Environ 3:323–337. https://doi.org/10.1038/s43017-022-00279-8

Buhler KJ, Snyman LP, Fuglei E, Davidson R, Ptochos S, Galloway T, Jenkins E (2023) A circumpolar parasite: Evidence of a cryptic undescribed species of sucking louse, *Linognathus* sp., collected from Arctic foxes, *Vulpes lagopus*, in Nunavut (Canada) and Svalbard (Norway). Med Vet Entomol 37(4):656–664. https://doi.org/10.1111/mve.12665

Busi SB, de Nies L, Pramateftaki P, Bourquin M, Kohler TJ, Ezzat L, Fodelianakis S, Michoud G, Peter H, Styllas M, Tolosano M, De Staercke V, Schön M, Galata V, Wilmes P, Battin T (2023) Glacier-Fed Stream Biofilms Harbor Diverse Resistomes and Biosynthetic Gene Clusters. Microbiol Spectr 11(1):e0406922. https://doi.org/10.1128/spectrum.04069-22

Cambray G, Guerout AM, Mazel D (2010) Integrons. Annu Rev Genet 44:141–166. https://doi.org/10.1146/annurev-genet-102209-163504

Canion A, Prakash O, Green SJ, Jahnke L, Kuypers MMM, Kostka JE (2013) Isolation and physiological characterization

3 https://doi.org/10.5281/zenodo.14455795

of psychrophilic denitrifying bacteria from permanently cold Arctic fjord sediments (Svalbard, Norway). Environ Microbiol 15(5):1606–1618. https://doi.org/10.1111/1462-2920.12110

Cappello S, Smedile F, Caruso G, Patania S, Lunetta A, Azzaro M (2023) A snapshot of the taxonomic composition and metabolic activity of the microbial community in an Arctic Harbour (Ny-Ålesund, Kongsfjorden, Svalbard). J Mar Sci Eng 11(5):1018. https://doi.org/10.3390/jmse11051018

Cardman Z, Arnosti C, Durbin A, Ziervogel K, Cox C, Steen AD, Teske A (2014) *Verrucomicrobia* are candidates for polysaccharide-degrading bacterioplankton in an arctic fjord of Svalbard. Appl Environ Microbiol 80(12):3749–3756. https://doi.org/10.1128/AEM.00899-14

Caruso G, Azzaro M, Caroppo C, Decembrini F, Monticelli LS, Leonardi M, Mimone G, Zaccone R, La Ferla R (2016a) Microbial community and its potential as descriptor of environmental status. ICES J Mar Sci 73(9):2174–2177. https://doi.org/10.1093/icesjms/fsw101

Caruso G, La Ferla R, Azzaro M et al (2016b) Microbial assemblages for environmental quality assessment: Knowledge, gaps and usefulness in the European Marine Strategy Framework Directive. Crit Rev Microbiol 42(6):883–904. https://doi.org/10.3109/1040841X.2015.1087380

Caruso G, Madonia A, Bonamano S, Miserocchi S, Giglio F, Maimone G, Azzaro F, Decembrini F, La Ferla R, Piermattei V, Piazzolla D, Marcelli M, Azzaro M (2020) Microbial abundance and enzyme activity patterns: Response to changing environmental characteristics along a transect in Kongsfjorden (Svalbard Islands). J Mar Sci Eng 8(10):824. https://doi.org/10.3390/jmse8100824

Caruso G, Rappazzo AC, Maimone G, Zappalà G, Cosenza A, Szubska M, Zaborska A (2024) Svalbard Fjord Sediments as a Hotspot of Functional Diversity and a Reservoir of Antibiotic Resistance. Environments 11:148. https://doi.org/10.3390/environments11070148

Choe YH, Kim M, Lee YK (2021) Distinct Microbial Communities in Adjacent Rock and Soil Substrates on a High Arctic Polar Desert. Front Microbiol 11:607396. https://doi.org/10.3389/fmicb.2020.607396

Choe YH, Kim M, Woo J, Lee MJ, Le JI, Lee EJ, Lee YK (2018) Comparing rock-inhabiting microbial communities in different rock types from a high arctic polar desert. FEMS Microbiol Ecol 94(6). https://doi.org/10.1093/femsec/fiy070

Choi Y, Kim K, Kim D, Moon H-B, Jeon J (2020) Ny-Ålesund-oriented organic pollutants in sewage effluent and receiving seawater in the Arctic region of Kongsfjorden. Environ Pollut 258:113792. https://doi.org/10.1016/j.envpol.2019.113792

Christaki E, Marcou M, Tofarides A (2020) Antimicrobial resistance in bacteria: mechanisms, evolution, and persistence. Journal of molecular evolution 88(1):26–40. https://doi.org/10.1007/s00239-019-09914-3

Conte A, Papale M, Amalfitano S, Mikkonen A, Rizzo C, De Domenico E, Michaud L, Lo Giudice A (2018) Bacterial community structure along the subtidal sandy sediment belt of a high Arctic fjord (Kongsfjorden, Svalbard Islands). Sci Total Environ 619–620:203–211. https://doi.org/10.1016/j.scitotenv.2017.11.077

Coulson SJ, Gillespie MAK, Loonen MJJE, Fossøy F, Sørensen JG, Gwiazdowicz DJ, Seniczak A, Bahrndorff S, Convey P (2025) Terrestrial and freshwater invertebrate science in Svalbard in a changing world: from regional to pan-Arctic scales. In: Runge et al (eds) SESS report 2024, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 182-197. https://doi.org/10.5281/zenodo.14425803

Cuthbertson L, Amores-Arrocha H, Malard LA, Els N, Sattler B, Pearce DA (2017) Characterisation of Arctic Bacterial Communities in the Air above Svalbard. Biology 6(2):29. https://doi.org/10.3390/biology6020029

Dayal A, Hodson AJ, Šabacká M, Smalley AL (2023) Seasonal snowpack microbial ecology and biogeochemistry on a high Arctic ice cap reveals negligible autotrophic activity during spring and summer melt. J Geophys Res Biogeosci 128:e2022JG007176. https://doi.org/10.1029/2022JG007176

de Groot TR, Kalenitchenko D, Moser M, Argentino C, Panieri G, Lindgren M, Dølven KO, Ferré B, Svenning MM, Niemann H (2024) Methanotroph activity and connectivity between two seep systems north off Svalbard. Front Earth Sci 12:1287226. https://doi.org/10.3389/feart.2024.1287226

Delpech IM, Vonnahme TR, McGovern M, Gradinger R, Praebel K, Poste AE (2021) Terrestrial inputs shape coastal bacterial and archaea communities in a high Arctic fjord (Isfjorden, Svalbard). Front Microbiol 12:614634. https://doi.org/10.3389/fmicb.2021.614634

Díaz E (2004) Bacterial degradation of aromatic pollutants: a paradigm of metabolic versatility. Int Microbiol 7(3):173–180.

Dobiński W (2020) Permafrost active layer. Earth-Science Rev 208:103301. https://doi.org/10.1016/j.earscirev.2020.103301

Dong K, Tripathi B, Moroenyane I, Kim W, Li N, Chu HY, Adams J (2016) Soil fungal community development in a high Arctic glacier foreland follows a directional replacement model, with a mid-successional diversity maximum. Sci Rep 6:26360. https://doi.org/10.1038/srep26360

Dong K, Yu Z, Kerfahi D, Lee SS, Li N, Yang T, Adams JM (2022) Soil microbial co-occurrence networks become less connected with soil development in a high Arctic glacier foreland succession. Sci Total Environ 813:152565. https://doi.org/10.1016/j.scitotenv.2021.152565

Dynowska M, Wojczulanis-Jakubas K, Pacyńska JA, Jakubas D, Ejdys E (2013) Potentially pathogenic yeast isolated from the throat and cloaca of an Arctic colonial seabird: the little auk (*Alle alle*). Polar Biol 36:343–348. https://doi.org/10.1007/s00300-012-1263-7

Eckhardt S, Hermansen O, Grythe H, Fiebig M, Stebel K, Cassiani M, Baecklund A, Stohl A (2013) The influence of cruise ship emissions on air pollution in Svalbard – a harbinger of a more polluted Arctic? Atmos Chem Phys 13:8401–8409. https://doi.org/10.5194/acp-13-8401-2013

Edwards A (2015) Coming in from the cold: Potential

microbial threats from the terrestrial cryosphere. Front Earth Sci 3:10–13. https://doi.org/10.3389/feart.2015.00012

Edwards A, Anesio AM, Rassner SM, Sattler B, Hubbard BP, Perkins WT, Young M, Griffith GW (2011) Possible interactions between bacterial diversity, microbial activity and supraglacial hydrology of cryoconite holes in Svalbard. ISME Journal 5:150–160. https://doi.org/10.1038/ismej.2010.100

Edwards A, Mur LA, Girdwood SE, Anesio AM, Stibal M, Rassner SM, Hell K, Pachebat JA, Post B, Bussell JS, Cameron SJ, Griffith GW, Hodson AJ, Sattler B (2014) Coupled cryoconite ecosystem structure-function relationships are revealed by comparing bacterial communities in alpine and Arctic glaciers. FEMS Microbiol Ecol 89(2):222-37. https://doi.org/10.1111/1574-6941.12283

Edwards A, Rassner SM, Anesio AM et al (2013) Contrasts between the cryoconite and ice-marginal bacterial communities of Svalbard glaciers. Polar Res 32:19468. https://doi.org/10.3402/polar.v32i0.19468

Ezhova E, Orlov D, Suhonen E et a. (2021) Climatic Factors Influencing the Anthrax Outbreak of 2016 in Siberia, Russia. EcoHealth 18:217–228. https://doi.org/10.1007/s10393-021-01549-5

Fang XM, Zhang T, Li J, Wang NF, Wang Z, Yu LY (2019) Bacterial community pattern along the sediment seafloor of the Arctic fjorden (Kongsfjorden, Svalbard). Antonie van Leeuwenhoek 112:1121–1136. https://doi.org/10.1007/s10482-019-01245-z

Flieder M, Buongiorno J, Herbold CW, Hausmann B, Rattei T, Lloyd KG, Loy A, Wasmund K (2021) Novel taxa of Acidobacteriota implicated in seafloor sulfur cycling. ISME J 15(11):3159–3180. https://doi.org/10.1038/s41396-021-00992-0

Garcia-Lopez E, Alcazar P, Alcazar M, Cid C (2022) Identification of sentinel microbial communities in cold environments. In: Hurst CJ (ed) Assessing the Microbiological Health of Ecosystems, 1st edn. WIley and Sons Ltd, Chapter 5, p 107–126.

Garcia-Lopez E, Rodriguez-Lorente I, Alcazar P, Cid C (2019) Microbial Communities in Coastal Glaciers and Tidewater Tongues of Svalbard Archipelago, Norway. Front. Mar. Sci. 5:512. https://doi.org/10.3389/fmars.2018.00512

Garcia-Moyano A, Austnes AE, Lanzén A, Gonzalez-Toril E, Aguilera AM, Ovreas L (2015) Novel and unexpected microbial diversity in acid mine drainage in Svalbard (78° N), revealed by culture-independent approaches. Microorganisms 3(4):667–694. https://doi.org/10.3390/microorganisms3040667

Gitay H, Suárez A, Watson R, Dokken D (2002) Climate change and biodiversity. IPCC Technical Paper V – April 2002. 86 pp IPCC, Geneva, Switzerland. https://archive.ipcc.ch/pdf/technical-papers/climate-changes-biodiversity-en.pdf

Glad T, Bernhardsen P, Nielsen KM, Brusetti L, Andersen M, Aars J, Sundset MA (2010) Bacterial diversity in faeces from polar bear (*Ursus maritimus*) in Arctic Svalbard. BMC Microbiol 10:10. https://doi.org/10.1186/1471-2180-10-10

Gokul JK, Hodson AJ, Saetnan ER, Irvine-Fynn TD, Westall PJ, Detheridge AP, Takeuchi N, Bussell J, Mur LA, Edwards A (2016) Taxon interactions control the distributions of cryoconite bacteria colonizing a High Arctic ice cap. Mol Ecol 25(15):3752–3767. https://doi.org/10.1111/mec.13715

Górniak D, Marszalek H, Kwasniak-Kominek M, Rzepa G, Manecki M (2017) Soil formation and initial microbiological activity on a foreland of an Arctic glacier (SW Svalbard) Appl Soil Ecol 114:34–44. https://doi.org/10.1016/j.apsoil.2017.02.017

Granberg ME, Ask A, Gabrielsen GW (2017) Local Contamination in Svalbard. Overview and Suggestions for Remediation Actions. Norwegian Polar Institute, Tromsø. Report no. 044. http://hdl.handle.net/11250/2456307

Grenni P, Ancona V, Barra Caracciolo A (2018) Ecological effects of antibiotics on natural ecosystems: A review. Microchem J 136:25–39. https://doi.org/10.1016/j.microc.2017.02.006

Grünberg I, Groenke B, Westermann S, Boike J (2024) Permafrost and active layer temperature and freeze/thaw timing reflect climatic trends at Bayelva, Svalbard. J Geophys Res: Earth Surface 129(7):e2024JF007648. https://doi.org/10.1029/2024JF007648

Grzesiak J, Górniak D, Świątecki A, Aleksandrzak-Piekarczyk T, Szatraj K, Zdanowski MK (2015). Microbial community development on the surface of Hans and Werenskiold Glaciers (Svalbard, Arctic): a comparison. Extremophiles 19(5):885–897. https://doi.org/10.1007/s00792-015-0764-z

Han D, Son M, Eom KH, Park YT, Choi M, Kim J, Kim TH (2022) Distribution of dissolved organic carbon linked to bacterial community composition during the summer melting season in Arctic fjords. Polar Biol 45:331–343. https://doi.org/10.1007/s00300-021-02995-1

Harcourt WD, Pearce DM, Gajek W, Lovell H, Luckman A, Benn D, Kohler J, Kääb A, Hann R (2025) Surging glaciers in Svalbard: Current knowledge and perspectives for monitoring. In: Runge et al (eds) SESS report 2024, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 84-105. https://doi.org/10.5281/zenodo.14425522

Harding T, Jungblut AD, Lovejoy C, Vincent WF (2011) Microbes in high arctic snow and implications for the cold biosphere. Appl Environ Microbiol 77(10):3234–3243. https://doi.org/10.1128/AEM.02611-10

Hatha AAM, Neethu CS, Nikhil SM, Mujeeb Rahiman KM, Krishnan KP, Saramma AV (2015) Relatively high antibiotic resistance among heterotrophic bacteria from arctic fjord sediments than water – Evidence towards better selection pressure in the fjord sediments. Polar Sci 9:382–388. https://doi.org/10.1016/j.polar.2015.10.002

Hodson A, Kleber G, Platt S, Kalenitchenko D, Hensgens G, Fynn TI, Senger K, Tveit A, Øvreås L, ten Hietbrink S, Hollander J, Ammerlaan F, Damm E, Römer M, Fransson A, Chierici M, Delpech L-M, Pirk N, Sen A, Redeker K (2025) Methane in Svalbard. In: Runge et al (eds) SESS report 2024, Svalbard Integrated Arctic Earth Observing System,

Longyearbyen, pp 106-137. https://doi.org/10.5281/zenodo.14425572

Hofmeister AM, Seckler JM, Criss GM (2021) Possible Roles of Permafrost Melting, Atmospheric Transport, and Solar Irradiance in the Development of Major Coronavirus and Influenza Pandemics. Int J Environ Res Public Health 18(6):3055. https://doi.org/10.3390/ijerph18063055

Høj L, Olsen RA, Torsvik V (2008) Effects of temperature on the diversity and community structure of known methanogenic groups and other archaea in high Arctic peat. The ISME Journal 2(1):37–48. https://doi.org/10.1038/ismej.2007.84

Holmes AH, Moore LS, Sundsfjord A, Steinbakk M, Regmi S, Karkey A, Guerin PJ, Piddock LJ (2016) Understanding the mechanisms and drivers of antimicrobial resistance. The Lancet 387(10014):176–187. https://doi.org/10.1016/S0140-6736(15)00473-0

Hop H, Sagerup K, Schlabach M, Gabrielsen GW (2001) Persistent organic pollutants in marine macro-benthos near urban settlements in Svalbard, Longyearbyen, Pyramiden, Barentsbug and Ny-Ålesund. Norsk Polarinstitutt Internrapport No. 8, pp. 43. http://hdl.handle.net/11250/172954

Jabir T, Jain A, Vipindas PV et al (2023) Stochastic Processes Dominate in the Water Mass–Based Segregation of Diazotrophs in a High Arctic Fjord (Svalbard). Microb Ecol 86:2733–2746. https://doi.org/10.1007/s00248-023-02276-w

Jain A, Krishnan KP (2017) A glimpse of the diversity of complex polysaccharide-degrading culturable bacteria from Kongsfjorden, Arctic Ocean. Ann Microbiol 67:203–214. https://doi.org/10.1007/s13213-016-1252-0

Jain A, Krishnan KP (2021) Marine Group-II archaea dominate particle-attached as well as free-living archaeal assemblages in the surface waters of Kongsfjorden, Svalbard, Arctic Ocean. Antonie van Leeuwenhoek 114:633–647. https://doi.org/10.1007/s10482-021-01547-1

James KL, Randall NP, Haddaway NR (2016) A methodology for systematic mapping in environmental sciences. Environ Evid 5:7. https://doi.org/10.1186/s13750-016-0059-6

Kalinowska A, Jankowska K, Fudala-Ksiazek S, Pierpaoli M, Luczkiewicz A (2021) The microbial community, its biochemical potential, and the antimicrobial resistance of *Enterococcus* spp. in Arctic lakes under natural and anthropogenic impact (West Spitsbergen). Sci Tot Environ 763:142998. https://doi.org/10.1016/j.scitotenv.2020.142998

Kalinowska A, Szopínska M, Chmiel S, Konczak M, Polkowska Z, Artichowicz W, Jankowska K, Nowak A, Łuczkiewicz A (2020) Heavy metals in a high Arctic fiord and their introduction with the wastewater: A case study of Adventfjorden-Longyearbyen system, Svalbard. Water 12(3):794. https://doi.org/10.3390/w12030794

Kang M, Choi TR, Ahn S, Heo HY, Kim H, Lee HS, Lee YK, Joo HS, Yune PS, Kim W, Yang YH (2022) Arctic Psychrotolerant *Pseudomonas* sp. B14-6 Exhibits Temperature-Dependent Susceptibility to Aminoglycosides. Antibiotics 11:1019. https://doi.org/10.3390/antibiotics11081019

Kastovská K, Elster J, Stibal M, Santrucková H (2005) Microbial assemblages in soil microbial succession after glacial retreat in Svalbard (high Arctic). Microb Ecol 50:396–407. https://doi.org/10.1007/s00248-005-0246-4

Kastovská K, Stibal M, Sabacká M, Cerná B, Santrucková H, Elster J (2007) Microbial community structure and ecology of subglacial sediments in two polythermal Svalbard glaciers characterized by epifluorescence microscopy and PLFA. Pol Biol 30:277–287. https://doi.org/10.1007/s00300-006-0181-y

Kerfahi D, Tripathi BM, Dong K, Kim M, Kim H, Slik JWF, Go R, Adams JM (2019) From the High Arctic to the Equator: Do Soil Metagenomes Differ According to Our Expectations? Microb Ecol 77:168–185. https://doi.org/10.1007/s00248-018-1215-z

Keuschnig C, Vogel TM, Barbaro E et al (2023) Selection processes of Arctic seasonal glacier snowpack bacterial communities. Microbiome 11:35. https://doi.org/10.1186/s40168-023-01473-6

Kim KE, Joo HM, Kim YJ, Kang D, Lee TK, Jung SW, Ha SY (2024) Ecological Interaction between Bacteriophages and Bacteria in Sub-Arctic Kongsfjorden Bay, Svalbard, Norway. Microorganisms 12:276. https://doi.org/10.3390/microorganisms12020276

Kolchev I, Marshall IPG, Jones E, Yde JC, Nornberg P, Rivera AM, Hodson AJ, Bak EN, Finster K (2022) Microbial iron reduction and greenhouse gas production in response to organic matter amendment and temperature increase of periglacial sediments, Bolterdalen, Svalbard. Arctic Antarctic Alpine Res 54(1):314–334. https://doi.org/10.1080/15230430.2022.2097757

Konieczna I, Wojtasik B, Kwinkowski M, Burska D, Nowiński K, Żarnowiec P, Kaca W (2011) Analysis of cultivable aerobic bacteria isolated from bottom sediments in the Wijdefjorden region, Spitsbergen. Polish Polar Res 32(2):181–195. http://dx.doi.org/10.2478/v10183-011-0012-x

Korkmaz EN, Aksu A, Karacık B, Bayırhan İ et al (2022) Presence of Some Commonly used Pharmaceutical Residues in Seawater and Net Plankton: a Case Study of Spitsbergen, Svalbard Archipelago. Int J Environ Geoinformatics 9(4):1–10. https://doi.org/10.30897/ijegeo.1057819

Kosek K, Luczkiewicz A, Kozioł K, Jankowska K, Ruman M, Polkowska Ż (2019) Environmental characteristics of a tundra river system in Svalbard. Part 1: Bacterial abundance, community structure and nutrient levels. Sci Total Env 653:1571–1584. https://doi.org/10.1016/j.scitotenv.2018.11.378

Kotas P, Santrucková H, Elster J, Kastovská E (2018) Soil microbial biomass, activity and community composition along altitudinal gradients in the High Arctic (Billefjorden, Svalbard). Biogeosciences 15:1879–1894. https://doi.org/10.5194/bg-15-1879-2018

Laybourn-Parry J, Marshall WA (2003) Photosynthesis, mixotrophy and microbial plankton dynamics in two high

Arctic lakes during summer. Polar Biol 26:517–524. http://doi.org/10.1007/s00300-003-0514-z

Lee SH, Jang I, Chae N, Choi T, Kang H (2013) Organic Layer Serves as a Hotspot of Microbial Activity and Abundance in Arctic Tundra Soils. Microb Ecol 65:405–414. https://doi.org/10.1007/s00248-012-0125-8

Legendre M, Lartigue A, Bertaux L, Jeudy S, Bartoli J, Lescot M, Alempic JM, Ramus C, Bruley C, Labadie K, Shmakova L, Rivkina E, Couté Y, Abergel C, Claverie JM (2015) In-depth study of *Mollivirus sibericum*, a new 30,000-y-old giant virus infecting *Acanthamoeba*. Proc Natl Acad Sci U S A. 112(38):E5327–E5335. https://doi.org/10.1073/pnas.1510795112

Lim PP, Pearce DA, Convey P, Lee LS, Chan KG, Tan GYA (2020) Effects of freeze-thaw cycles on High Arctic soil bacterial communities. Polar Science 23:100487. https://doi.org/10.1016/j.polar.2019.100487

Lim PPJ, Newsham KK, Convey P, Gan HM, Yew WC, Tan GYA (2018) Effects of field warming on a High Arctic soil bacterial community: a metagenomic analysis. Current Science 115(9):1697–1700. https://doi.org/10.18520/cs/v115/i9/1697-1700

Lin F, Xiang L, Zhang Z, Li N, Yan B, He C, Hao Z, Che G (2022) Comprehensive review on catalytic degradation of Cl-VOCs under the practical application conditions. Crit Rev Environ Sci Technol 52(3):311-355. http://dx.doi.org/10.1080/10643389.2020.1818490

Literak I, Manga I, Wojczulanis-Jakubas K, Chroma M, Jamborova I, Dobiasova H, Htoutou Sedlakova M, Cizek A (2014) *Enterobacter cloacae* with a novel variant of ACT AmpC beta-lactamase originating from glaucous gull (*Larus hyperboreus*) in Svalbard. Vet Microbiol 171(3–4):432–435. https://doi.org/10.1016/j.vetmic.2014.02.015

Liu JP, Fan YP, Liu XZ, Wang JX (2018) Communities and diversities of bacteria and Archaea in Arctic seawater. Evol Ecol Res 19:407–421.

Loganathachetti DS, Venkatachalam S, Jabir T, Vipindas PV, Krishnan KP (2022) Total nitrogen influence bacterial community structure of active layer permafrost across summer and winter seasons in Ny-Ålesund, Svalbard. World J Microbiol Biotechnol 38:28. https://doi.org/10.1007/s11274-021-03210-3

Lowther JA, Gustar NE, Powell AL, Hartnell RE, Lees DN (2012) Two-year systematic study to assess norovirus contamination in oysters from commercial harvesting areas in the United Kingdom. Appl Environ Microbiol 78:5812–5817. https://doi.org/10.1128/aem.01046-12

Luláková P, Santrucková H, Elster J, Hanáce M, Kotas P, Meador T, Tejnecky V, Bárta J (2023) Mineral substrate quality determines the initial soil microbial development in front of the Nordenskiöldbreen, Svalbard. FEMS Microbiol Ecol 99:fiad104. https://doi.org/10.1093/femsec/fiad104

Lutz S, Anesio AM, Edwards A, Benning LG (2017) Linking microbial diversity and functionality of arctic glacial surface habitats. Environ Microbiol 19(2):551–565. https://doi.org/10.1111/1462-2920.13494

Ma D, Cook DN, Alberti M, Pon NG, Nikaido H, Hearst JE (1995) Genes acrA and acrB encode a stress-induced efflux system of *Escherichia coli*. Mol Microbiol 16 (1):45–55. https://doi.org/10.1111/j.1365-2958.1995.tb02390.x

Macdonald RW, Harner TT, Fyfe J (2005) Recent climate change in the Arctic and its impact on contaminants pathway and interpretation on temporal trend data. Sci Total Environ 342:5–86. https://doi.org/10.1016/j.scitotenv.2004.12.059

Mackelprang R, Waldrop M, DeAngelis K et al (2011) Metagenomic analysis of a permafrost microbial community reveals a rapid response to thaw. Nature 480:368–371. https://doi.org/10.1038/nature10576

Makowska N, Zawierucha K, Nadobna P, Piątek-Bajan K, Krajewska A, Szwedyk J, Iwasieczko P, Mokracka J, Koczura R (2020) Occurrence of integrons and antibiotic resistance genes in cryoconite and ice of Svalbard, Greenland, and the Caucasus glaciers. Sci Total Env 716:137022. https://doi.org/10.1016/j.scitotenv.2020.137022

Makowska-Zawierucha N, Mokracka J, Małecka M, Balazy P, Chełchowski M, Ignatiuk D, Zawierucha K (2022) Quantification of class 1 integrons and characterization of the associated gene cassettes in the high Arctic – Interplay of humans and glaciers in shaping the aquatic resistome. Ecol Indic 145:109633. https://doi.org/10.1016/j.ecolind.2022.109633

Makowska-Zawierucha N, Trzebny A, Zawierucha K, Manthapuri V, Bradley JA, Pruden A (2024). Arctic plasmidome analysis reveals distinct relationships among associated antimicrobial resistance genes and virulence genes along anthropogenic gradients. Glob Change Biol 30:e17293. https://doi.org/10.1111/gcb.17293

Malard L, Avila-Jimenez M, Convey P, Larose C, Hodson A, Øvreås L, Schmale J, Anwar MZ, Pearce D (2019) Microbial activity monitoring by the Integrated Arctic Earth Observing System. In: Orr et al. (eds): SESS report 2018, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 48-81. https://doi.org/10.5281/zenodo.4778348

McCann CM, Wade MJ, Gray ND, Roberts JA, Hubert CRJ, Graham DW (2016) Microbial communities in a High Arctic Polar Desert Landscape. Front Microbiol 7:419. https://doi.org/10.3389/fmicb.2016.00419

McCann CM, Christgen B, Roberts JA, Su JQ, Arnold KE, Gray ND, Zhu YG, Graham DW (2019) Understanding drivers of antibiotic resistance genes in High Arctic soil ecosystems. Environ Int 125:497-504. https://doi.org/10.1016/j.envint.2019.01.034

Mechirackal Balan B, Shini S, Krishnan KP, Mohan M (2018) Mercury tolerance and biosorption in bacteria isolated from Ny-Ålesund, Svalbard, Arctic. J Basic Microbiol 58(4):286–295. https://doi.org/10.1002/jobm.201700496

Miksch S, Meiners M, Meyerdierks A, Probandt D, Wegener G, Titschack J, Jensen MA, Ellrott A, Amann R, Knittel K (2021) Bacterial communities in temperate and polar coastal sands are seasonally stable. ISME Comm 1:29. https://doi.org/10.1038/s43705-021-00028-w

Miksch S, Orellana LH, de Orube MO, Vidal-Melgosa

S, Solanki V, Hehemann JH, Amann R, Knittel K (2024) Taxonomic and functional stability overrules seasonality in polar benthic microbiomes. ISME J 18(1):wrad005. https://doi.org/10.1093/ismejo/wrad005

Mogrovejo DC, Perini L, Gostinčar C, Sepčić K, Turk M, Ambrožič-Avguštin J, Brill FHH, Gunde-Cimerman N (2020b) Prevalence of Antimicrobial Resistance and Hemolytic Phenotypes in Culturable Arctic Bacteria. Front Microbiol 11:570. https://doi.org/10.3389/fmicb.2020.00570

Mogrovejo-Arias DC, Brill FHH, Wagner D (2020a) Potentially pathogenic bacteria isolated from diverse habitats in Spitsbergen, Svalbard. Environ Earth Sci 79:109. https://doi.org/10.1007/s12665-020-8853-4

Müller O, Bang-Andrease T, White RA, Elberling B, Tas N, Kneafsey T, Jansson JK, Ovreås L (2018) Disentangling the complexity of permafrost soil by using high resolution profiling of microbial community composition, key functions and respiration rates. Environ Microbiol 20:4328–4342. https://doi.org/10.1111/1462-2920.14348

Nash MV, Anesio AM, Barker G, Tranter M, Varliero G, Eloe-Fadrosh EA, Nielsen T, Turpin-Jelfs T, Benning LG, Sánchez-Baracaldo P (2018) Metagenomic insights into diazotrophic communities across Arctic glacier forefields. FEMS Microbiol Ecol. 1:94(9):fiy114. https://doi.org/10.1093/femsec/fiy114

Neethu CS, Mujeeb Rahiman KM, Saramma AV, Mohamed Hatha AA (2015) Heavy-metal resistance in Gram-negative bacteria isolated from Kongsfjord, Arctic. Can J Microbiol 61(6):429–435. https://doi.org/10.1139/cjm-2014-0803

Ntougias S, Polkowska Z, Nikolaki S, Dionyssopoulou E, Stathopoulou P, Doudoumis V, Ruman M, Kozak K, Namiesnik J, Tsiamis G (2016) Bacterial Community Structures in Freshwater Polar Environments of Svalbard. Microbes Environ 31(4):401–409. https://doi.org/10.1264/jsme2.me16074

Olaniran AO, Balgobind A, Pillay B (2013) Bioavailability of Heavy Metals in Soil: Impact on Microbial Biodegradation of Organic Compounds and Possible Improvement Strategies. Int J Mo. Sci 14:10197–10228. https://doi.org/10.3390/ijms140510197

Papale M, Caruso G, Maimone G, La Ferla R, Lo Giudice A, Rappazzo AC, Cosenza A, Azzaro F, Ferretti R, Paranhos R et al (2023) Microbial community abundance and metabolism close to the ice-water interface of the Blomstrandbreen glacier (Kongsfjorden, Svalbard): A sampling survey using an Unmanned Autonomous Vehicle. Water 15:556. https://doi.org/10.3390/w15030556

Park SJ, Park BJ, Jung MY, Kim SJ, Chae JC, Roh Y, Rhee SK (2011) Influence of deglaciation on microbial communities in marine sediments off the coast of Svalbard, Arctic Circle. Microb Ecol 62(3):537–548. https://doi.org/10.1007/s00248-011-9860-5

Pearson C, Howard D, Moore C, Obrist D (2019) Mercury and trace metal wet deposition across five stations in Alaska: controlling factors, spatial patterns, and source regions. Atmos Chem Phys 19:6913–6929. https://doi.org/10.5194/acp-19-6913-2019

Pereira Freitas G, Adachi K, Conen F, Heslin-Rees D, Krejci R, Tobo Y, Yttri KE, Zieger P (2023) Regionally sourced bioaerosols drive high-temperature ice nucleating particles in the Arctic. Nat Commun 14(1):5997. https://doi.org/10.1038/s41467-023-41696-7

Pereira Freitas G, Kopec B, Adachi K, Krejci R, Heslin-Rees D, Yttri KE, Hubbard A, Welker JM, Zieger P (2024) Contribution of fluorescent primary biological aerosol particles to low-level Arctic cloud residuals. Atmos Chem Phys 24:5479–5494. https://doi.org/10.5194/acp-24-5479-2024

Perini L, Gostinčar C, Gunde-Cimerman N (2019) Fungal and bacterial diversity of Svalbard subglacial ice. Sci Rep 9:20230. https://doi.org/10.1038/s41598-019-56290-5

Pessi IS, Pushkareva E, Lara Y, Borderie F, Wilmotte A, Elster J (2019) Marked Succession of Cyanobacterial Communities Following Glacier Retreat in the High Arctic. Microb Ecol 77:136–147. https://doi.org/10.1007/s00248-018-1203-3

Piquet AMT, Scheepens JF, Bolhuis H et al (2010) Variability of protistan and bacterial communities in two Arctic fjords (Spitsbergen). Polar Biol 33:1521–1536. https://doi.org/10.1007/s00300-010-0841-9

Pouch A, Zaborska A (2015) Climate change influence on migration of contaminants in the Arctic marine environment. In: Zielínski WT et al (Eds.) Impact of Climate Changes on Marine Environments. GeoPlanet: Earth and Planetary Sciences, pp. 75–90. ISBN 978-3-319-14282-1 http://dx.doi.org/10.1007/978-3-319-14283-8_7

Pouch A, Zaborska A, Legeżyńska J, Deja K, Pazdro K (2023) Assessment of exposure of benthic organisms to selected organochlorine pollutants in the west Spitsbergen fjords. Sci Tot Environ 896:165262. https://doi.org/10.1016/j.scitotenv.2023.165262

Pouch A, Zaborska A, Mazurkiewicz M, Winogradow A, Pazdro K (2021) PCBs, HCB and PAHs in the seawater of Arctic fjords - Distribution, sources and risk assessment. Mar Pollut Bull 164:111980. https://doi.org/10.1016/j.marpolbul.2021.111980

Pouch A, Zaborska A, Pazdro K (2017) Concentrations and origin of polychlorinated biphenyls (PCBs) and polycyclic aromatic hydrocarbons (PAHs) in sediments of western Spitsbergen fjords (Kongsfjorden, Hornsund, and Adventfjorden). Environ Monit Assess 189(4):175. https://doi.org/10.1007/s10661-017-5858-x

Prakash EA, Hromádková T, Jabir T, Vipinda PV, Krishnan KP, Mohamed Hatha AA, Breidis M (2022) Dissemination of multidrug resistant bacteria to the polar environment - Role of the longest migratory bird Arctic tern (*Sterna paradisaea*). Sci Tot Environ 815:152727. https://doi.org/10.1016/j.scitotenv.2021.152727

Prasad S, Manasa P, Buddhi S et al (2014) Diversity and Bioprospective Potential (Cold-Active Enzymes) of Cultivable Marine Bacteria from the Subarctic Glacial Fjord, Kongsfjorden. Curr Microbiol 68: 233–238. https://doi.org/10.1007/s00284-013-0467-6

Pushkareva E, Elster J, Holzinger A, Niedzwiedz S, Becker B (2022) Biocrusts from Iceland and Svalbard: Does microbial community composition differ substantially? Front Microbiol

13:1048522. https://doi.org/10.3389/fmicb.2022.1048522

Pushkareva E, Pessi IS, Wilmotte A, Elster J (2015) Cyanobacterial community composition in Arctic soil crusts at different stages of development. FEMS Microbiol Ecol 91:fiv143. https://doi.org/10.1093/femsec/fiv143

Rafiq M, Hayat M, Zada S, Sajjad W, Hassan N, Hasan F (2019) Geochemistry and bacterial recovery from Hindu Kush Range glacier and their potential for metal resistance and antibiotic production. Geomicrobiol J 36:326–338. https://doi.org/10.1080/01490451.2018.1551947

Rather PN, Mann PA, Mierzwa R, Hare RS, Miller GH, Shaw KJ (1993) Analysis of the aac(3)-Vla gene encoding a novel 3-N-acetyltransferase. Antimicrob Agents Chemother 37 (10):2074–2079. https://doi.org/10.1128/aac.37.10.2074

Rauseo J, Spataro F, Pescatore T, Patrolecco L (2024) Multiresidue determination and predicted risk assessment of emerging contaminants in sediments from Kongsfjorden, Svalbard. Sci Total Environ 922:171156. https://doi.org/10.1016/j.scitotenv.2024.171156

Ravenschlag K, Sahm K, Amann R (2001) Quantitative molecular analysis of the microbial community in marine Arctic sediments (Svalbard). Appl Environ Microbiol 67(1):387–395. https://doi.org/10.1128/aem.67.1.387-395.2001

Revich B, Tokarevich N, Parkinson AJ (2012) Climate change and zoonotic infections in the Russian Arctic. Int J Circumpolar Health 71(6):18792. https://doi.org/10.3402/ijch.v71i0.18792

Rudnicka-Kepa P, Zaborska A (2021) Sources, fate and distribution of inorganic contaminants in the Svalbard area, representative of a typical Arctic critical environment-a review. Environ Monit Assess 193:724. https://doi.org/10.1007/s10661-021-09305-6

Samreen IA, Malak HA, Abulreesh HH (2021) Environmental antimicrobial resistance and its drivers: a potential threat to public health. Journal of Global Antimicrobial Resistance 27:101–111. https://doi.org/10.1016/j.jgar.2021.08.001

Schostag M, Stibal M, Jacobsen CS, Bælum J, Tas N, Elberling B, Jansson JK, Semenchuk P, Priemé A (2015) Distinct summer and winter bacterial communities in the active layer of Svalbard permafrost revealed by DNA-and RNA-based analyses. Front Microbiol 6:399. https://doi.org/10.3389/fmicb.2015.00399

Schütte UME, Abdo Z, Bent SJ, Williams CJ, Schneider GM, Solheim B, Forney LJ (2009) Bacterial succession in a glacier foreland of the High Arctic. ISME J 3:1258–1268. https://doi.org/10.1038/ismej.2009.71

Schuur EAG, McGuire AD, Schädel C, Grosse G, Harden JW, Hayes DJ, Hugelius G, Koven CD, Kuhry P, Lawrence DM, Natali SM, Olefeldt D, Romanovsky VE, Schaefer K, Turetsky MR, Treat CC, Vonk JE (2015) Climate change and the permafrost carbon feedback. Nature 520:171–179. https://doi.org/10.1038/nature14338

Senger K, Ammerlaan F, Betlem P, Dumais M-A, Eagles G, Foster W, Geissler WH, Grundvåg S-A, Hodson A, Horota R, Hurum J, Jones M, Kierulf HP, Majka J, Marsden L, Michalski K, Minakov A, Ogata K, Olaussen S, Osmundsen PT, Planke S, Ruppel A, Sartell A, Shephard GE, Śliwińska KK, Smeraglia L, Smyrak-Sikora A, Spiegel-Behnke C, Zuchuat V (2025) Geology of Svalbard: Deep-time and Deep-Earth. In: Runge et al (eds) SESS report 2024, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 52-83. https://doi.org/10.5281/zenodo.14425478

Shatilovich A, Gade VR, Pippel M, Hoffmeyer TT, Tchesunov AV, Stevens L, Winkler S, Hughes GM, Traikov S, Hiller M, Rivkina E, Schiffer PH, Myers EW, Kurzchalia TV (2023) A novel nematode species from the Siberian permafrost shares adaptive mechanisms for cryptobiotic survival with C. elegans dauer larva. PLoS Genet 19(7):e1010798. https://doi.org/10.1371/journal.pgen.1010798

Singh SM, Gawas-Sakhalkar P, Naik S, Ravindra R, Sharma J, Upadhyay AK, Mulik RU, Bohare P (2015a) Elemental composition and bacterial incidence in firn-cores at Midre Lovénbreen glacier, Svalbard. Polar Record. 51(1):39-48. https://doi.org/10.1017/S0032247413000533

Singh P, Singh SM, Dhakephalkar P (2014) Diversity, cold active enzymes and adaptation strategies of bacteria inhabiting glacier cryoconite holes of High Arctic. Extremophiles 18(2):229–242. https://doi.org/10.1007/s00792-013-0609-6

Singh P, Singh SM, Roy U (2015b) Taxonomic characterization and the bio-potential of bacteria isolated from glacier ice cores in the High Arctic. J Basic Microbiol 56(3):275–285. https://doi.org/10.1002/jobm.201500298

Singh P, Singh SM, Singh RN et al (2017) Bacterial communities in ancient permafrost profiles of Svalbard, Arctic. J Basic Microbiol 57(12):1018–1036. https://doi.org/10.1002/jobm.201700061

Sinha RK, Krishnan KP, Kerkar S, Divya David T (2017a) Spatio-Temporal Monitoring and Ecological Significance of Retrievable Pelagic Heterotrophic Bacteria in Kongsfjorden, an Arctic Fjord. Indian J Microbiol 57(1):116–120. https://doi.org/10.1007/s12088-016-0621-5

Sinha RK, Krishnan KP, Mohamed Hatha AA, Rahiman M, Thresyamma DD, Kerkar S (2017b) Diversity of retrievable heterotrophic bacteria in Kongsfjorden, an Arctic fjord. Brazil J Microbiol 48:51–61. https://doi.org/10.1016/j.bjm.2016.09.011

Sokolowski A, Mordec M, Caban M, Øverjordet IB, Wielogorska E, Wlodarska-Kowalczuk M, Balazy P, Chelchowski M, Lepoint G (2024) Bioaccumulation of pharmaceuticals and stimulants in macrobenthic food web in the European Arctic as determined using stable isotope approach. Sci Total Env 909:168557. https://doi.org/10.1016/j.scitotenv.2023.168557

Søreide JE, Pitusi V, Vader A, Damsgård B, Nilsen F, Skogseth R, Poste A, Bailey A, Kovacs KM, Lydersen C, Gerland S, Decamps S, Strøm H, Renaud PE, Christensen G, Arvnes MP, Moiseev D, Singh RK, Bélanger S, Elster J, Urbański J, Moskalik M, Wiktor J, Węsławski JM (2021) Environmental status of Svalbard coastal waters: coastscapes and focal ecosystem components. In: Moreno-Ibáñez et al

(eds) SESS report 2020, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 142-174. https://doi.org/10.5281/zenodo.4293849

Spolaor A, Salzano R, Scoto F, Barbaro E, Luks B, Laska M, Sobota I, Maetzke R, Malnes E, Vickers H, Larose C, Dahlke S, Maturilli M (2025) Understanding and analysing recurrent warm events in Svalbard: a comprehensive review on land cryosphere. In: Runge et al (eds) SESS report 2024, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 182-197. https://doi.org/10.5281/zenodo.14425903

Stalder T, Barraud O, Casellas M, Dagot C, Ploy MC (2012) Integron involvement in environmental spread of antibiotic resistance. Front Microbiol 3:119. https://doi.org/10.3389/fmicb.2012.00119

Strauss J, Schirrmeister L, Mangelsdorf K, Eichhorn L, Wetterich S, Herzschuh U (2015) Organic-matter quality of deep permafrost carbon – a study from Arctic Siberia. Biogeosciences 12:2227–2224. http://dx.doi.org/10.5194/bg-12-2227-2015

Sułowicz S, Bondarczuk K, Ignatiuk D, Jania JA, Piotrowska-Seget Z (2020) Microbial communities from subglacial water of naled ice bodies in the forefield of Werenskioldbreen, Svalbard. Sci Total Env 723 138025. https://doi.org/10.1016/j.scitotenv.2020.138025.

Sunde M, Ramstad SN, Rudi K, Porcellato D, Ravi A, Ludvigsen J, das Neves CG, Tryland M, Ropstad E, Slettemeås JS, Telke AA (2021) Plasmid-associated antimicrobial resistance and virulence genes in *Escherichia coli* in a high arctic reindeer subspecies. JGAR 26:317–322. https://doi.org/10.1016/j.jgar.2021.06.003

Tait K, Laverock B, Widdicombe S (2014) Response of an Arctic Sediment Nitrogen Cycling Community to Increased CO2. Est Coasts 37:724–735. https://doi.org/10.1007/s12237-013-9709-x

Teske A, Durbin A, Ziervogel K, Cox C, Arnosti C (2011) Microbial community composition and function in permanently cold seawater and sediments from an Arctic fjord of Svalbard. Appl Environ Microbiol 77:2008–2018. https://doi.org/10.1128/aem.01507-10

Thomas FA, Mohan M, Krishnan KP (2021) Bacterial diversity and their metabolic profiles in the sedimentary environments of Ny-Ålesund, Arctic. Antonie Van Leeuwenhoek 114(9):1339–1360. https://doi.org/10.1007/s10482-021-01604-9

Thomas FA, Sinha RK, Krishnan KP (2020) Bacterial community structure of a glacio-marine system in the Arctic (Ny-Ålesund, Svalbard). Sci Total Environ 718:135264. https://doi.org/10.1016/j.scitotenv.2019.135264

Tian C, Lv YX, Yang ZF, Zhang RF, Zhu ZY, Ma HM, Li J, Zhang Y (2023) Microbial Community Structure and Metabolic Potential at the Initial Stage of Soil Development of the Glacial Forefields in Svalbard. Microb Ecol 86:933–946. https://doi.org/10.1007/s00248-022-02116-3

Tian F, Yu Y, Chen B, Li HR, Yao YF, Guo XK (2009) Bacterial, archaeal and eukaryotic diversity in Arctic sediment as revealed by 16S rRNA and 18S rRNA gene clone libraries analysis. Pol Biol 32:93–103. http://dx.doi.org/10.1007/s00300-008-0509-x

Underwood E (2014) Melting Arctic ice releases deadly seal parasite. https://www.science.org/content/article/melting-arctic-ice-releases-deadly-seal-parasite

Van den Heuvel-Greve MJ, Szczybelski AS, van den Brink NW, Kotterman MJJ, Kwadijk CJAF, Evenset A, Murk AJ (2016) Low organotin contamination of harbour sediment in Svalbard. Polar Biol 39(10):1699–1709. https://doi.org/10.1007/s00300-016-1907-0

Vayssier-Taussat M, Albina E, Citti C, Cosson J-F, Jacques M-A, Lebrun M-H, Le Loir Y, Ogliastro M, Petit M-A, Roumagnac P, Candresse T (2014) Shifting the paradigm from pathogens to pathobiome: new concepts in the light of meta-omics. Front Cell Infect Microbiol 4:29. https://doi.org/10.3389/fcimb.2014.00029

Venkatachalam S, Gopinath A, Krishnan KP (2023) Fjords of the western and northern regions of Svalbard harbour distinct bacterioplankton community structures. World J Microbiol Biotechnol 39(2):57. https://doi.org/10.1007/s11274-022-03493-0

Venkatachalam S, Kannan VM, Saritha VN, Loganathachetti DS, Mohan M, Krishnan KP (2021) Bacterial diversity and community structure along the glacier foreland of Midtre Lovenbreen, Svalbard, Arctic. Ecol Ind 126:107704. https://doi.org/10.1016/j.ecolind.2021.107704

Venkatachalam S, Vipindas PV, Jabir T, Jain A, Krishnan KP (2024) Metagenomic insights into novel microbial lineages with distinct ecological functions in the Arctic glacier foreland ecosystems. Environ Res 241:117726. https://doi.org/10.1016/j.envres.2023.117726

Vipindas PV, Krishnan KP, Jabir T, Rehitha TV, Chetti DSL (2020) Diversity of sediment associated Planctomycetes and its related phyla with special reference to anammox bacterial community in a high Arctic fjord. World J Microbiol Biotechnol 36(7):107. https://doi.org/10.1007/s11274-020-02886-3

Vishnupriya S, Jabir T, Adarsh BM, Kattatheyil H, Kabeer SS, Krishnan KP, Radhakrishnan CK, Hatha AAM (2023) Diversity of complex polysaccharide degrading bacteria from the sediments of interlinked high Arctic fjords, Svalbard. Reg Studies Mar Sci 63(3):102989. http://dx.doi.org/10.1016/j.rsma.2023.102989

Vishnupriya S, Jabir T, Akhil Prakash E, Mohamed Hatha AA (2024) Antibiotic resistance of heterotrophic bacteria from the sediments of adjoining high Arctic fjords, Svalbard. Braz J Microbiol 55:2371–2383. https://doi.org/10.1007/s42770-024-01368-0

Vonnahme TR, Devetter M, Žárský JD, Šabacká M, Elster J (2016) Controls on microalgal community structures in cryoconite holes upon high-Arctic glaciers, Svalbard. Biogeosciences 13:659–674. https://doi.org/10.5194/bg-13-659-2016

Walsh TR, Weeks J, Livermore DM, Toleman MA (2011) Dissemination of NDM-1 positive bacteria in the New Delhi environment and its implications for human health:

an environmental point prevalence study. Lancet Infect Dis 11:355–362. https://doi.org/10.1016/s1473-3099(11)70059-7

Wang NF, Zhang T, Yang X, Wang S, Yu Y, Dong LL, Guo YD, Ma YX, Zang JY (2016) Diversity and Composition of Bacterial Community in Soils and Lake Sediments from an Arctic Lake Area. Front Microbiol 7:1170. https://doi.org/10.3389/fmicb.2016.01170

Weber B, Belnap J, Büdel B, Antoninka AJ, Barger NN, Chaudhary VB et al (2022) What is a biocrust? A refined, contemporary definition for a broadening research community. Biol Rev 97:1768–1785. https://doi.org/10.1111/brv.12862

Wojcik R, Donhauser J, Frey B, Holm S, Holland A, Anesio AM, Pearce DA, Malard L, Wagner D, Benning LG (2018) Linkages between geochemistry and microbiology in a proglacial terrain in the High Arctic. Ann Glaciol 59(77):95–110. https://doi.org/10.1017/aog.2019.1

Wutkowska M, Vader A, Mundra S, Cooper EJ, Eidesen PB (2019) Dead or Alive; or Does It Really Matter? Level of Congruency Between Trophic Modes in Total and Active Fungal Communities in High Arctic Soil. Front Microbiol 9:3243. https://doi.org/10.3389/fmicb.2018.03243

Xue Y, Jonassen I, Øvreås L, Taş N (2020) Metagenome-assembled genome distribution and key functionality highlight importance of aerobic metabolism in Svalbard permafrost. FEMS Microbiol Ecol 96(5):fiaa057. https://doi.org/10.1093/femsec/fiaa057

Yang S, Wen X, Wu T, Wu X, Wang X, Jin X, Li X, Yang X, Yang L, Wang H (2024) Carbon-cycling microorganisms in permafrost and their responses to a warming climate: A review. Permafrost Periglac Process 35:218–231. https://doi.org/10.1002/ppp.2206

Yarzábal LA, Salazar LMB, Batista-García RA (2021) Climate change, melting cryosphere and frozen pathogens: Should we worry…? Environ Sustain (Singap). 4(3):489–501. https://doi.org/10.1007/s42398-021-00184-8

Zarsky JD, Stibal M, Hodson A, Sattler B, Schostag M, Hansen LH, Jacobsen CS, Psenner R (2013) Large cryoconite aggregates on a Svalbard glacier support a diverse microbial community including ammonia-oxidizing archaea. Environ Res Lett 8(3):035044. https://doi.org/10.1088/1748-9326/8/3/035044

Zeng Y, Zheng T, Li H (2009) Community composition of the marine bacterioplankton in Kongsfjorden (Spitsbergen) as revealed by 16S rRNA gene analysis. Polar Biol 32:1447–1460. https://doi.org/10.1007/s00300-009-0641-2

Zeng YX, Yan M, Yu Y, Li HR, He JF, Sun K, Zhang F (2013) Diversity of bacteria in surface ice of Austre Lovénbreen glacier, Svalbard. Arch Microbiol 195(5):313–322. https://doi.org/10.1007/s00203-013-0880-z

Zeng YX, Yu Y, Li HR, Luo W (2017) Prokaryotic Community Composition in Arctic Kongsfjorden and Sub-Arctic Northern Bering Sea Sediments As Revealed by 454 Pyrosequencing. Front Microbiol 8:2498. https://doi.org/10.3389/fmicb.2017.02498

Zhang T, Li J, Wang N, Wang H, Yu L (2022) Metagenomic analysis reveals microbiome and resistome in the seawater and sediments of Kongsfjorden (Svalbard, High Arctic) Sci Total Env 809:151937. https://doi.org/10.1016/j.scitotenv.2021.151937

Polar Night in Longyearbyen – on the day the idea for this chapter was conceived. (Photo: Carmen Rizzo, CNR-ISP, SZN)

Terrestrial and freshwater invertebrate science in Svalbard in a changing world: from regional to pan-Arctic scales (STAFIEN - Svalbard Terrestrial and Freshwater Invertebrate Ecology Network)

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1. Introduction

This chapter covers invertebrates, a group that consists of a large and diverse range of taxa including worms, water bears, springtails, mites, spiders, insects and Crustacea of various types (Figure 1). The invertebrate community plays a central role globally in many key terrestrial ecosystem processes (Figure 2) such as decomposition, nutrient cycling, energy flow, herbivory, pollination, parasitism and as prey items (Losey and Vaughan 2006; Wagner 2020), and this is also believed to be the case in the polar regions (Thomas et al. 2008; Gillespie et al. 2020; Aronsson 2021). In a generally still understudied Arctic, Svalbard stands out as having over a century of terrestrial biology research dating back to Summerhayes and Elton (1923). Many invertebrate species were first described from the archipelago (Seniczak et al. 2020) and Svalbard remains one of the benchmark locations for the study and knowledge of Arctic invertebrate biodiversity. While much remains to be learnt about the terrestrial diversity of Svalbard's invertebrates and their precise ecosystem roles, the levels of species endemism already apparent (i.e., species only known from the archipelago) further emphasise the great conservation value of the archipelago in the context of key international agreements such as the Convention on Biodiversity (CBD 2024) and, hence, the need for its effective and informed management.

Svalbard's invertebrate fauna includes many taxa and 1 091 recorded species (Coulson et al. 2024a,b). The terrestrial and freshwater invertebrate fauna of Scandinavia and Svalbard is of global interest because it possibly has great geological age, for instance with rotifers displaying distinct genetic lineages suggesting their presence precedes the Quaternary (> 2.58 mya) (Shain et al. 2024). Given the general lack and widely inconsistent level of detailed knowledge of terrestrial and freshwater ecosystems across the Arctic, Svalbard also stands out for its high potential both as an exemplar, or sentinel, of research in Arctic environmental change, and to provide a foundation to upscale to the pan-Arctic (e.g., Bischoff et al. 2019; Gillespie et al. 2020; Pedersen et al. 2021).

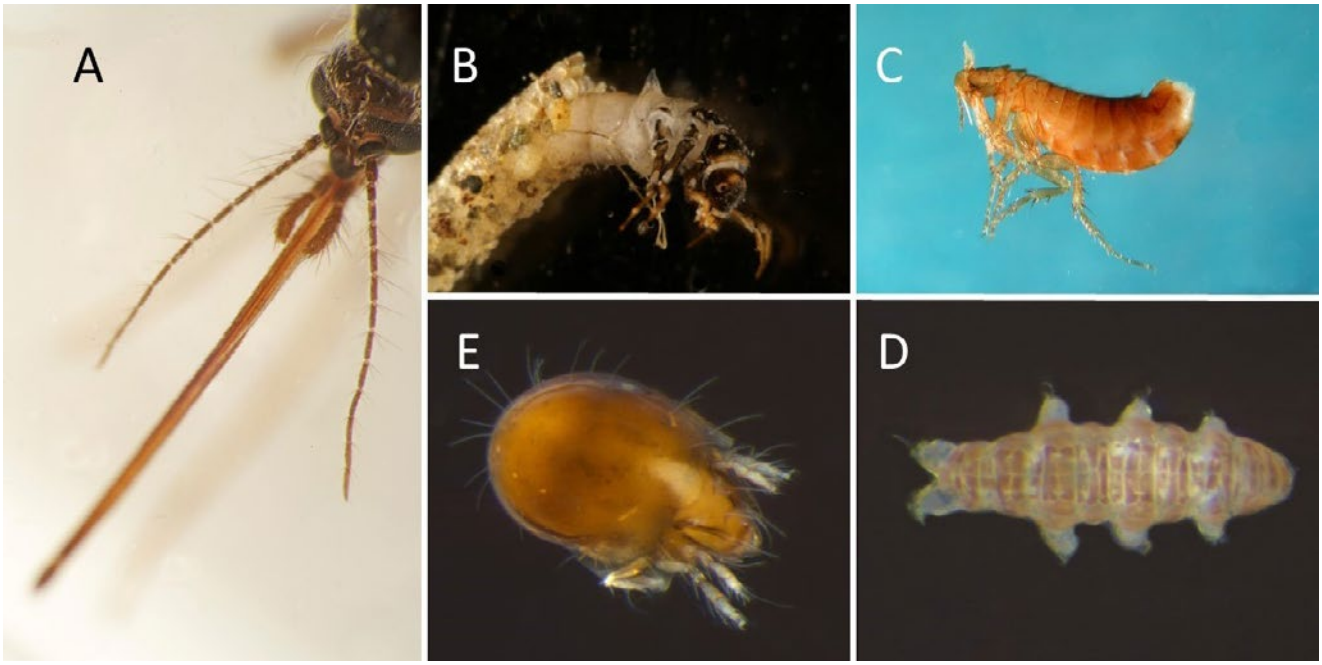

Figure 1: Examples of some invertebrate groups present in Svalbard; A=Diptera (mosquito) (P Hermansen), B=Trichoptera (caddisfly) (SJ Coulson), C=Siphonaptera (flea) (SJ Coulson), D=Tardigrade (water bear) (K. Zawierucha), E=Oribatida (mite) (SJ Coulson).

With the very noticeable recent environmental and climatic changes in the Arctic generally, and Svalbard specifically (ACIA 2005; Pedersen et al. 2021), the role of invertebrates as bioindicators becomes crucial in identifying and understanding the responses and resilience of polar ecosystems. However, despite their recognised importance and the research already done in Svalbard, there currently remains a disproportionate lack of focus on invertebrate ecology compared to other less diverse taxonomic groups. This deficiency has not previously been considered in a State of Environmental Science in Svalbard (SESS) report. Society is demanding that researchers provide information on biodiversity, ecosystem function and the rapid changes that we are experiencing to underpin adaptation to, and mitigation of, their wide-ranging impacts. Nonetheless, the latest Conservation of Arctic Flora and Fauna (CAFF) status report and the evidence of trends in Arctic terrestrial biodiversity that it describes (Aronsson et al. 2021) clearly highlights the lack of information concerning the terrestrial and freshwater invertebrate fauna across the Arctic. In particular, the extreme paucity of studies providing repeated information over time (time series data) is a striking feature of invertebrate research in Svalbard. Further, there is a lack of knowledge on species-specific responses to both abiotic and biotic variables, as well as on species interactions across invertebrate taxa and with other species groups such as plants, vertebrates and microorganisms. Anthropogenic perturbations in Arctic regions are increasing, as for example stressors such as pollution, introduction of non-native species, infrastructure construction and land use change. Research is desperately needed to fill knowledge gaps before irreparable damage prevents a complete understanding of Svalbard's unique invertebrate fauna. Without this understanding it is difficult to fully comprehend terrestrial and freshwater ecosystems, their functioning, or project how they will respond to ongoing environmental change.

This report sets out to (a) describe the current state of knowledge of the terrestrial and freshwater invertebrate fauna in Svalbard, (b) the role of Svalbard in the Arctic as a wider region, and

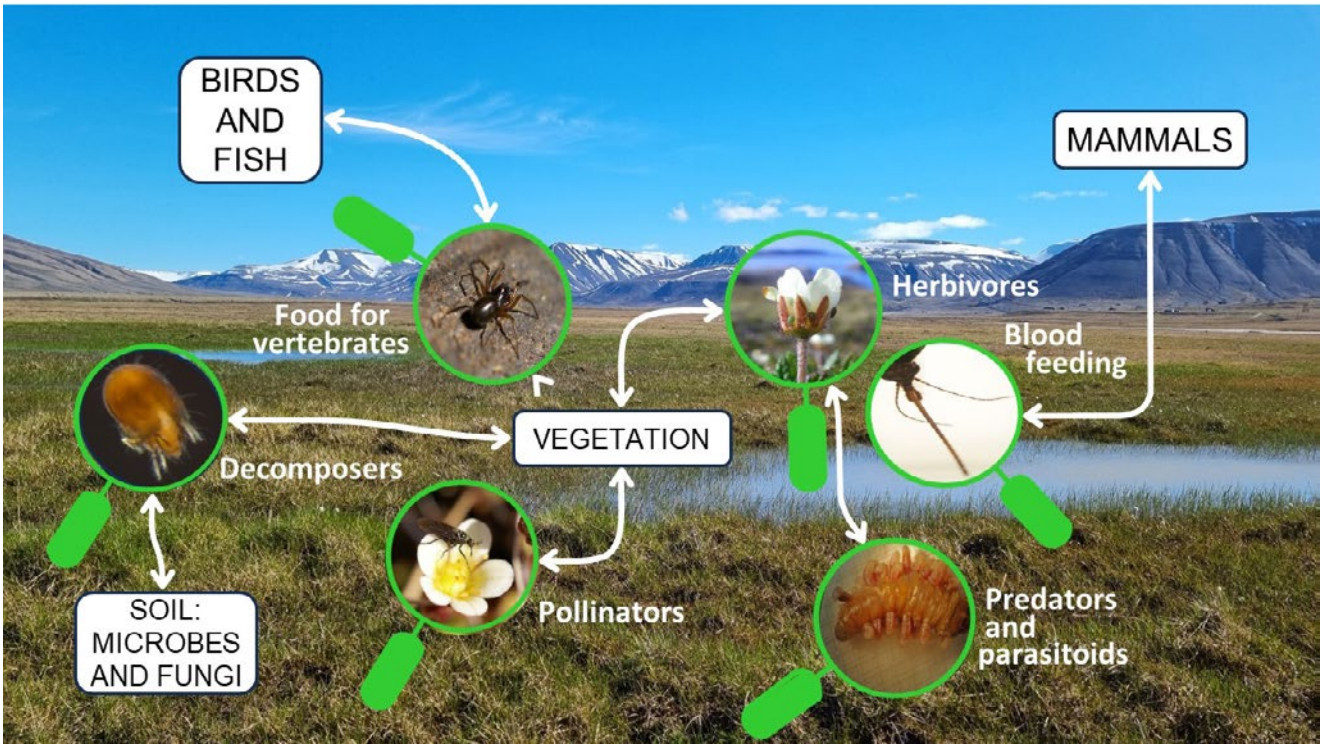

Figure 2: Simplified conceptual model of the Focal Ecosystem Components (FECs) defined in the Arctic Terrestrial Ecosystem Monitoring Plan (Christensen et al. 2013) and the State of the Arctic Terrestrial Biodiversity Report (Aronsson et al. 2021), and processes mediated by more than 2 500 species of Arctic arthropods known from Greenland, Iceland, Svalbard, and Jan Mayen (based on Aronsson et al. 2021).

(c) identify key knowledge gaps, opportunities and data requirements to provide the required understanding, including (d) how the Svalbard Integrated Arctic Earth Observing System organisation (SIOS) might contribute to invertebrate ecology, for example by facilitating novel sample acquisition opportunities.

2. Overview of existing knowledge

The terrestrial and freshwater invertebrate diversity of Svalbard is one of the best known for any region in the Arctic (Coulson et al. 2014) and the recent publication of a critically assessed species inventory with 1 091 species is a significant advance (Coulson et al. 2024a, Table 1). Moreover, the resultant inventory has been matched to molecular sequence data currently available in the Barcode of Life Data Systems (BOLD), revealing that approximately 51% of these species have NCBI GenBank entries and providing a shortlist of 522 species to target for DNA sequencing. New species are regularly recorded from the archipelago, especially when studies address the less-accessible eastern and northern regions. For example, after only a brief visit to Edgeøya, Ávila-Jimenez et al. (2019) reported 140 invertebrate species belonging to 69 genera of which 16 were new records for Svalbard and six were new to science. Given that the number of publications featuring Svalbard invertebrates has increased exponentially since the first records in 1869, new findings are likely to occur more frequently, including those of "invasive alien species" – species for which anthropogenic assistance plays a key role in arrival and establishment in Svalbard. This is exemplified by Coulson (2015), who surveyed the literature and identified 15 species of terrestrial invertebrate considered to be recent anthropogenic introductions. While no invertebrate species are currently known to have spread beyond synanthropic environments (i.e., settlements and sites of direct human activity), many of the species identified in the anthropogenic soils in Barentsburg (Coulson et al. 2013) or Pyramiden (Coulson et al. 2015) are known to be resident in both the potential source regions (former Soviet Ukraine and Svalbard). The possible impact of introduced conspecifics on genetic diversity of native Svalbard populations remains to be studied.

While knowledge of Svalbard species diversity matches that of some other Arctic locations, such as Greenland (Bøcher et al. 2015), and is more advanced than many other locations (Gillespie et al. 2020), a detailed inventory provides only one perspective on invertebrate ecology. Far less is known about geographical distributions, species interactions, relative abundance, community and age structure, population dynamics or trends and the relative importance of different species to ecosystem functions. It is clear that, in general, we lack spatial and temporal data relating to different invertebrate species. These aspects of invertebrate ecology are vital to understanding the impacts of environmental changes to invertebrate biodiversity and the functions they perform (Aronsson et al. 2021). The knowledge gaps are partly due to the challenges involved in accessing varied invertebrate habitats in Svalbard, which result in knowledge of many aspects of invertebrate ecology being heavily skewed towards the west, particularly around Longyearbyen and Ny-Ålesund, and to certain taxa (Figures 3, 4). For instance, while the oribatid and mesostigmatid mite communities have been recently reassessed based on new sampling and up to date taxonomies (Seniczak and Seniczak 2020; Seniczak et al. 2020; Coulson et al. 2024a), the same cannot be said for other important taxa, such as nematode or enchytraeid worms.

In addition to geographical bias, studies of Arctic invertebrate ecology are commonly too limited in time and space to generate high-quality, generalisable information. For example, Gillespie and Cooper (2022) provided the first study of plant and insect pollinator interactions for Svalbard, revealing tight links between flower visitation by insects and the timing of snow melt. Nevertheless, this study was restricted in scope due to limited

Table 1: Species diversity in Svalbard. Number of species total = total number of valid species, synonyms removed; numbers in bold font indicate the total number of species in the phylum; in italics the total number of species in the class; in normal font the number of species in the sub-classes or orders.

Phylum	Class	Sub-class	Order	Total number of species
Rotifera	Eurotatoria			**184** *184*
Gastrotricha	Chaetonotida			**50** *50*
Nematoda	Adenophorea Chromadorea Enoplea			**136** *4* *95* *37*
Platyhelminthes	Cestoda Trematoda			**29** *23* *6*
Annelida	Oligochaeta			**41** *41*
Tardigrada	Heterotardigrada Eutardigrada			**99** *17* *82*
Chelicerata	Arachnida	Acari Araneae		**212** *212* 194 18
Mandibulata	Collembola Insecta		Hemiptera Thysanoptera Phthiraptera Coleoptera Hymenoptera Trichoptera Lepidoptera Siphonaptera Diptera	**290** *67* *223* 3 1 35 16 33 1 3 2 129
Crustacea	Branchiopoda Copepoda Malacostraca Ostracoda			**50** *16* *20* *4* *10*
			Sum	1 091

species identification ability, plot-level observations which do not necessarily scale up to the broader landscape, and covered only a single season and location. Year-to-year and spatial variability may impact both plant flowering and insect abundance: future studies will require support to be broader in scope (Gillespie et al. 2020). Many reports from Svalbard, such as that of Ávila-Jiménez et al. (2019) referred to above, also represent a snapshot in time, albeit identifying important results. Generally, there is a lack of long-term data throughout the Arctic with suitable spatial and habitat coverage and species-level identifications, with the best available currently being from Zackenberg (Høye et al. 2021) and Nuuk (Topp-Jørgensen et al. 2015) as part of the Greenland Ecosystem Monitoring programme (GEM). Without long time-series data it is impossible to disentangle the considerable

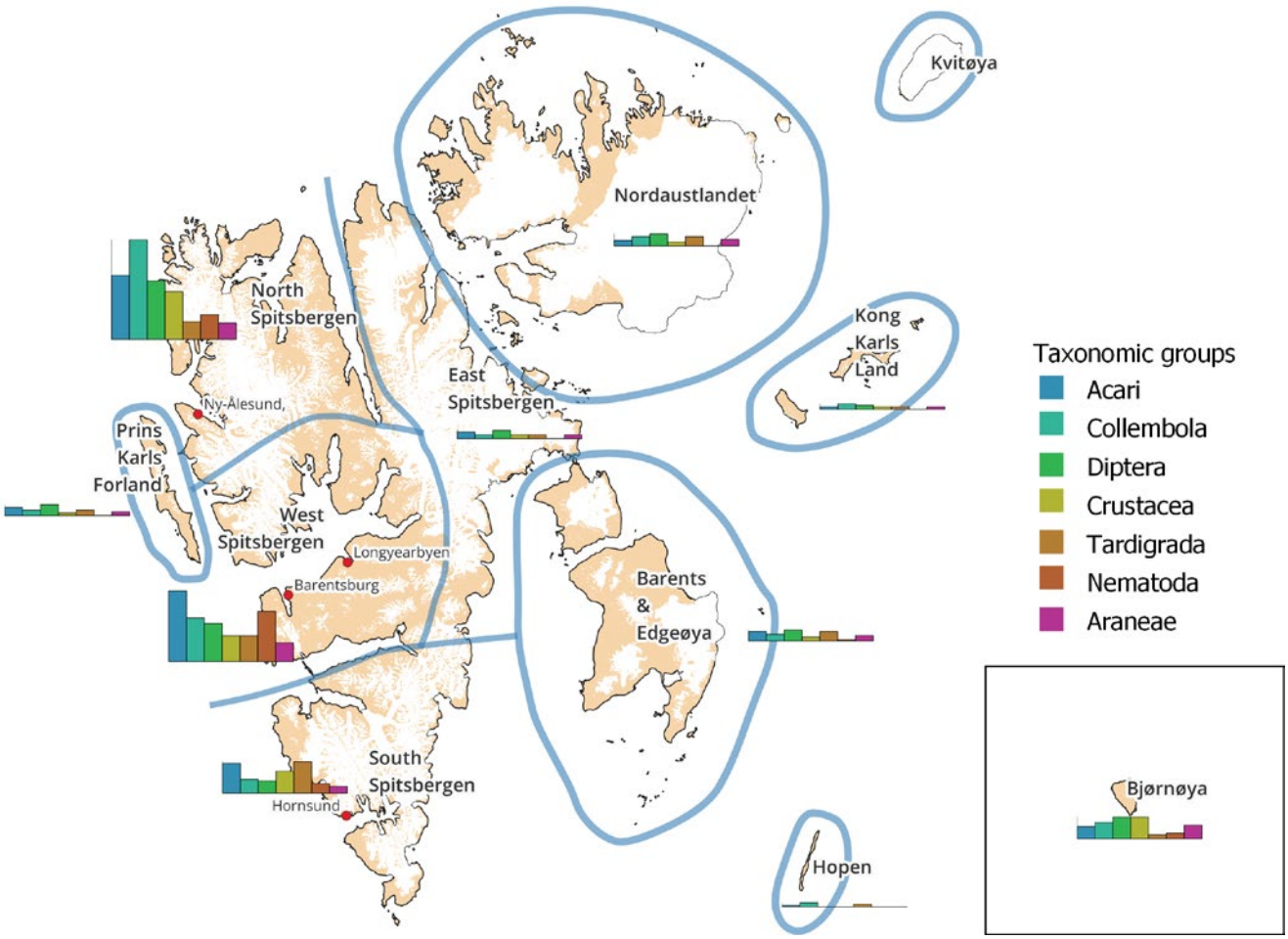

Figure 3: Bar charts showing the regional bias in the numbers of papers considering the top seven most studied taxonomic groups of the terrestrial and freshwater fauna of Svalbard. This figure is created from 460 papers published between 1869 and 2023 which listed specific locations and taxonomic information (see Coulson et al. 2024b) and were not general review articles. Articles covering more than one region/taxa are counted more than once. For reference, the tallest bar (Collembola in North Spitsbergen) has a value of 73 papers.

intra- and interannual fluctuations in abundances that are characteristic of many invertebrates, from long-term population responses to environmental change.

There is also incomplete understanding of how different abiotic and biotic stressors interact to affect different Arctic terrestrial invertebrates, or whether these responses can be generalised across taxa (Høye et al. 2021). For example, recent studies have suggested that Arctic arthropods respond negatively to longer term exposures to moderate to high temperatures (e.g., Sørensen et al. 2024; Christoffersen et al. 2024) and that changes in humidity may exacerbate these effects (Christoffersen et al. 2024). Follow-up research is required to determine whether these effects are general or species-specific, and what their consequences will be. Furthermore, environmental change may also have cascading effects that require deeper understanding. For example, parasitic gut nematodes are believed to play a role in suppressing the fecundity of their host, Svalbard reindeer (*Rangifer tarandus platyrhyncus;* Albon et al. 2002). The free-living stages of the parasitic gut nematode *Ostertagia gruehneri* have recently been shown to avoid desiccating conditions by potentially moving deeper into the vegetation profile and, should this happen, are less likely to be ingested and re-infect the host (Moerman et al. under revision). To better comprehend the resilience of significant taxa to environmental change there

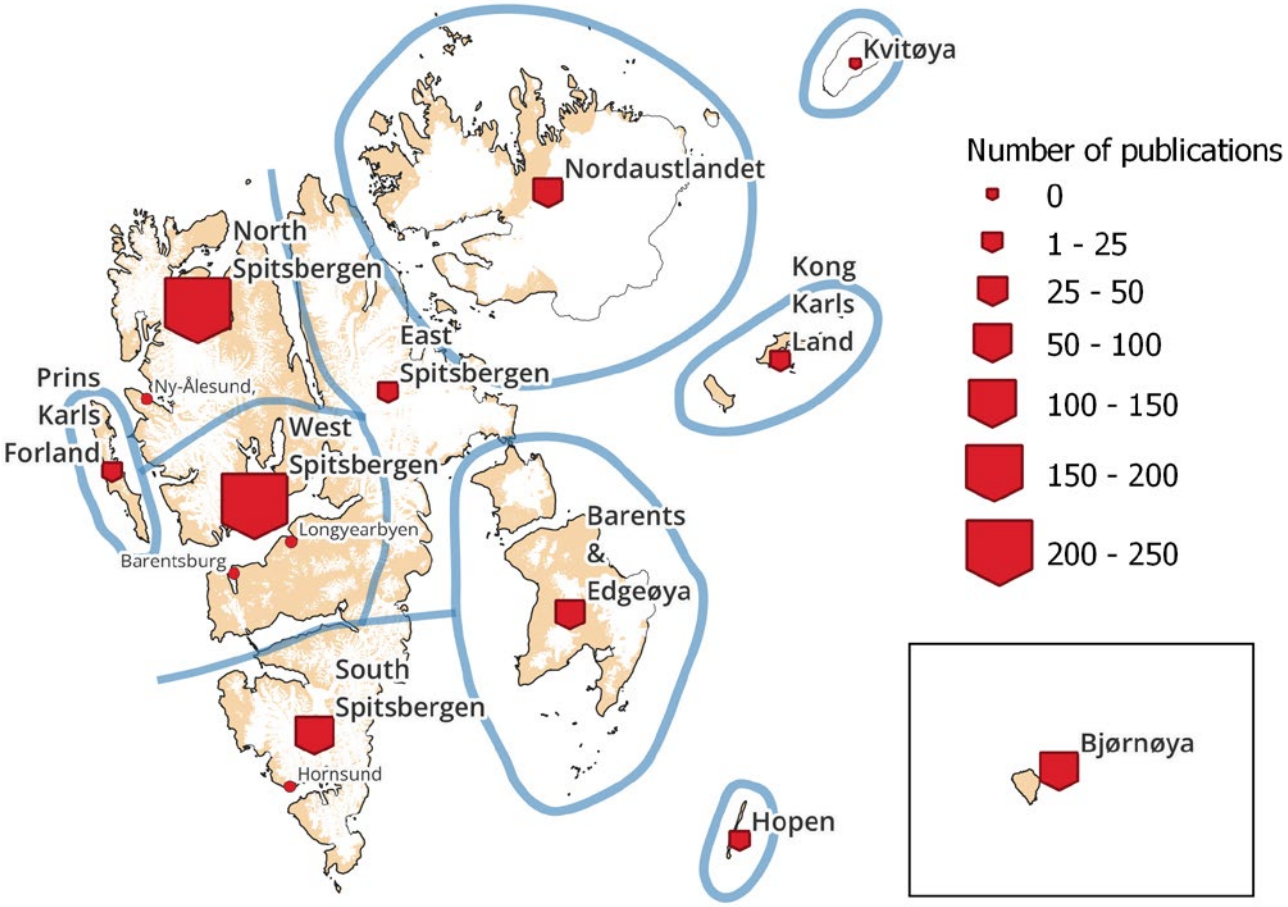

Figure 4: Numbers of papers considering the terrestrial and freshwater fauna of Svalbard in various regions. This figure is created from 472 papers published between 1869 and 2023 which listed specific locations (see Coulson et al. 2024b) and were not general review articles. Articles covering more than one region are counted more than once.

is an urgent requirement for baseline data and structured inventories, particularly at key locations, and a focus on key gradients and variables.

It is well understood that invertebrates have many functions in the terrestrial and freshwater ecosystems. For example, beyond Svalbard, much is known about important species of flower pollinators (e.g., Hallett et al. 2017) and decomposers (e.g., Ott et al. 2012). In Svalbard, however, knowledge of the presence, abundance and frequency of species interactions is insufficient to establish the roles and importance of invertebrates to ecosystem functions such as pollination and nutrient cycling. Nevertheless, the concept of the Functional Ecosystem Component (FEC) has been developed as part of the Arctic Terrestrial Biodiversity Monitoring Plan produced by the CAFF programme, together with associated "parameters" and "attributes" (Christensen 2013; Gillespie et al. 2020; Aronsson et al. 2021). Focal Ecosystem Components were defined in the Circumpolar Terrestrial Biodiversity Monitoring Plan (Christensen 2013) as key and indicative elements of biodiversity identified for each Arctic ecosystem considered. Changes in status of FECs likely indicate changes in the overall environments that require further attention and study. In the original terrestrial biodiversity plan five FECs were identified for the terrestrial and freshwater invertebrate fauna: Decomposers, Pollinators, Herbivores, Food for vertebrates, and Blood feeders. A sixth FEC, Predators and Parasites, was identified by Gillespie et al. (2020), and is included in the most recent CAFF Status and Trends of Arctic Terrestrial Biodiversity report (Aronsson et al. 2021) (Figure 2). Note that the State of the Arctic Freshwater Biodiversity Report (Lento et al. 2019) identified two FECs relevant

to this SESS chapter, Zooplankton and Benthic Macroinvertebrates, but these are not included in Figure 2 for simplicity and are here considered as within the six FECs described. It has been recommended that monitoring efforts focus on the status and trends of these FECs (e.g., species diversity, abundance, ecosystem function of key species in each FEC), but as a recent review found, we lack even the most basic information for the vast majority of species and regions (Gillespie et al. 2020). Furthermore, this conceptual classification of species is based on a combination of knowledge of ecosystem service provision by invertebrates from more temperate and tropical locations (e.g., Losey and Vaughn 2006), and scant observations of actual Arctic ecological roles (e.g., Gillespie and Cooper 2022). While all of the FECs identified for invertebrates by the Arctic Council's Circumpolar Biodiversity Monitoring Programme (CBMP) are well represented in Svalbard (Gillespie et al. 2020), no studies to date have confirmed the species involved in those functions, their effectiveness and their resilience to environmental change. Even within a single FEC subclass, such as "Prey for birds", studies of invertebrates in bird diets rarely identify invertebrates to species-level and generally report overall biomass figures. Although some studies are starting to employ sequencing techniques to identify taxa (Stolz et al. 2023), expansion of such sampling would provide a huge resource to invertebrate researchers (see section 3). In general, much research is required to confirm many species' FEC membership and, therefore, to identify the most important species providing key functional roles. Thus, for future coordinated monitoring efforts to be most effective, an extensive initial research effort is required in Svalbard and beyond, maybe expanding the national Norwegian insect monitoring programme, based on DNA-metabarcoding of Malaise traps (NINA 2024).

In addition to the general lack of data, there is also a concerning dearth of studies addressing topics crucial to Svalbard biosecurity. Ninety eight alien vascular plant species are recorded from Svalbard (Artsdatabanken 2018), 27 which are considered established or "door-knocker" species (Artsdatabanken 2023), while Bartlett et al. (2021) in a recent survey identified 36 alien plant species exclusively associated with areas of human activity. Moreover, climate modelling studies indicate that 19 of 27 established alien door-knocker species were considered to have the climate potential to spread to 75% of non-glaciated areas (Speed et al. 2024). Analogous studies addressing invasive alien invertebrates are largely lacking, but the potential for establishment of these species in Svalbard is likely to be great. Evidence from the Antarctic overwhelmingly points to the national operators being the primary source for introduced species, followed historically by trade and exploitation industries in the periods when they were active, with tourism as yet being less important (Hughes et al. 2019; Siegert et al. 2023). In Svalbard such colonisation records are focused on sites such as Barentsburg and Pyramiden (Coulson et al. 2013, 2015) and the active settlements and research stations of Longyearbyen, Ny-Ålesund, Barentsburg and Hornsund. Together with climate change, the spread and impacts of alien and invasive species on native Arctic ecosystems and species may be particularly significant (Speed et al. 2024) and information is urgently needed on which to base future planning, mitigation measures, and environmental management of Arctic terrestrial ecosystems. Enhanced collaboration with other disciplines and actors can provide a profitable approach to make this a reality.

3. Contributions to interdisciplinarity

The Svalbard research community has long recognised the existence of multiple key interconnections between taxonomic groups (Aronsson et al. 2021; Pedersen et al. 2021) and these are exemplified by the six Arctic terrestrial FECs of the Arctic Terrestrial Biodiversity Monitoring Plan (Christensen et al. 2013; Gillespie et al. 2020), all of which imply multi-trophic

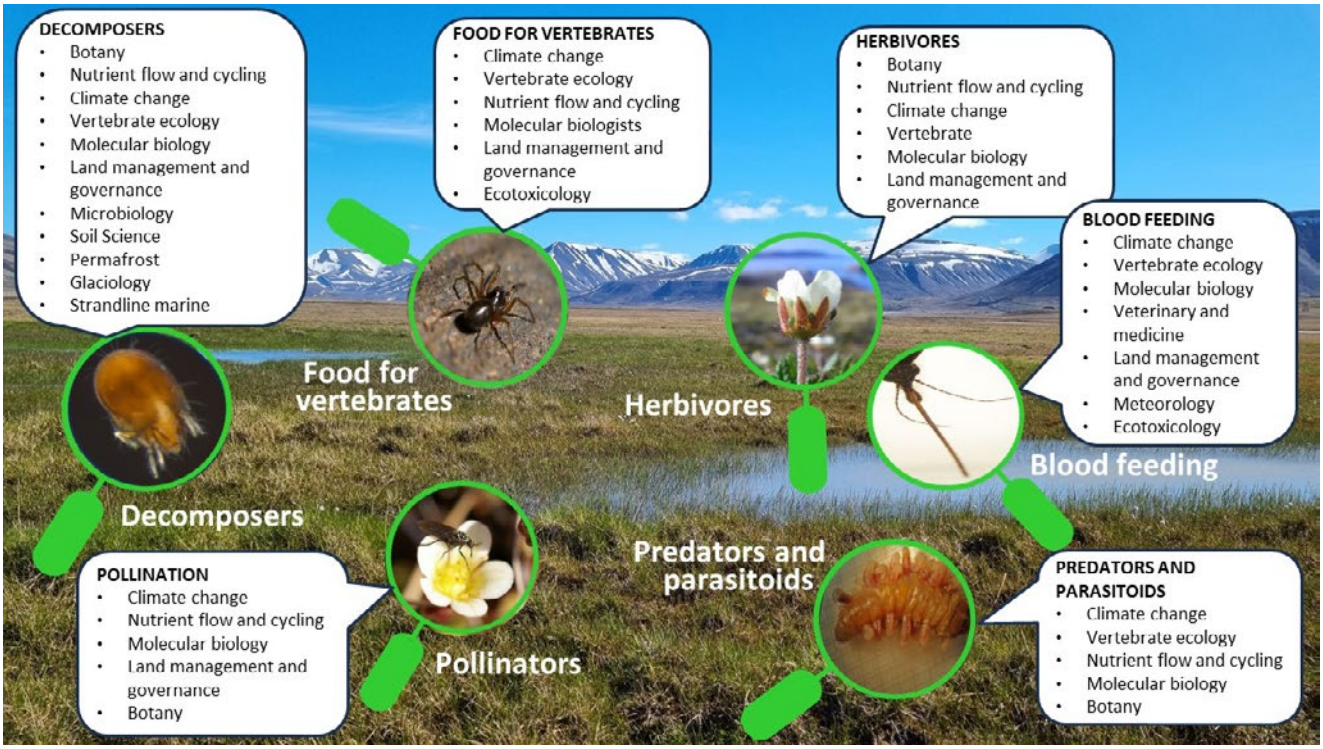

Figure 5: Conceptual model of the FECs and processes mediated by more than 2 500 species of Arctic arthropods known from Greenland, Iceland, Svalbard, and Jan Mayen and the interconnections with other science disciplines in Svalbard (based on Gillespie et al. 2020).

interactions (Figure 5). Each of the FEC groupings are functional components because they link to other species groups and demonstrate that invertebrates have interactions with many other taxa and themes (see the example of Figure 5). For instance, invertebrates play vital roles in plant pollination and seed set (Gillespie et al. 2016), in decomposition of dead organic matter and nutrient cycling (Koltz et al. 2017), in herbivory of plants (Strathdee and Bale 1996; Gillespie et al. 2007), and in vertebrate blood feeding and potential disease transmission (Müllerová et al. 2018). They also have impacts on reindeer fecundity via gastrointestinal parasites (Albon et al. 2002), serve as prey items for nesting birds and affect fledging success (Bolduc et al. 2013; Wirta et al. 2015; Schmidt et al. 2017; Stolz et al. 2023), All of these areas of overlap between trophic levels highlight opportunities to combine research effort and resources across ecological disciplines, and when pursued, have resulted in some excellent cross-disciplinary research initiatives. In addition to these, there are further areas of interdisciplinary need or opportunity beyond biology that are yet to be explored.

1. Climate changes causing, for example, glacial retreat or alterations in the timing and pattern of snowmelt, create new environmental conditions including revealing new land surfaces for colonisation. These events can be monitored using invertebrates as bioindicators. In this way, it is possible to follow succession processes and community assembly from single pioneer species arriving to more complex communities consisting of many taxa and individuals. Even wingless invertebrates have relatively large dispersal abilities (spreading) using anemochory (wind), hydrochory (ocean currents) or zoochory (animal) including the special case of anthropochory (via human actions). This type of research requires cooperation between taxa specialists, for example acarologists, entomologists and ornithologists as well as physical scientists including meteorologists, glaciologists and permafrost and soil specialists. There are opportunities for tighter collaboration with, for example, vegetation and microbial ecologists who study the same successional patterns (e.g., Yoshitake et al. 2011; Těšitel et al. 2014; Masumoto et al. 2023; Rola et al. 2023), or other fields such as geology (Kim et al. 2022)

and efforts could be combined more often to reveal co-occurring plant and invertebrate successional changes.

2. The species composition of invertebrate communities is often closely related to the quantity and type of food available. For many species of soil invertebrates, soil fungi, algae and bacteria are the main–or the only–food and, therefore, determine the structure of invertebrate communities. Separately, high springtail (Collembola) abundance can have a negative effect on nitrogen-fixing cyanobacteria and hence nitrogen fixation (Birkemoe and Liengen 2000) and vascular plant performance in the nutrient-limited ecosystems characteristic of Svalbard (Jónsdóttir 2005) and other parts of the Arctic. Thus, opportunities for collaboration between ecologists and soil scientists abound.
3. Invertebrates form a key prey item for various taxa including breeding migratory birds in the Arctic (Chagnon-Lafortune et al. 2024) and freshwater fish (Svenning et al. 2024). A snow bunting monitoring project has collected data on snow bunting breeding success in Adventdalen since 1998 (Fossøy et al. 2015) and includes trapping of arthropods since 2014. Arthropods represent the main food source for snow bunting nestlings, and the project aims to understand how climate change affects arthropod availability within and among years, and in turn how this affects snow bunting breeding success. Trapping data includes collection of insects from pitfall traps every fourth day from early June to mid-July every year, in order to estimate the phenological change in total biomass of arthropods throughout the snow bunting breeding period (Stolz et al. 2023; Jöesaar 2024).
4. Linkages with human impacts could, and need to be, further explored. Local sources of direct impacts, such as tourism and industry, can have severe implications for ecosystem functioning. Not only are there direct effects of human activities in these regions, for example ground trampling and introduction of pollutants, but there is a risk that introduced species may establish and, over time, colonise more widely within Svalbard. While the presence of introduced plants is reasonably well documented (Ware et al. 2012; Governor of Svalbard 2014), introduction of invertebrates, including hidden genetic diversity, is less well understood even though known to have occurred (Coulson et al. 2013, 2015).
5. To better understand the overall functioning of the ecosystem it is necessary for ecologists from various disciplines to approach the problem from their own respective taxonomic and/or functional expertise but with a focus on integration through the system. The TERRA project provides one example of a project focused on the effects of a combination of abiotic (surface icing) and biotic (goose grazing and soil nitrification) factors on the soil system (TERRA 2024).
6. The outcomes of invertebrate studies (e.g., bioindicators, parasitology) need to be readily available to environmental managers and those involved in governance. It is critical to share timely and accessible knowledge on Svalbard invertebrates with all relevant parties, to improve public understanding of the complexity of ecological processes and of our impacts on these processes (for example the possibilities to limit spreading of invasive alien species). Inherent in this is a need to engage with citizen science practitioners and outreach activities to develop and disseminate knowledge about the invertebrate fauna, its role and threats.
7. Many other disciplines carry out one-off or regular fieldwork activities in less visited parts of the Svalbard archipelago. At the same time, many invertebrate or habitat sampling methods are simple, fast and effective. By actively linking more closely with other disciplines and actors, such as the tourist industry in Svalbard, as is increasingly happening in other parts of the Arctic (e.g., Greenland) and Antarctic, sample collection opportunities can be considerably enhanced, developing the currently lacking crucial knowledge of the invertebrate (and, indeed other) communities from these locations. Such integration and cooperation will also contribute to addressing the often-stated aim of minimising the human footprint of research and other activities in Svalbard.

8. Traditional "on-the-ground" approaches to invertebrate survey and research are currently irreplaceable. There is a need to further integrate the traditional approaches by engaging with and increasing application of cutting-edge technological disciplines, such as remote sensing through drones and satellite imagery, eDNA, and Large Language Models and AI. These technologies offer new possibilities for sample and/or data collection, as well as enhancing specimen identification and sample analysis. However, due to the general poor knowledge base within the field of ecology these techniques require institutional support and external expertise.
9. There are direct linkages to social science, public understanding of science and the role of Svalbard science in a global context. Greater outreach can be encouraged, for example via Svalbard Environmental Fund funding. Increased data and knowledge transfer to governance organisations, including the Governor of Svalbard, the Norwegian Ministry for Climate and Environment, and the Arctic Council and its bodies, is essential as a foundation for knowledge-based governance decision making and actions. Here we see an important role for SIOS in enhancing the visibility of invertebrate science in Svalbard internationally to ensure Svalbard data are employed globally.

Such interdisciplinary collaboration could be enhanced by SIOS by creating and hosting online protocol handbooks or guidance for recommended data and types of samples and how to collect them. Other key SIOS actions identified include connecting researchers studying invertebrates in Svalbard with researchers involved in other disciplines and raising awareness of possibilities for synergy and assistance in sample collection during fieldwork activities related to other scientific disciplines, for example, collection of soil/vegetation cores for invertebrate community/biodiversity analyses.

4. Unanswered questions

In summary, while research on Arctic invertebrates in Svalbard has a long history and the current inventory is amongst the best available and quality-assured for any Arctic region, the Arctic generally, and many regions of Svalbard specifically, remain desperately understudied. To a large extent there is lack of coverage in terms of spatial and temporal patterns of biodiversity at all levels and in the application of integrated approaches linking trophic levels and energy and nutrient fluxes. Specifically, while lists of species recorded and described are available, the abundance, community age structure and functional significance of these species and populations are largely undocumented or unknown. Finally, there is a general lack of understanding of the sensitivity of most species to changes in climate, land use and other anthropogenic drivers, and the consequent cascading effects on linked biological systems.

Specific knowledge gaps include:

1. Baseline documentation of the invertebrate biodiversity of Svalbard including temporal and spatial descriptions of the distribution and abundance of this biodiversity (i.e., alpha, beta, gamma biodiversity) and a description of community structure and genetic variation in, and between, invertebrate populations. A comprehension of the great differences in species composition across relatively small geographic scales is lacking.
2. Improved understanding is required of the origin and history of colonisation of invertebrate species and populations and the potential for genetic exchange with other populations across geographical scales. Monitoring of potential invasive alien species and their likely effects on native biodiversity is lacking (e.g., through direct competition, vectoring of disease, parasitism).

3. Identification of taxa that respond to, or are vulnerable to, change and/or have possible range shifts. There is a clear lack of understanding of the local adaptation of species/populations and their resilience to climate change, changes in land use, pollution and other anthropogenic and biotic drivers. This includes the ability of species to adjust their physiologies or life histories sufficiently to enable them to show resilience to projected environmental change.
4. The ecological roles of species and linkages across trophic levels, for instance nutrient cycling, pollination and seed production, population dynamics of birds and reindeer through parasitism and food, are very far from understood. The same is true of links across the marine/terrestrial biospheres.
5. Knowledge, dynamics and challenges from Svalbard need to be translated across other Arctic systems (and vice versa), allowing Svalbard to act as an early warning system, or sentinel, for wider global patterns and effects of change. The upscaling of data from Svalbard to other parts of the Arctic is largely unaddressed.
6. There is no monitoring of invasive alien species or the potential threat that these species may represent to the native Svalbard flora and fauna communities. A risk assessment is currently lacking for Svalbard, and the archipelago must be incorporated fully into the current invasive alien species risk assessment toolkits.
7. It is necessary to develop procedures for how these data and conclusions can be used in management and policy frameworks.

5. Recommendations for the future

To enhance invertebrate ecological research in Svalbard, and address many of the important gaps highlighted above, we provide five key recommendations, including how SIOS can contribute to terrestrial and freshwater invertebrate science.

- *Develop and implement a sustained effort to document biodiversity and drivers of biodiversity change over time.*
- Invertebrates are key indicators of environmental change and are crucial in identifying and understanding the responses and resilience of polar ecosystems. There is an urgent requirement to collect baseline data and to establish future data collection foci, such as the key measurable attributes of Arctic invertebrate biodiversity. In the context of determining resilience to environmental change future data collection should focus preferably on taxa that: (a) are relatively well-studied with existing data; (b) respond to, or are vulnerable to, change; (c) face possible range shifts; d) are important for ecosystem services; and e) are or may be defined as invasive alien species, in which case their potential routes of entry should also be studied.
- *Engage with other actors and researchers to promote and enhance collaboration opportunities within Svalbard.*
- The logistics of working in the Arctic require that scientific disciplines collaborate and that science opportunities are exploited in an efficient manner. Here there are clear opportunities for collaboration with other actors, such as the tourist industry, the Governor of Svalbard's officials or research institutions involved in environmental monitoring of Svalbard (for instance MOSJ 2024) to enable access to less visited regions and to boost data collecting possibilities.
- *Build connections within and beyond the Svalbard research community to secure a pan-Arctic synthesis.*
- The above datasets should not be pursued in isolation, as other Arctic regions and disciplines face the same challenges. There is a need to establish strong cross-disciplinary and pan-Arctic connections to ensure coordination in the collection of time-series data, identification of focal key drivers, completion of molecular libraries, and assessment of the risks of invasive

alien species.

- *Create and make available online collaboration tools to facilitate enhanced data collection.*
- Tools such as a frequently updated online protocol handbook and a catalogue of recommended equipment, will enable the acquisition of the standardised samples required for efficient and accurate collection of key data. Such tools can be employed by ecologists and non-ecologists alike and could help raise the profile of invertebrate science in Svalbard, enabling data collection that would otherwise be impossible.
- *Leverage SIOS in Svalbard to raise the profile of invertebrate science and unlock new research opportunities.*
- With a focal role in Svalbard science, SIOS can play an important part in enhancing the visibility of invertebrate science in Svalbard, coordinating biogeographic analyses and data archiving, providing infrastructure support, including funding, and enabling time series data to be collected, samples to be processed, and analysis pipelines to be developed (e.g., large-scale computing). Moreover, SIOS can facilitate collaboration with current data collection and monitoring programmes such as the Greenland Integrated Observing System (GIOS.org) or the Isaaffik Arctic Gateway (isaaffik.org), and make data public via the SIOS Data Portal (sios-svalbard.org/Data) and other outreach activities.

6. Data availability

Dataset	Parameter	Period	Location	Metadata access (URL)	Dataset provider
Svalbard invertebrate inventory	Species occurrence	1869 to 2024	Svalbard	https://www.gbif.org/dataset/443d4938-8d5a-4e2e-a5b8-53fd139bb1d6	Coulson SJ stevec@unis.no

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8. References

ACIA (2005) Arctic Climate Impact Assessment. ACIA Overview report. Cambridge University Press. 1020 pp. ISBN-13 978-0-521- 86509

Albon SD, Stien A, Irvine RJ, Langvatn R, Ropstad E, Halvorsen O (2002) The role of parasites in the dynamics of a reindeer population. Proc Roy Soc B 269:1625–1632. https://doi.org/10.1098/rspb.2002.2064

Aronsson M, Heiðmarsson S, Jóhannesdóttir H, Barry T, Braa J, Burns CT, Coulson SJ, Cuyler C, Falk K, Helgason H, Lárusson KF, Lawler JP, Kulmala P, MacNearney D, Oberndorfer E, Ravolainen V, Schmidt NM, Soloviev M, Coon C, Christensen T (2021) State of the Arctic Terrestrial Biodiversity Report. Conservation of Arctic Flora and Fauna International Secretariat, Akureyri, Iceland. ISBN 978-9935-431-94-3.

Artsdatabanken (2018) Fremmedartslista 2018. Alien species list 2018. Artsdatabanken (Norwegian Biodiversity Information Centre). https://artsdatabanken.no/fremmedartslista2018 Accessed 02/07/24.

Artsdatabanken (2023) Fremmedartslista 2023. Alien species list 2023. Artsdatabanken (Norwegian Biodiversity Information Centre). https://www.artsdatabanken.no/lister/fremmedartslista/2023 Accessed 11/07/24.

Ávila-Jiménez ML, Solhøy T, Gwiazdowicz DJ, Fjellberg A, Dózsa-Farkas K, Monson F, de Smet W, Stur E, Ekrem T, Coulson SJ (2019) The invertebrate fauna of Edgeøya, Svalbard: Arctic landscape community composition reflects pan-Arctic biogeography patterns Polar Biol 42:837–850. https://doi.org/10.1007/s00300-019-02471-x

Birkemoe T, Liengen T (2000) Does collembolan grazing influence nitrogen fixation by cyanobacteria in the high Arctic? Polar Biol 23:589–592. https://doi.org/10.1007/s003000000133

Bischof K, Convey P, Duarte P, Gattuso J-P, Granberg M, Hop H, Hoppe C, Jimenez C, Lisitsyn L, Martinez B, Roleda MY, Wikto J, Gabrielsen GW (2019) Kongsfjorden as harbinger of the future Arctic: knowns, unknowns and research priorities. In: Advances in Polar Ecology, volume 2. The Ecosystem of Kongsfjorden, Svalbard, eds. Hop H and Wiencke C. Chapter 14, pp. 537–562, Springer.

Bartlett JC, Westergaard KB, Paulsen IMG, Wedegärtner REM, Wilken F, Ravolainen V (2021) Moving out of town? The status of alien plants in high-Arctic Svalbard, and a method for monitoring of alien flora in high-risk, polar environments. Ecol Solut Evid 2(1):e12056. https://doi.org/10.1002/2688-8319.12056

Bolduc E, Casajus N, Legagneux P, McKinnon L, Gilchrist HG, Leung M, Morrison RIG, Reid D, Smith PA, Buddle CM (2013) Terrestrial arthropod abundance and phenology in the Canadian Arctic: modelling resource availability for Arctic-nesting insectivorous birds. Can Entomol 145:155–170. https://doi.org/10.4039/tce.2013.4

Böcher J, Kristensen NP, Pape T, Vilhelmsen L (2015) The Greenland entomofauna: an identification manual of insects, spiders and their allies. Fauna Entomol Scand 44. p 881. ISBN:978-90-04-25640-8

CBD (2024) Convention on Biological Diversity. https://www.cbd.int/gbf. Accessed June 2024.

Chagnon-Lafortune A, Duchesne É, Legagneux P, McKinnon L, Reneerkens J, Casajus N, Abraham KF, Bolduc É, Brown GS, Brown SC, Gates HR, Gilg O, Giroux M-A, Gurney K, Kendall S, Kwon E, Lanctot RB, Lank DB, Lecomte N, Leung M, Liebezeit JR, Guy Morrison RI, Nol E, Payer DC, Reid D, Saalfeld ST, Sandercock BK, Smith PA, Schmidt NM, Tulp I, Ward DH, Høye TT, Berteaux D, Bêty J (2024) A circumpolar study unveils a positive non-linear effect of temperature on arctic arthropod availability that may reduce the risk of warming-induced trophic mismatch for breeding shorebirds. Global Change Biol 30(6):e17356. https://doi.org/10.1111/gcb.17356

Christensen T, Payne J, Doyle M, Ibarguchi G, Taylor J, Schmidt NM, Gill M, Svoboda M, Aronsson M, Behe C, Buddle C, Cuyler C, Fosaa AM, Fox AD, Heiðmarsson S, Henning Krogh P, Madsen J, McLennan D, Nymand J, Rosa C, Salmela J, Shuchman R, Soloviev M, Wedege M (2013) The Arctic Terrestrial Biodiversity Monitoring Plan. CAFF Monitoring Series Report Nr. 7. CAFF International Secretariat. Akureyri, Iceland. ISBN:978-9935-431-26-4

Christoffersen SN, Pertoldi C, Sørensen JG, Kristensen TN, Bruhn D, Bahrndorff S (2024) Strong acclimation effect of temperature and humidity on heat tolerance of the Arctic collembolan *Megaphorura arctica*. J Exp Biol 227(12): jeb247394. https://doi.org/10.1242/jeb.247394

Coulson SJ (2015) The alien terrestrial invertebrate fauna of the High Arctic archipelago of Svalbard: potential implications for the native flora and fauna. Polar Res 34:27364. https://doi.org/10.3402/polar.v34.27364

Coulson SJ, Fjellberg A, Gwiazdowicz DJ, Lebedeva NV, Melekhina EN, Solhøy T, Erséus C, Maraldo K, Miko L, Schatz H, Schmelz RM, Søli G, Stur E (2013) Introduction of invertebrates into the High Arctic via imported soils: the case of Barentsburg in Svalbard. Biol Invasions 15:1–5. https://doi:10.1007/s10530-012-0277-y

Coulson SJ, Convey P, Aakra K, Aarvik L, Ávila-Jiménez ML, Babenko A, Biersma E, Boström S, Brittain JE, Carlsson AM, Christoffersen KS, De Smet WH, Ekrem T, Fjellberg A, Füreder L, Gustafsson D, Gwiazdowicz DJ, Hansen LO, Holmstrup M, Kaczmarek L, Kolicka M, Kuklin V, Lakka HK, Lebedeva N, Makarova O, Maraldo K, Melekhina E, Ødegaard F, Pilskog HE, Simon JC, Sohlenius B, Solhøy T, Søli G, Stur E, Tanaevitch A, Taskaeva A, Velle G, Zawierucha K, Zmudczyńska-Skarbek K (2014) The terrestrial and freshwater invertebrate biodiversity of the archipelagoes of the Barents Sea: Svalbard Franz Josef Land and Novaya Zemlya. Soil Biol Biochem 68:440–470. https://doi.org/10.1016/j.soilbio.2013.10.006

Coulson SJ, Fjellberg A, Melekhina EN, Taskaeva AA, Lebedeva NV, Belkina O, Seniczak S, Seniczak A, Gwiazdowicz DJ (2015) Microarthropod communities of disturbed or imported soils in the High Arctic; the abandoned coal mining town of Pyramiden, Svalbard. Biodivers Conserv 24:1671–1690. https://doi.org/10.1007/s10531-015-0885-9

Coulson SJ, Bartlett J, Boström S, Brittain J, Christoffersen KS, Convey P, de Smet W, Dózsa-Farkas K, Ekrem T, Fjellberg A, Füreder L, Gillespie MA, Gustafsson D, Gwiazdowicz DJ, Kaczmarek Ł, Kolicka M, Laniecki R, Moerman TM, Seniczak S, Seniczak A, Simon JC, Stur E, Søli G, Wieczorek K, Zawierucha K, Zmudczynska-Skarbek K (2024a) On the terrestrial and freshwater invertebrate diversity of the High Arctic archipelago of Svalbard: a revised species inventory and synopsis of the community composition. Arctic Sci 00:1–16. (2024) https://doi.org/10.1139/as-2024-0017

Coulson SJ, Bartlett J, Boström S, Brittain J, Christoffersen KS, Convey P, De Smet W, Dózsa-Farkas K, Ekrem T, Fjellberg A, Füreder L, Gillespie MA, Gustafsson D, Gwiazdowicz DJ, Kaczmarek Ł, Kolicka M, Laniecki R, Moerman TM, Seniczak S, Seniczak A, Simon J, Stur E, Søli G, Wieczorek K, Zawierucha K, Zmudczynska-Skarbek K (2024b) Inventory of the terrestrial and freshwater fauna of the Svalbard archipelago. Version 1.3. The University Centre in Svalbard. GBIF Dataset. Accessed March 2024 https://www.gbif.org/dataset/443d4938-8d5a-4e2e-a5b8-53fd139bb1d6

Fossøy F, Stokke BG, Kåsi TK, Dyrse K, Espmark Y, Hoset KS, Wedege MI, Moksnes A (2015). Reproductive success is strongly related to local and regional climate in the Arctic snow bunting (*Plectrophenax nivalis*). Polar Biol 38:393–400. https://doi.org/10.1007/s00300-014-1595-6

Gillespie MAK, Hodkinson ID, Cooper EJ, Bird JM, Jonsdottir IS (2007) Life history and host-plant relationships of the rare endemic Arctic aphid Acyrthosiphon calvulus in a changing environment. Entomol Exp Appl 123:229–237. https://doi.org/10.1111/j.1570-7458.2007.00547.x

Gillespie MAK, Baggesen N, Cooper EJ (2016) Present and future Arctic and boreal productivity and biomass changes. Environ Res Lett 11:115006. https://doi.org/10.1088/1748-9326/11/11/115006

Gillespie MKA, Alfredsson M, Barrio IC, Bowden J, Convey P, Culler LE, Coulson SJ, Krögh PH, Koltz AM, Koponen S, Loboda S, Marusik Y, Sandstrøm JP, Sikes D, Høye TT (2020) Status and trends of Arctic terrestrial arthropod diversity of the North Atlantic region: the case of the Araneae. Ambio 49:704–717. https://doi.org/10.1007/s13280-019-01162-5

Gillespie MAK, Cooper EJ (2022) The seasonal dynamics of a High Arctic plant–visitor network: temporal observations and responses to delayed snow melt. Arctic Sci 8:786–803. https://doi.org/10.1139/as-2020-0056

Governor of Svalbard (2014) Handlingsplan mot skadelige fremmede arter på Svalbard (Action plan for harmful alien species in Svalbard.) Longyearbyen: Office of the Governor of Svalbard.

Hughes KA, Convey P, Pertierra LR, Vega GC, Aragón P, Olalla-Tárraga MÁ (2019) Human-mediated dispersal of terrestrial species between Antarctic biogeographic regions: A preliminary risk assessment. J Environ Manage 232:73–89. https://doi.org/10.1016/j.jenvman.2018.10.095

Høye TT, Loboda S, Koltz AM, Schmidt NM (2021) Nonlinear trends in abundance and diversity and complex responses to climate change in Arctic arthropods. PNAS 118:e2002557117. https://doi.org/10.1073/pnas.2002557117

Jónsdóttir IS (2005) Terrestrial ecosystems on Svalbard: heterogeneity, complexity and fragility from an Arctic Island perspective. Biol Environ 105B:155–165. https://doi.org/20728565

Jöesaar MB (2024) Snow bunting *Plectrophenax nivalis* breeding in a warming high Arctic: Does spring advancement influence breeding phenology and success? MSc thesis, Uppsala University.

Kim YJ, Laffly D, Kim S, Nilsen L, Chi J, Nam S, Lee YB, Jeong S, Mishra U, Lee YK, Jung Y (2022) Chronological changes in soil biogeochemical properties of the glacier foreland of Midtre Lovénbreen, Svalbard, attributed to soil-forming factors. Geoderma 415:115777. https://doi.org/10.1016/j.geoderma.2022.115777

Koltz AM, Asmus A, Gough L, Pressler Y, Moore JC (2017) The detritus-based microbial-invertebrate food web contributes disproportionately to carbon and nitrogen cycling in the Arctic. Polar Biol 41:1531. https://doi.org/10.1007/s00300-017-2201-5

Lento J, Goedkoop W, Culp J, Christoffersen KS, Lárusson KF, Guðbergsson FG, Liljaniemi P, Ólafsson JS, Sandøy S, Zimmerman C, Christensen T, Chambers P, Heino J, Hellsten S, Kahlert M, Keck F, Laske S, Lau DCP, Lavoie I, Levenstein B, Mariash H, Rühland K, Saulnier- Talbot E, Schartau AK, Svenning M (2019) State of the Arctic Freshwater Biodiversity. Conservation of Arctic Flora and Fauna International Secretariat, Akureyri, Iceland. http://hdl.handle.net/11374/2367

Losey JE, Vaughan M (2006) The economic value of ecological services provided by insects. BioScience 56:311–323. https://doi.org/10.1641/0006-3568(2006)56[311:TEVOES]2.0.CO;2

Masumoto S, Mori AS, Nishizawa K, Naka M, Matsuoka S, Wong S, Uchida M (2023) Synergistic effects of succession and microtopography of moraine on the fungal spatial diversity in a glacier forefield. Microbiol Ecol 99:1–10. https://doi.org/10.1093/femsec/fiad090

Moerman TM, Wetherbee R, Renčo M, Stien A, Coulson SJ, Loe LE (Under revision) Arctic field experiment reveals an effect of moisture but not temperature effect on the distribution of the free-living stages of a parasitic nematodes of Svalbard reindeer in soil and vegetation. Polar Biol

Müllerová J, Elsterová J, Černý J, Ditrich OD, Žárský J, Culler LE, Kampen H, Walther D, Coulson SJ, Růžek D, Grubhoffer L (2018) No indication of arthropod vectored viruses among mosquitoes in Greenland and Svalbard. Polar Biol 41:1–6. https://doi.org/10.1007/s00300-017-2242-9

NINA (2024) The Norwegian Institute for Nature Research https://www.nina.no/Naturmangfold/Insekter/Test-Overv%C3%A5king-av-insekter

Ott D, Rall BC, Brose U (2012) Climate change effects on macrofaunal litter decomposition: The interplay of temperature, body masses and stoichiometry. Phil Trans Roy Soc B 367:3025–30. https://doi.org/10.1098/rstb.2012.0240

Rola K, Rożek K, Chowanieca K, Błaszkowski J, Gielas I, Stanek M, Wietrzyk-Pełka P, Węgrzyn M, Fałowska P, Dziurowicz P, Nicia P, Bejger R, Zadrożny P, Pliszko A, Zalewska-Gałosz J, Zubeka S (2023) Vascular plant and cryptogam abundance as well as soil chemical properties shape microbial communities in the successional gradient of glacier foreland soils. Sci Tot Environ 860>160550. http://dx.doi.org/10.1016/j.scitotenv.2022.160550

Pedersen ÅØ, Convey P, Fuglei E, Ravolainen V, Newsham KK, Augusti A, Biersma EM, Cooper EJ, Coulson SJ, Gabrielsen GW, Gallet JC, Jensen TC, Karsten U, Kristiansen SM, Svenning MM, Tveit AT, Uchida M, Baneschi I, Calizza E, Cannone N, de Goede EM, Doveri M, Elster J, Giamberini MS, Hansen BB, Hayashi K, Lang SI, Lee YK, Mosbacher JB, Nakatsubo T, Pasquali V, Pedersen C, Peng F, Provenzale A, Pushkareva E, Sandström CAM, Sklet V, Stach A, Tojo M,

Tytgat B, Tømmervik H, Velazquez D, Verleyen E, Welker JM, Yao Y-F, Loonen MJJE (2022) High Arctic terrestrial research in Ny-Ålesund, Svalbard: A synthesis. Polar Res 4:6310. http://dx.doi.org/10.33265/polar.v41.6310

Schmidt NM, Hardwick B, Gilg O, Hoye TT, Krogh PH, Meltofte H, Michelsen A, Mosbacher JB, Raundrup K, Reneekens J, Stewart L, Wirta H, Roslin T (2017) Interaction webs in arctic ecosystems: Determinants of arctic change? Ambio 46:S12–S25. https://doi.org/10.1007/s13280-016-0862-x

Seniczak S, Seniczak A (2020) Diversity of oribatid mites (Acari: Oribatida) in the Svalbard archipelago: a historical overview. Zootaxa 4834:041–065. https://doi.org/10.11646/zootaxa.4834.1.3

Seniczak A, Seniczak S, Schwarzfeld M, Coulson SJ, Gwiazdowicz DJ (2020) Diversity and distribution of mites (Acari: Ixodida, Mesostigmata, Trombidiformes, Sarcoptiformes) in the Svalbard archipelago. Diversity 12. https://doi.org/10.3390/d12090323

Shain DH, Rogozhina J, Fontaneto D, Nesje A, Saglam N, Bartlett J, Zawierucha K, Kielland ON, Dunshea G, Arnason E, Rosvold J (2024) Ice-inhabiting species of Bdelloidea Rotifera reveal a pre-Quaternary ancestry in the Arctic cryosphere. Biol Lett 20:20230546. https://doi.org/10.1098/rsbl.2023.0546

Siegert M, Bentley M, Atkinson A, Bracegirdle T, Convey P, Davies B, Downie R, Hogg AE, Holmes C, Hughes KA, Meredith MP, Ross N, Rumble J, Wilkinson J (2023) Antarctic extreme events. Front Environ Sci 11. https://doi.org/10.3389/fenvs.2023.1229283

Speed JDM, Pertierra LR, Westergaard KB (2024) The potential area of occupancy of non-native plants across a warming high-Arctic archipelago: Implications for strategic biosecurity management. NeoBiota 93:157–175. https://doi.org/10.3897/neobiota.93.114854

Stolz C, Varpe Ø, Ims RA, Sandercock BK, Stokke BG, Fossøy F (2023) Predator–prey interactions in the Arctic: DNA metabarcoding reveals that nestling diet of snow buntings reflects arthropod seasonality. Environ DNA 5:1234–1251. https://doi.org/10.1002/edn3.439

Strathdee AT, Bale JS (1996) Life cycle and morph production in the Arctic aphid *Acyrthosiphon brevicorne*. Polar Biol 16:293–300. https://doi.org/10.1007/s003000050056

Summerhayes VS, Elton CS (1923) Contributions to the ecology of Spitsbergen and Bear Island. J Ecol 11:214–286. https://doi.org/10.2307/2255864

Svenning MA, Skogstad OC, Borgstrøm R (2024) *Mysis segerstralei*, an unexpected but important prey for resident Arctic charr (*Salvelinus alpinus*) in a Svalbard lake. Polar Biol 47:963–971. https://doi.org/10.1007/s00300-024-03261-w

Sørensen JG, Noer NK, Kristensen TN, Bahrndorff S (2024). Acclimation to moderate temperatures can have strong negative impacts on heat tolerance of arctic arthropods. Func Ecol 38:1549–1561. https://doi.org/10.1111/1365-2435.14573

TERRA (2024) TERRA, a research project about goose herbivory and climate change in the High Arctic. https://terra.w.uib.no/ Accessed 02/07/24.

Těšitel J, Těšitelová T, Bernardová A, Janková Drdová E, Lučanová M, Klimešová J (2014) Demographic population structure and fungal associations of plants colonizing High Arctic glacier forelands, Petuniabukta, Svalbard. Polar Res 33. https://doi.org/10.3402/polar.v33.20797

Thomas DN, Fogg G, Convey P, Fritsen C, Gilli J-M, Gradinger R, Laybourne-Parry J, Reid K, Walton DWH (2008) The Biology of Polar Regions. Oxford University Press, Oxford. https://academic.oup.com/book/3899

Topp-Jørgensen E, Tairova Z, Rasch M, Hansen J (2015) INTERACT Research and Monitoring, Aarhus: DCE – Danish Centre for Environment and Energy, Aarhus University, 148 p. https://doi.org/10.2312/GFZ.LIS.2015.004

Wagner DL (2020) Insect declines in the Anthropocene. Ann Rev Entomol 65:457–480. https://doi.org/10.1146/annurev-ento-011019-025151

Ware C, Bergstrom DM, Müller E, Alsos IG (2012) Humans introduce viable seeds to the Arctic on footwear. Biol Invasions 14:567–577. https://doi.org/10.1007/s10530-011-0098-4

Wirta HK, Vesterinen EJ, Hambäck PA, Weingartner E, Rasmussen C, Reneerkens R, Schmidt NM, Gilg O, Roslin T (2015) Exposing the structure of an Arctic food web. Ecol Evol 5:3842–3856. https://doi.org/10.1002/ece3.1647

Yoshitake S, Uchida M, Ohtsuka T, Kanda H, Koizumi H, Nakatsubo T (2011) Vegetation development and carbon storage on a glacier foreland in the High Arctic, Ny-Ålesund, Svalbard. Polar Sci 5:391–397. http://dx.doi.org/10.1016/j.polar.2011.03.002

Operationalisation of COAT in SIOS – an example of adaptive ecosystem-based monitoring in practice (COAT)

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1. COAT in a nutshell

The *Climate Ecological Observatory for Arctic Tundra* (COAT) is a long-term observation system for real-time detection, documentation, understanding and predictions of climate impacts on Norwegian Arctic tundra ecosystems (Ims et al. 2013). COAT Svalbard is integrated into the *Svalbard Integrated Arctic Earth Observing System* (SIOS), as an essential component of the ecosystem-based biosphere monitoring (Pedersen et al. 2020, 2022). During 2016–2023, COAT has implemented research infrastructure related to data collection, field logistics and data management across five biotic monitoring modules and a climate monitoring network in Svalbard. In 2024, COAT received funding from the state budget to UiT – The Arctic University of Norway to enter the operational phase of the long-term monitoring.

2. Operationalisation of ecosystem-based adaptive monitoring

The COAT Svalbard observation systems cover the wide range of existing variation in climatic gradients and management contexts. The system is implemented according to the ecological hypotheses and study designs in the COAT Science Plan (Ims et al. 2013). In this update chapter, we present the essence of the climate monitoring network and the five biotic modules, together with a brief description of the status.

2.1. The COAT climate monitoring network and its operation

The climate in Svalbard is undergoing rapid transformation (Isaksen et al. 2022b), with further changes anticipated (Hanssen-Bauer et al. 2019). To quantitatively evaluate the impacts of climate change on tundra ecosystems, comprehensive data of spatial and temporal variability of weather are required.

In Svalbard, climatic variability is driven by topography and distance from the coast, generating marked differences between coastal and inland regions. Prior to the establishment of COAT, the full-scale automatic weather stations (AWSs) were mostly located along the west coast, with a notable absence of stations in the inland and at higher elevations, complicating the understanding of the physical processes that connect snow cover and snow structure to weather parameters and the biotic ecosystem components. Between 2019 and 2021, seven new AWSs were established in Svalbard. An additional AWS was established at Agard in eastern Spitsbergen in 2024, completing the west–east transect across central Spitsbergen (Figure 1). These AWSs provide hourly, real-time data on air, soil, and permafrost temperatures, soil moisture, wind direction and speed, snow depth, air humidity, and radiation. These are the main climatic variables expected to act as drivers on ecosystem components and are essential for the monitoring basal ice cover, timing of snowmelt, permafrost thawing and onset of seasons.

A network of ground temperature loggers (N > 300) are implemented at scales relevant to the measurements in the five biotic monitoring modules (Appendix 1). At each of the ground temperature logger sites, snow conditions are assessed in snow pits in late winter, with measures of snow depth and structure of the snow cover, particularly the presence and thickness of ice layers both at the ground and within the snowpack. Additionally, snow cover is assessed at a broader spatial scale using snow models (run on data from 1957–2021) at spatial resolution of 100 × 100 m and remote sensing techniques, such as the MODIS snow products.

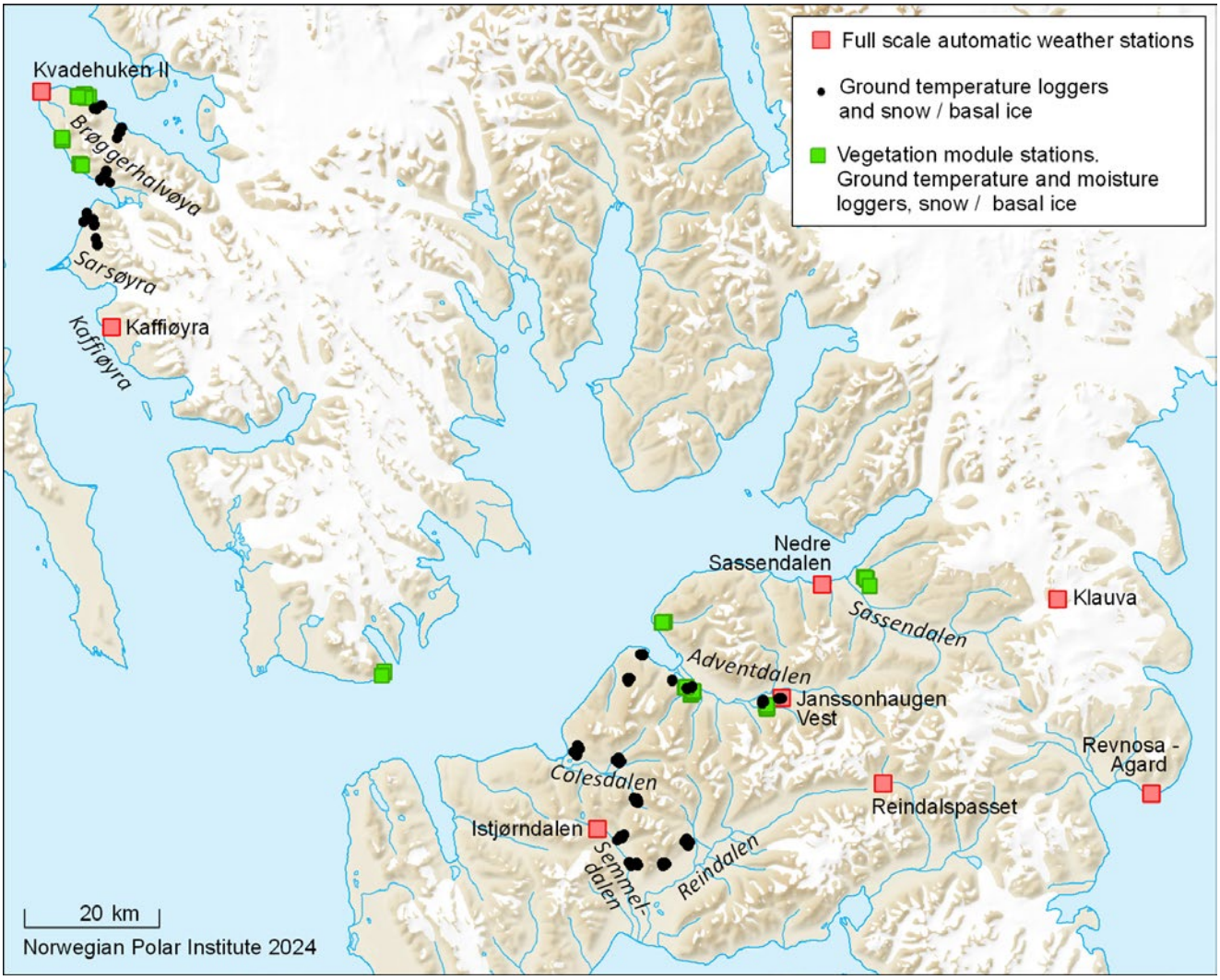


Figure 1: Map of the COAT Svalbard climate monitoring network, including eight full-scale automatic weather stations and > 300 ground surface temperature loggers, and the vegetation monitoring stations (N=57) where a suite of climate-related variables are collected. Note that symbols group sites for both loggers and vegetation monitoring stations. The network is spatially distributed in important climatic gradients (i.e., coast – inland and valley bottom – higher elevations) across the two study regions, Nordenskiöld Land and Brøgger peninsula and surroundings. At all logger sites, snow depth and basal ground ice is measured annually. Map: Anders Skoglund / Norwegian Polar Institute

2.2. The COAT biotic monitoring modules and their operation

The ecosystem-based monitoring is implemented through five food web monitoring modules and the climate monitoring network. Each of the five food web modules is based on a *conceptual "climate impact path model"* that outlines a set of *monitoring targets* in terms of climate sensitive key species or functional groups in the tundra food web and *a priori* hypotheses for their key process relations. These are described in the COAT Science Plan (Ims et al. 2013) and further developed in Nater et al. (2021) [Arctic fox module], Marolla et al. (2021) and Henden et al. (2017) [ptarmigan module] and Ravolainen et al. (2020) [vegetation module].

3. Status and trends in the Svalbard terrestrial ecosystem

3.1. Climate characteristics and implications for the food web

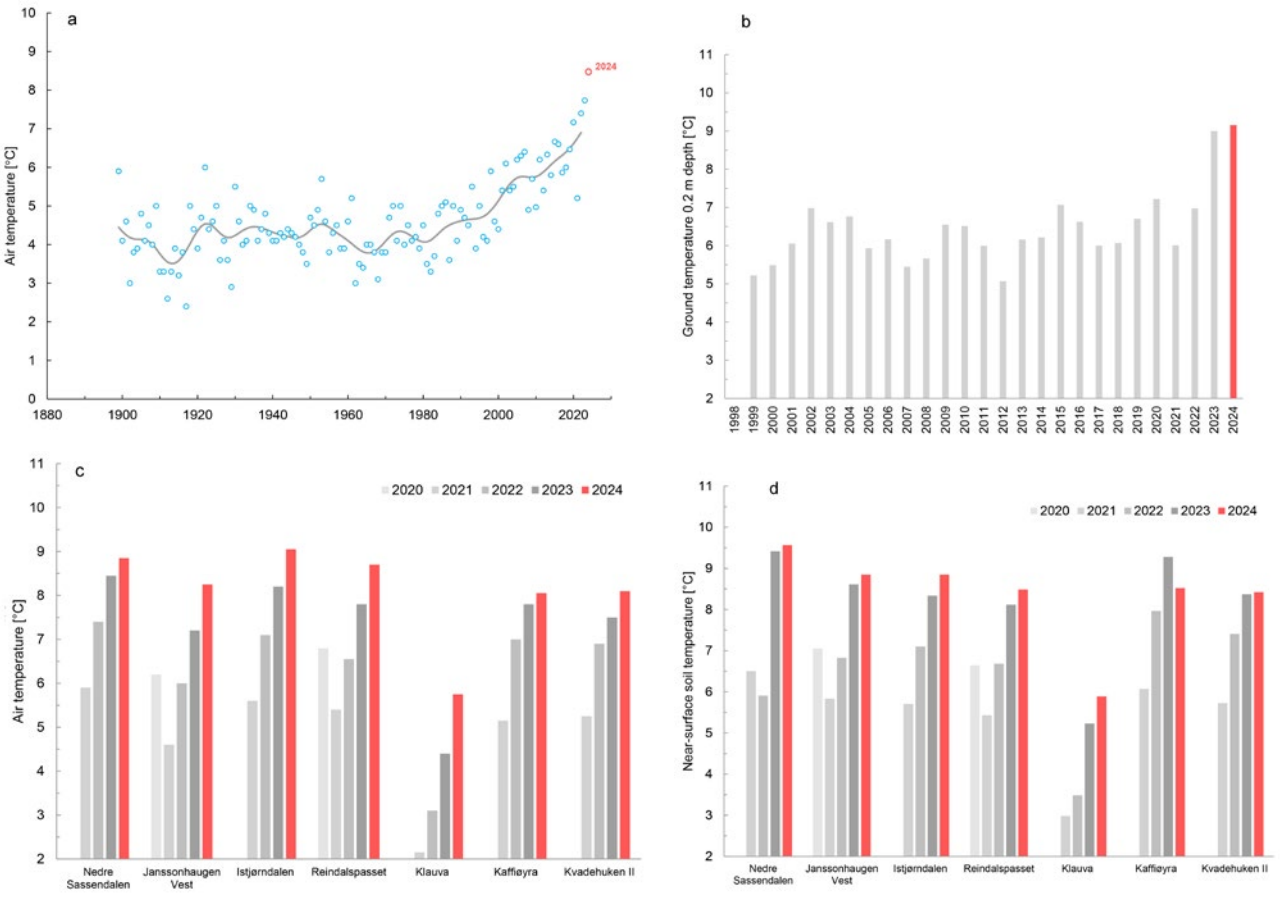
Since 1971, air temperature in Svalbard has increased 3–5˚C, particularly in the winter season (Hanssen-Bauer et al. 2019). Winters are characterised by fewer extremely cold days (Nordli et al. 2020), more frequent mild days with precipitation as rain (Peeters et al. 2019) and lack of sea ice (Urbanski and Litwicka 2022). Since 1991, the most significant warming rates were observed in the northern and eastern regions of Svalbard, reaching levels that were nearly double those previously recorded in this region (Isaksen et al. 2022b). July temperature is a key characteristic of the plant growing season and determines the Arctic bioclimatic zones. Climatically, most of the Svalbard tundra has shifted by an entire bioclimatic sub-zone (Pedersen et al. 2021). Such changes are expected to be accompanied by changes in function, structure and productivity of the ecosystems (Ims et al. 2013).

Precipitation: Annual precipitation has increased by 30–45% during the past 60 years (Førland et al. 2020). Higher winter temperatures cause more frequent episodes of winter rain, often resulting in basal ice formation and locked grazing grounds for herbivores. Peeters et al. (2019) documented a cryosphere regime-shift wherein basal ground ice has formed every winter since 1998, while formerly such winters occurred every three to four years.

Snow-free season: Snow cover duration is decreasing everywhere in Svalbard, but most rapidly in the middle-Arctic tundra zone (Pedersen et al. 2021). The length of the snow season has decreased by approximately 20 days since the middle of the last century and this trend is expected to continue, resulting in shifts in spring and winter onset and prolonged growing seasons (Hanssen-Bauer et al. 2019). Recently, Svalbard experienced three record-breaking summers in a row (2022–2024, Box 1), which has never previously been recorded by MET Norway on the mainland or in Svalbard. The data series indicated that the growing seasons, especially in 2023 and 2024, were exceptionally warm and prolonged. In 2023, air temperature data from stations in Nedre Sassendalen and Svalbard Airport revealed for the first time that Svalbard experienced suitable conditions for tree growth, based on the criteria set by Paulsen and Körner (2014). Nevertheless, these conditions need to be maintained over several years for trees to grow in Svalbard. In 2023, the increase in near-surface soil temperature at the majority of COAT weather stations exceeded the rise in air temperature compared to previous summers (Box 1). The likely explanation for this situation is the remarkably low frequency of cloudy days, which in turn caused a substantial rise in radiation measured at the COAT weather stations during that summer. Despite the additional increase in air temperature in 2024, the near-surface soil temperature remained more aligned with the measurements recorded in 2023 (Box 1).

Permafrost: Since 1998, permafrost has been measured at Janssonhaugen, Nordenskiöld Land. This station holds the longest complete time series among all the MET Norway permafrost stations. Studies focusing on temperature changes at various depths reveal significant warming of the permafrost. The most notable warming is observed at depths of 10 and 20 metres, with temperature trends of 0.9°C/decade and 0.7°C/decade, respectively (Isaksen et al. 2022a). Unlike the changes in deeper permafrost temperatures, variations in active layer thickness (ALT), are mainly governed by summer air temperatures and the snow cover. Higher summer season temperatures result in increased deepening of ALT, causing thawing of the near-surface permafrost (Hanssen-Bauer et al. 2019; Isaksen et al. 2022a), which impacts the tundra structure, hydrology and vegetation growing conditions (Hanssen-Bauer et al. 2019).

Box 1: Temperature records – the first 5 years of the COAT climate monitoring network



Temperatures in Svalbard during the recent extreme summers, with the warmest summer (2024) marked in red. a) Summer (JJA) air temperatures at the weather station Svalbard Airport. The composite series from Svalbard Airport, covering the years from 1898 to the present, is a rare example of a long-term temperature record from the High Arctic (Nordli et al. 2020). The record warm recent summers are also confirmed by other climate data records, like the high-resolution Copernicus Arctic Regional ReAnalysis (CARRA[1]). b) Mean July-August ground temperature in a permafrost borehole at 0.2 m, Janssonhaugen (see Isaksen et al. 2022). c) Mean July-August air temperatures from the seven established COAT weather stations (displayed from coast to inland). d) Mean July-August near-surface soil temperatures measured at 0.05 m depth at the COAT weather stations.

3.2. Climate-related changes in vegetation

In the Arctic, vegetation changes, e.g., phenology (Bjorkman et al. 2020), and remote-sensed indices of biomass (Berner et al. 2020), are heterogenous and the same is true for Svalbard. A trend towards an earlier start of the growing season and increased maximum productivity was found using satellite imagery (Pedersen et al. 2021) and Karlsen et al. (2024) found that large parts of Svalbard have become greener (based on data from 2000–2022).

Moss tundra is an example of a habitat that is challenging to interpret from the satellite record (e.g., Karlsen et al. 2024), while being an important herbivore habitat in Svalbard (Pedersen et al. 2023; Ravolainen et al. 2024; Grimsby et al. 2023). Herbivore impact can there be detected in remote-sensed vegetation index values (e.g., the Normalized Difference Vegetation Index (NDVI); Eischeid et al. 2021) and pink-footed geese disturb locally large proportions of moss tundra (23–80%) (Eischeid et al. 2021, 2023). At the same time, areal coverage of shared, suitable herbivore habitat is very small (Ravolainen et al. 2024) and changes in foraging conditions within the focal habitats will likely influence herbivore populations. Impacts of changing herbivore populations will, in turn, concentrate on these suitable portions of the

1 https://climate.copernicus.eu/esotc/2023/arctic-temperature

landscape. For example, the accumulated carbon stock, which is high in the focal habitats (Juselius et al. 2022), can be modified by herbivory (Speed et al. 2010; Bon et al. 2021). These interactions highlight the need for continued monitoring of herbivores and vegetation in an integrated manner.

Major changes in plant community composition are not apparent. Above-ground vascular plant biomass varies annually (www.mosj.no/no; van der Wal and Stien 2014) and invasive alien plant species in Svalbard are confined to the settlements (Bartlett et al. 2021). The adaptive, ecosystem-based monitoring ensures that potential surprises by invasive alien vascular plant species will be captured in the future (Bartlett et al. 2021; Ravolainen et al. 2020).

3.3. Climate-related changes in higher trophic levels

The Svalbard tundra has undergone rapid, substantial changes in abiotic conditions (Pedersen et al. 2021). Despite such changes, the abundance of the monitored resident and migratory vertebrate populations show both stable (Arctic fox, Nater et al. 2021) and increasing trends (pink-footed goose, Johnson et al. 2020; barnacle goose, Heldbjerg et al. 2021; Svalbard rock ptarmigan, Marolla et al. 2021; Svalbard reindeer, Hansen et al. 2019b) (see also Figure 3 in Pedersen et al. 2022). The reindeer populations, however, show contrasting dynamics with both increasing and decreasing trends, possibly because climate forces act differently on coastal and inland populations (Hansen et al. 2019b). Joint analysis of four types of fox data (1997–2019) revealed relatively stable population size and age structure despite rapid environmental change linked to climate warming (Nater et al. 2021). The monitored vertebrate community is adapted to variation in food resources and Arctic weather conditions and currently appears be coping with the rapid climate changes (Pedersen et al. 2021). Because Svalbard is an isolated archipelago, influx of potentially competing mammalian species is restricted (Sokolova et al. 2024). However, for migrants, factors outside their Arctic breeding range, like diseases (e.g., the bird flu caused a 30 % mortality in the winter 2021/2022; Griffin 2022), can cause declines in the breeding population.

The extended **snow free season** (i.e., earlier springs, Vickers et al. 2020) and increased plant biomass (i.e., greening and prolonged growing seasons, Karlsen et al. 2024) likely reduce food constraints and allow for better body condition of herbivores, which is essential to reproduction and survival (Layton-Matthews et al. 2020 [barnacle goose], Jensen et al. 2014 [pink-footed goose], Albon et al. 2017; Loe et al. 2021 [Svalbard reindeer], Eva Fuglei pers. comm. [introduced East European vole]). Moreover, snow melt patterns modify interactions between herbivores and vegetation (Eischeid et al. 2023; Anderson et al. 2016). They determine where and how intensively herbivores disturb the vegetation (Eischeid et al. 2021) and access high-quality food and nesting sites, consequently affecting breeding success (Jensen et al. 2014; Lameris et al. 2019).

The changing **precipitation patterns**, resulting in large-scale "rain-on-snow" events (ROS) and often subsequent basal ice, have over decades (1990 to 2010) had major negative influence on the population fluctuations of the resident terrestrial vertebrates in Svalbard. The precipitation changes synchronised the population abundances of the year-round resident herbivores – the Svalbard reindeer and Svalbard rock ptarmigan and the introduced East European vole – while inducing a one-year lag in the only terrestrial predator/scavenger, the Arctic fox (Hansen et al. 2013). While severe winter rain events can have drastic short-term consequences on vertebrate population abundances and vegetation (Milner et al. 2016), Hansen et al. (2019a) found that ROS (via interactions with density and intrinsic factors) had a stabilising effect on reindeer population dynamics in the long run. Recent single-species studies have indicated a weakened relative impact of ROS on population growth (e.g., Marolla et al. 2021 on Svalbard rock ptarmigan). Population densities of ptarmigan have doubled since monitoring of the breeding population started in 2000 (Pedersen et al. 2012; Marolla et al. 2021), and reindeer numbers have tripled in central Spitsbergen since the start of the long-term monitoring in 1979

(Hansen et al. 2019b, www.mosj.no/no). Currently, the negative ROS effect appears to be outweighed by positive effects of: 1) an extended snow free season, particularly due to later onset of winter, improving autumn body condition and therefore enhancing winter survival; and 2) increased summer temperatures resulting in more plant biomass for herbivores, in turn buffering against winter mortality and population declines. However, it is still unclear whether increasing temperatures will result in winters so mild that forage access is improved for herbivores (due to snow melting), rather than blocking access to foraging grounds (due to ground ice formation). Also, there is uncertainty about whether the lack of **sea ice** for dispersal and genetic exchange within the Svalbard archipelago (Peeters et al. 2020), will negatively influence populations (particularly Arctic fox and reindeer). However, the reindeer populations have adapted successfully, despite low genetic diversity from origin, and appear robust (Dussex et al. 2023).

4. Contributions to interdisciplinarity

COAT combines ecology and geophysical disciplines (i.e., meteorology, snow geophysics etc.) and is a highly multidisciplinary adaptive ecosystem-based programme that contribute to conservation and management of climate-sensitive components of Norwegian Arctic ecosystems.

5. Challenges and recommendations for the future

As COAT has entered the operational phase, the use of the observation system and its data to model causal relations and predictions for ecological forecasting (Dietze et al. 2018) is of high priority.

We recommend:

- Quantification of the conceptual models, including multi-driver analyses with climate and management as the main impact pathways, for the biotic modules not yet quantified.
- Development of short-term, iterative predictive models for key components of the terrestrial food web, based on the causal relations quantified in step 1, to provide management recommendations.

6. Data availability

The COAT data management system is a crucial part of the research infrastructure. COAT's data portal[2] builds on international metadata standards (DCAT, schema.org-structured data and ISO 19115/CSW) compatible with SIOS's digital infrastructure on the discovery level. All data from COAT weather stations are found on SEKLIMA[3].

2 https://data.coat.no/
3 https://seklima.met.no/observations/

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8. References

Albon SD, Irvine RJ, Halvorsen O, Langvatn R, Loe LE, Ropstad E, Veiberg V, Van Der Wal R, Bjørkvoll EM, Duff EI, Hansen BB, Lee AM, Tveraa T, Stien A (2017) Contrasting effects of summer and winter warming on body mass explain population dynamics in a food-limited Arctic herbivore. Global Change Biol 23(4):1374–1389. https://doi.org/10.1111/gcb.13435

Anderson HB, Speed JDM, Madsen J, Pedersen AO, Tombre IM, van der Wal R (2016) Late snow melt moderates herbivore disturbance of the Arctic tundra. Ecoscience 23(1–2):29–39. https://doi.org/10.1080/11956860.2016.1212684

Bartlett JC, Bakke-Westergaard K, Paulsen IMG, Wedegärtner REM, Wilken F, Ravolainen V (2021) Moving out of town? The status of alien plants in high-Arctic Svalbard, and a method for monitoring of alien flora in high-risk, polar environments. Ecol Solutions and Evidence 2(1). https://doi.org/10.1002/2688-8319.12056

Berner LT, Massey R, Jantz P, Forbes BC, Macias-Fauria M, Myers-Smith I, Kumpula T, Gauthier G, Andreu-Hayles L, Gaglioti BV, Burns P, Zetterberg P, D'Arrigo R, Goetz SJ (2020) Summer warming explains widespread but not uniform greening in the Arctic tundra biome. Nature Comm 11(1). https://doi.org/10.1038/s41467-020-18479-5

Bjorkman AD, Criado MG, Myers-Smith IH, Ravolainen V, Jonsdottir IS, Westergaard KB, Lawler JP, Aronsson M, Bennett B, Gardfjell H, Heidmarsson S, Stewart L, Normand S (2020) Status and trends in Arctic vegetation: Evidence from experimental warming and long-term monitoring. Ambio 49(3):678–692. https://doi.org/10.1007/s13280-019-01161-6

Bon MP, Böhner H, Bråthen KA, Ravolainen VT, Jónsdóttir IS (2021) Variable responses of carbon and nitrogen contents in vegetation and soil to herbivory and warming in high-Arctic tundra. Ecosphere 12(9). https://doi.org/10.1002/ecs2.3746

British Trust for Ornithology (2022) https://www.bto.org/understanding-birds/avian-influenza/avian-influenza-2021-22-outbreak

Dietze MC, Fox A, Beck-Johnson LM, Betancourt JL, Hooten MB, Jarnevich CS, Keitt TH, Kenney MA, Laney CM, Larsen LG, Loescher HW, Lunch CK, Pijanowski BC, Randerson JT, Read EK, Tredennick AT, Vargas R, Weathers KC, White EP (2018) Iterative near-term ecological forecasting: Needs, opportunities, and challenges. Proceedings of the National Academy of Sciences of the United States of America 115(7):1424–1432. https://doi.org/10.1073/pnas.1710231115

Dussex N, Torresen OK, van der Valk T, Le Moullec M, Veiberg V, Tooming-Klunderud A, Skage M, Garmann-Aarhus B, Wood J, Rasmussen JA, Pedersen AO, Martin SLF, Roed KH, Jakobsen KS, Dalén L, Hansen BB, Martin MD (2023) Adaptation to the High-Arctic island environment despite long-term reduced genetic variation in Svalbard reindeer. Iscience 26(10). doi:10.1016/j.isci.2023.107811

Eischeid I, Madsen J, Ims RA, Nolet BA, Pedersen Å, Schreven KHT, Soininen EM, Yoccoz NG, Ravolainen VT (2023) Snowmelt progression drives habitat selection and vegetation disturbance by an Arctic avian herbivore. Ecosphere 14(12). https://doi.org/10.1002/ecs2.4729

Eischeid I, Soininen EM, Assmann JJ, Ims RA, Madsen J, Pedersen AO, Pirotti F, Yoccoz NG, Ravolainen VT (2021) Disturbance Mapping in Arctic Tundra Improved by a Planning Workflow for Drone Studies: Advancing Tools for Future Ecosystem Monitoring. Remote Sens 13(21). https://doi.org/10.3390/rs13214466

Førland EJ, Isaksen K, Lutz J, Hanssen-Bauer I, Schuler TV, Dobler A, Gjelten HM, Vikhamar-Schuler D (2020) Measured and Modeled Historical Precipitation Trends for Svalbard. J Hydrometeorol 21(6):1279–1296. https://doi.org/10.1175/JHM-D-19-0252.1

Griffin, LR (2022) Svalbard Barnacle Goose distribution around the Solway Firth 2021-2022: Flock counts from the Solway Goose Management Scheme area. Final Report to NatureScot. Prepared by ECO-LG Ltd., Dumfries, Scotland.

38 pages

Grimsby AC, Pedersen Å, Ehrich D, Mosbacher JB, Paulsen IMG, Brockmann FK, Ravolainen V (2023) Spatiotemporal distribution of Arctic herbivores in spring: Potential for competition? Global Ecol Conserv 45. https://doi.org/10.1016/j.gecco.2023.e02521

Hansen BB, Gamelon M, Albon SD, Lee AM, Stien A, Irvine RJ, Saether BE, Loe LE, Ropstad E, Veiberg V, Grotan V (2019a) More frequent extreme climate events stabilize reindeer population dynamics. Nature Comm 10. https://doi.org/10.1038/s41467-019-09332-5

Hansen BB, Grotan V, Aanes R, Saether BE, Stien A, Fuglei E, Ims RA, Yoccoz NG, Pedersen AO (2013) Climate events synchronize the dynamics of a resident vertebrate community in the High Arctic. Science 339(6117):313–315. https://doi.org/10.1126/science.1226766

Hansen BB, Pedersen O, Peeters B, Le Moullec M, Albon SD, Herfindal I, Sæther BE, Grotan V, Aanes R (2019b) Spatial heterogeneity in climate change effects decouples the long-term dynamics of wild reindeer populations in the high Arctic. Global Change Biol 25(11):3656–3668. https://doi.org/10.1111/gcb.14761

Hanssen-Bauer I, Førland EJ, Hisdal H, Mayer S, Sandø AB, Sorteberg A (2019) Climate in Svalbard 2100 – a knowledge base for climate adaptation. NCCS report no 1/2019. http://dx.doi.org/10.25607/OBP-888

Henden JA, Ims RA, Fuglei E, Pedersen AO (2017) Changed Arctic-alpine food web interactions under rapid climate warming: implication for ptarmigan research. Wildl Biol 2017(SP1). https://doi.org/10.2981/wlb.00240

Ims RA, Jepsen JU, Stien A, Yoccoz NG (2013) Science Plan for COAT: Climate-ecological Observatory for Arctic Tundra. Fram Centre Report Series No. 1. Fram Centre, Tromsø. https://www.coat.no/portals/coat/SciencePlanCOAT_web.pdf

Ims RA, Yoccoz NG (2017) Ecosystem-based monitoring in the age of rapid climate change and new technologies. Current Opin Environ Sustain 29:170–176. https://doi.org/10.1016/j.cosust.2018.01.003

Isaksen K, Lutz J, Sorensen AM, Godoy O, Ferrighi L, Eastwood S, Aaboe S (2022a) Advances in operational permafrost monitoring on Svalbard and in Norway. Environ Res Letters 17(9). https://doi.org/10.1088/1748-9326/ac8e1c

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

Jensen GH, Madsen J, Johnson FA, Tamstorf MP (2014) Snow conditions as an estimator of the breeding output in high-Arctic pink-footed geese Anser brachyrhynchus. Polar Biol 37(1):1–14. https://doi.org/10.1007/s00300-013-1404-7

Juselius T, Ravolainen V, Zhang H, Piilo S, Muller M, Gallego-Sala A, Valiranta M (2022) Newly initiated carbon stock, organic soil accumulation patterns and main driving factors in the High Arctic Svalbard, Norway. Scientific Reports 12(1). https://doi.org/10.1038/s41598-022-08652-9

Karlsen SR, Elvebakk A, Stendardi L, Hogda KA, Macias-Fauria M (2024) Greening of Svalbard. Science Tot Environ 945. https://doi.org/10.1016/j.scitotenv.2024.174130

Lameris TK, de Jong ME, Boom MP, van der Jeugd HP, Litvin KE, Loonen M, Nolet BA, Prop J (2019) Climate warming may affect the optimal timing of reproduction for migratory geese differently in the low and high Arctic. Oecologia 191(4):1003–1014. https://doi.org/10.1007/s00442-019-04533-7

Loe LE, Liston GE, Pigeon G, Barker K, Horvitz N, Stien A, Forchhammer M et al (2021) The neglected season: Warmer autumns counteract harsher winters and promote population growth in Arctic reindeer. Global Change Biology 27(5):993–1002. https://doi.org/10.1111/gcb.15458

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

Milner JM, Varpe O, van der Wal R, Hansen BB (2016) Experimental icing affects growth, mortality, and flowering in a high Arctic dwarf shrub. Ecol Evol 6(7):2139–2148. https://doi.org/10.1002/ece3.2023

MOSJ (2024) MOSJ Miljøovervåking Svalbard og Jan Mayen. http://www.mosj.no/no/

Nater CR, Eide NE, Pedersen AO, Yoccoz NG, Fuglei E (2021) Contributions from terrestrial and marine resources stabilize predator populations in a rapidly changing climate. Ecosphere 12(6). https://doi.org/10.1002/ecs2.3546

Nordli O, Wyszynski P, Gjelten HM, Isaksen K, Lupikasza E, Niedzwiedz T, Przybylak R (2020) Revisiting the extended Svalbard Airport monthly temperature series, and the compiled corresponding daily series 1898-2018. Polar Res 39. https://doi.org/10.33265/polar.v39.3614

Paulsen J, Körner C (2014) A climate-based model to predict potential treeline position around the globe. Alpine Botany 124(1):1–12. https://doi.org/10.1007/s00035-014-0124-0

Pedersen AO, Soininen EM, Hansen BB, Le Moullec M, Loe LE, Paulsen IMG, Eischeid I, Karlsen SR, Ropstad E, Stien A, Tarroux A, Tommervik H, Ravolainen V (2023) High seasonal overlap in habitat suitability in a non-migratory High Arctic ungulate. Glob Ecol Conserv 45. https://doi.org/10.1016/j.gecco.2023.e02528

Pedersen ÅØ, Albon S, Beumer LT, Fuglei E, Isaksen K, Liston G et al (2022) Climate-Ecological Observatory for Arctic Tundra (COAT) — Adaptive system for long-term terrestrial monitoring. In: Feldner et al (eds) SESS Report 2021, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 38–55. https://doi.org/10.5281/zenodo.5751761

Pedersen ÅØ, Jepsen JU, Paulsen IMG, Fuglei E, Mosbacher JB, Ravolainen V et al. (2021) Norwegian Arctic Tundra: a Panel-based Assessment of Ecosystem Condition. Norwegian

Polar Institute, Report Series 153. https://www.researchgate.net/publication/369489469_Norwegian_Arctic_Tundra_a_Panel-based_Assessment_of_Ecosystem_Condition

Pedersen ÅØ, Stien J, Albon S, Fuglei E, Isaksen K, Liston G, Jepsen JU et al (2020) Climate-ecological Observatory for Arctic Tundra (COAT). In: Van den Heuvel et al (eds) SESS Report 2019, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 58–83. https://doi.org/10.5281/zenodo.4704475

Peeters B, Le Moullec M, Raeymaekers JAM, Marquez JF, Roed KH, Pedersen Å, Veiberg V, Loe LE, Hansen BB (2020) Sea ice loss increases genetic isolation in a high Arctic ungulate metapopulation. Global Change Biol. 26(4):2028–2041. https://doi.org/10.1111/gcb.14965

Peeters B, Pedersen AO, Loe LE, Isaksen K, Veiberg V, Stien A, Kohler J, Gallet JC, 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 Letters 14(1). https://doi.org/10.1088/1748-9326/aaefb3

Ravolainen V, Paulsen IMG, Eischeid I, Forbey JS, Fuglei E, Hájek T, Hansen BB, Loe LE, Macek P, Madsen J, Soininen EM, Speed JDM, Stien A, Tommervik H, Pedersen Å (2024) Low spatial habitat overlap of herbivores in the High Arctic tundra. Global Ecol Conserv 49. https://doi.org/10.1016/j.gecco.2024.e02797

Ravolainen V, Soininen EM, Jonsdottir IS, Eischeid I, Forchhammer M, van der Wal R, Pedersen AO (2020) High Arctic ecosystem states: Conceptual models of vegetation change to guide long-term monitoring and research. Ambio 49(3):666–677. https://doi.org/10.1007/s13280-019-01310-x

Sokolova NA, Fufachev IA, Ehrich D, Shtro VG, Sokolov VA, Sokolov AA (2024) Expansion of voles and retraction of lemmings over 60 years along a latitudinal gradient on Yamal Peninsula. Global Change Biol 30(2). https://doi.org/10.1111/gcb.17161

Speed JDM, Woodin SJ, Tommervik H, van der Wal R (2010) Extrapolating herbivore-induced carbon loss across an arctic landscape. Polar Biol 33(6):789–797. https://doi.org/10.1007/s00300-009-0756-5

Urbanski JA, Litwicka D (2022) The decline of Svalbard land-fast sea ice extent as a result of climate change. Oceanologia 64(3):535–545. https://doi.org/10.1016/j.oceano.2022.03.008

van der Wal R, Stien A (2014) High arctic plants like it hot: a long term investigation of between-year variability in plant biomass across habitats and species. Ecology 95(12):3414–3427. https://doi.org/10.1890/14-0533.1

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). https://doi.org/10.3390/rs12071123

Appendix 1. COAT biotic monitoring modules

In this appendix we present a summary of new information, not available in the COAT Science Plan (Ims et al. 2013), particularly related to the vegetation module and the implemented infrastructure and main results of the other four biotic modules. The ecological hypothesis and study designs of the monitoring modules are described in detail in Ims et al. (2013).

The **vegetation module** focuses on monitoring of plant abundance, nutrient content, and season development, with climate and herbivores as the main drivers. A premise underlying the choice of target habitats, state variable and study designs is

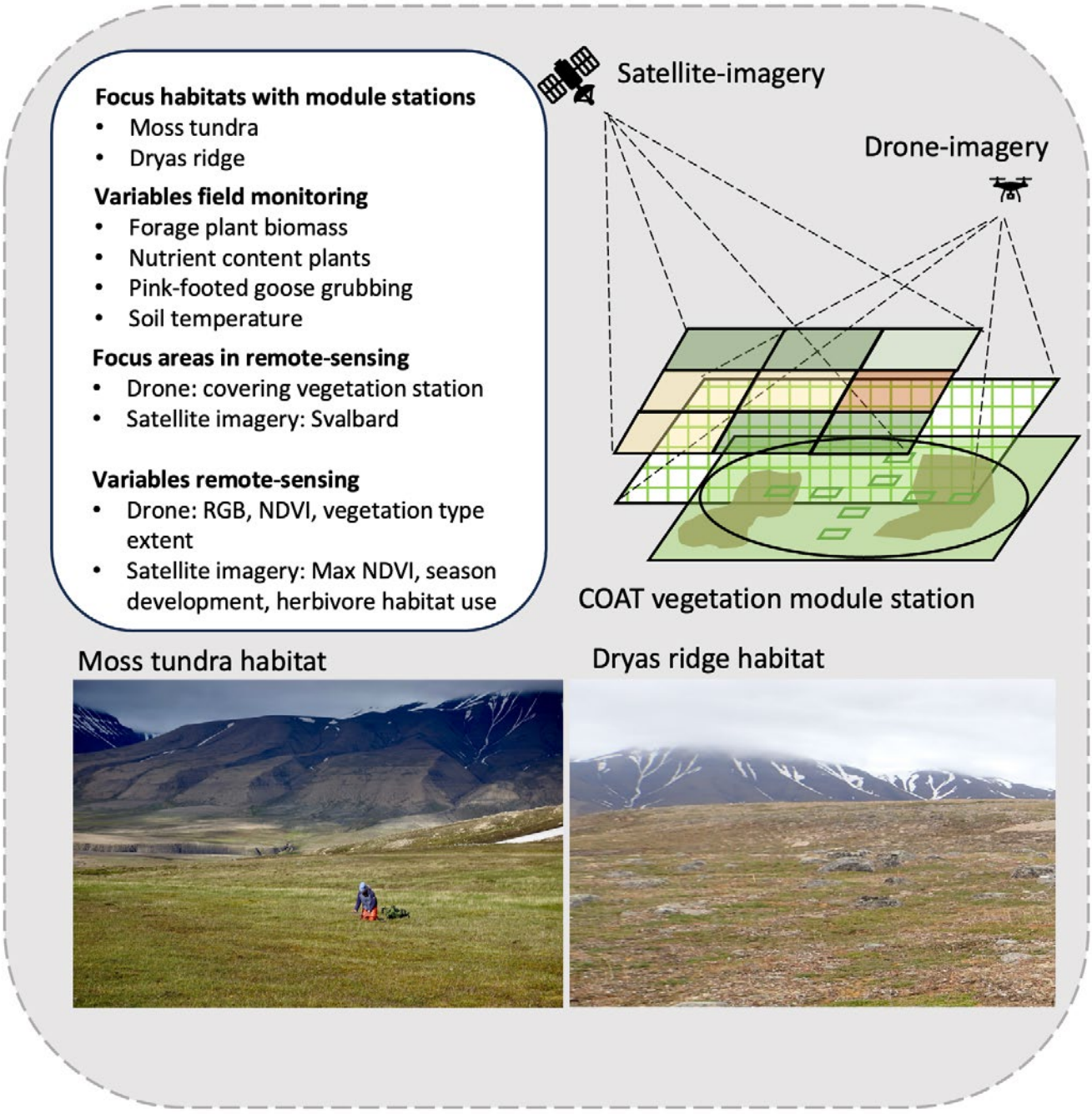

Figure A1: Overview of the study designs, focal habitats and variables collected at the 57 vegetation monitoring module stations in the two COAT regions (see also Figure 1 in chapter text).

that the increased temperatures and precipitation will influence vegetation, combined with an expected strong influence from increasing herbivore populations. The module develops its theoretical background and hypotheses in Ravolainen et al. (2020).

Moss tundra is a focus habitat due to its importance for a broad range of ecosystem functions and services. Moist and wet tundra holds high biodiversity and serves as an important habitat for wildlife. The functional groups of plants in moss tundra are expected to respond quickly to a warmer climate (Ravolainen et al. 2020; van der Wal and Stien 2014). Due to herbivore winter habitats being located on ridges, and to account for a broader range of climate effects (winter ground-ice episodes in particular), a dry, gravelly habitat type is also included, namely *Dryas octopetala* ridges. These habitats form the core of the field monitoring, organized in 57 module stations, where several variables are measured annually (Figure A1). While it was possible to base the module on extensive research and knowledge on plants and vegetation in Svalbard, very few field-based long time-series on plants exist from Svalbard. The Semmeldalen plant biomass time-series started in 1998 (van der Wal and Stien 2014) and is continued in the COAT monitoring. We also combine annual measurements of vegetation with an experiment where herbivores are excluded by means of fences in Adventdalen (n=14, started 2020) and on Brøggerhalvøya (n=18, started 2021) in the same core habitat types.

To capture landscape scale changes and phenological development, we utilise imagery acquired with drones and satellites. Drone flights cover module stations and herbivore exclosures, capturing RGB and multispectral imagery, for calculation of the commonly used Normalized Difference Vegetation Index (NDVI), a measure of "greenness" correlated with plant productivity (Karlsen et al. 2018). NDVI imagery is also acquired from MODIS and Sentinel satellites for larger scale analysis (Figure A2).

The **goose module** covers the two most abundant goose species breeding in Svalbard, the pink-footed goose *Anser brachyrhynchus* and barnacle goose *Branta leucopsis*; however, the focus has been on the pink-footed goose and its food web interactions, with climate and population management as the main drivers. Monitoring is carried out by counting of nests post-hatching to capture hatching success and by automated camera traps, laid out along an elevational gradient, recording timing of snow melt, nest occupancy, phenology of egg-laying and hatching and predation events. Population counts of overall abundance are organised annually under the African-Eurasian Migratory Waterbird Agreement management plan framework (Madsen et al. 2017). Pink-footed geese modify vegetation coverage and composition by their feeding mode, grubbing, which removes plants by the root, and causes vegetation disturbances (Fox et al. 2006; Eischeid et al. 2021). Grubbing is mostly used as foraging mode in mesic and wet moss tundra at the time of snow melt and varies between years depending on the timing of snow melt (Eischeid et al. 2023). Therefore, grubbing occurrence is monitored in the context of this and the vegetation module. Moreover, Arctic fox abundances and reproductive rates at goose colonies are monitored under the Arctic fox module.

The **ptarmigan module** focuses on monitoring of abundance and reproduction of Svalbard rock ptarmigan, with climate and management as the main drivers. In Svalbard, the rock ptarmigan is endemic and the only resident herbivorous bird.

The climate impact path model predicts effects on the ptarmigan population dynamics by variation in the numbers of Arctic fox, reindeer (carcasses) and geese as indirect mediators of climate impacts either through predation (Arctic fox) or inter-specific competition (geese) for selected food plants (Ims et al. 2013). Marolla et al. (2021) parameterised the conceptual ptarmigan model described in Henden et al. (2017), by including both biotic and abiotic drivers expected to impact population dynamics (Figure A2) and exemplified the importance of ecosystem-based monitoring and the application of multi-driver statistical modelling to assess and forecast the state of ptarmigan populations.

The **ungulate module** focuses on monitoring of abundance, demographics, vital rates and key life history traits of the Svalbard reindeer, with climate and management as the main drivers (Hansen et al. 2019b, www.mosj.no/no; Albon et al. 2017). The Svalbard reindeer is endemic to Svalbard and the only large herbivore in the archipelago. Monitoring is carried out by manual field measurements of population abundance, calving rates and mortality (e.g., Hansen et al. 2019), capture–mark–recapture studies (Albon et al. 2017; Veiberg et al. 2017) and automated GPS transmitters tracking space use of individuals in real-time (e.g., Loe et al. 2016; Pedersen et al. 2023). Results of the module show that population development differs between regions depending on the balance of positive effects of summer temperature and negative effects of extreme winter weather, particularly rain-on-snow (Hansen et al. 2019,).The research highlights the importance of having long time-series at different spatial and temporal scales and individual-based data to understand critical life history traits (Albon et al. 2017; Veiberg et al. 2017; Pigeon et al. 2022). A key link of the ungulate module to the climate monitoring network is the network of ground temperature loggers, tailored to reindeer habitat use (see Loe et al. 2016 for an example of application), which contributes a suite of ecologically relevant climate parameters (e.g., onset of seasons, season length and mild winter spells) for understanding climate impacts on the foraging behaviour (Dwinnell et al. 2024) and energetics (Trondrud et al. 2021) of Svalbard reindeer.

The **Arctic fox module** focuses on monitoring of abundance, demographics, vital rates and key life history traits of the Arctic fox, with climate and management as main drivers. Data collection of the module has developed from manual field measurements (Fuglei et al. 2023) to automatic cameras, improving data on occupancy rate of breeding dens and the number of pups produced each year (Fuglei et al. 2003; Eide et al. 2012; Nater et al. 2021). It also includes satellite transmitters to track seasonal habitat use and dispersal (Fuglei and Tarroux 2019). Since changes in Arctic fox population size affect the prevalence of zoonoses in Svalbard, the module also includes automatic camera monitoring, developed in cooperation with COAT Finnmark (Mölle et al. 2022) to capture dispersal of the introduced East European vole *Microtus mystacinus*, and the prevalence of the zoonotic parasite *Echinococcus multilocularis*.

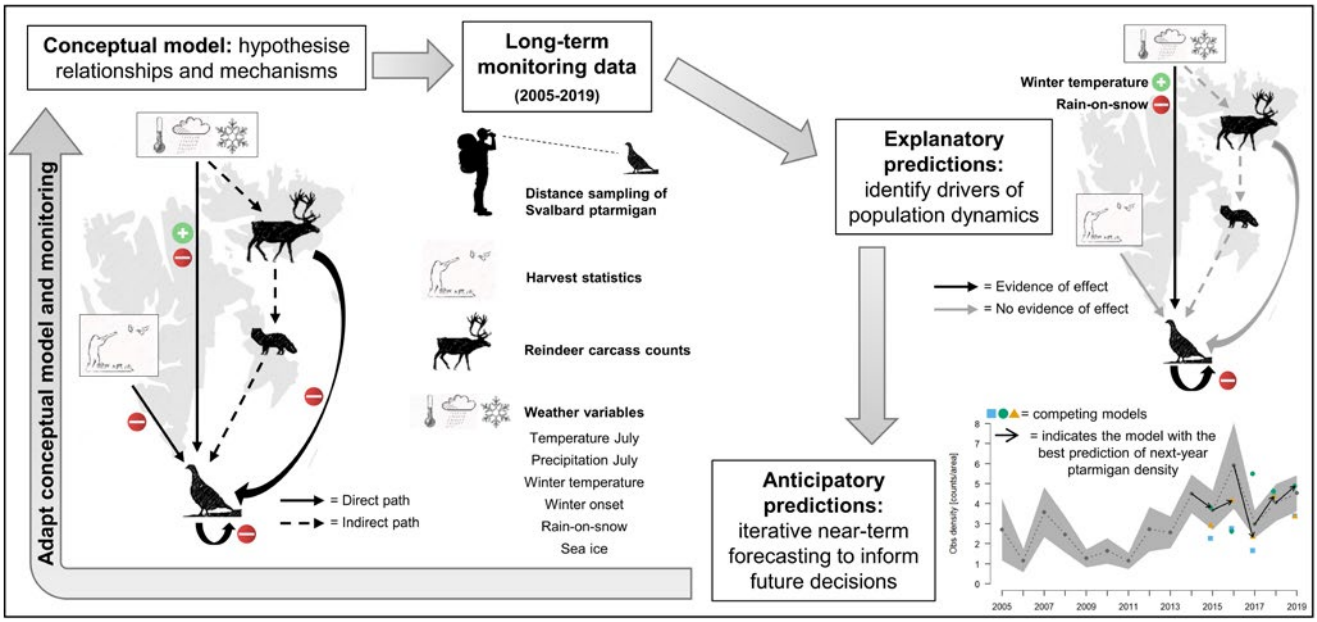

Figure A2: The graphical abstract, from Marolla et al. (2021), shows the parametrisation of the climate impact path model for the Svalbard rock ptarmigan where effects of manageable and non-manageable drivers on population dynamics were estimated. The most influential explanatory predictor on population dynamics was winter temperature. As winters become warmer, ptarmigans appear to benefit, likely because their energy needs for thermoregulation are reduced, which improves body condition and survival, thereby buffering negative impacts from rainy winters and harvest.

References

Albon SD, Irvine RJ, Halvorsen O, Langvatn R, Loe LE, Ropstad E, Veiberg V, Van Der Wal R, Bjørkvoll EM, Duff EI, Hansen BB, Lee AM, Tveraa T, Stien A (2017) Contrasting effects of summer and winter warming on body mass explain population dynamics in a food-limited Arctic herbivore. Global Change Biol 23(4):1374–1389. https://doi.org/10.1111/gcb.13435

Dwinnell SMH, Beumer LT, van der Wal R, Albon SD, Pedersen ÅØ, Holand Ø et al (2024) Get it while it's hot: benefits of a large herbivore exploiting stochastic resource pulses in a time of food scarcity, Ecosphere (in press)

Eide NE, Stien A, Prestrud P, Yoccoz NG, Fuglei E (2012) Reproductive responses to spatial and temporal prey availability in a coastal Arctic fox population. J Anim Ecol 81(3):640–648. https://doi.org/10.1111/j.1365-2656.2011.01936.x

Eischeid I, Madsen J, Ims RA, Nolet BA, Pedersen Å, Schreven KHT, Soininen EM, Yoccoz NG, Ravolainen VT (2023) Snowmelt progression drives habitat selection and vegetation disturbance by an Arctic avian herbivore. Ecosphere 14(12). https://doi.org/10.1002/ecs2.4729

Eischeid I, Soininen EM, Assmann JJ, Ims RA, Madsen J, Pedersen AO, Pirotti F, Yoccoz NG, Ravolainen VT (2021) Disturbance Mapping in Arctic Tundra Improved by a Planning Workflow for Drone Studies: Advancing Tools for Future Ecosystem Monitoring. Remote Sens 13(21). https://doi.org/10.3390/rs13214466

Fox TA, Francis IS, Bergersen E (2006) Diet and habitat use of Svalbard Pink-footed Geese Anser brachyrhynchus during arrival and pre-breeding periods in Adventdalen. Ardea 94(3):691-699. https://www.researchgate.net/publication/289907339_Diet_and_habitat_use_of_Svalbard_Pink-footed_Geese_Anser_brachyrhynchus_during_arrival_and_pre-breeding_periods_in_Adventdalen

Fuglei E, Oritsland NA, Prestrud P (2003) Local variation in arctic fox abundance on Svalbard, Norway. Polar Biol 26 (2):93-98. https://doi.org/10.1007/s00300-002-0458-8

Fuglei E, Tarroux A (2019) Arctic fox dispersal from Svalbard to Canada: one female's long run across sea ice. Polar Res 38. https://doi.org/10.33265/polar.v38.3512

Hansen BB, Pedersen O, Peeters B, Le Moullec M, Albon SD, Herfindal I, Sæther BE, Grotan V, Aanes R (2019) Spatial heterogeneity in climate change effects decouples the long-term dynamics of wild reindeer populations in the high Arctic. Global Change Biol 25(11):3656–3668. https://doi.org/10.1111/gcb.14761

Henden JA, Ims RA, Fuglei E, Pedersen AO (2017) Changed Arctic-alpine food web interactions under rapid climate warming: implication for ptarmigan research. Wildl Biol. doi:10.2981/wlb.00240 Wildl Biol 2017(SP1). https://doi.org/10.2981/wlb.00240

Ims RA, Jepsen JU, Stien A, Yoccoz NG (2013) Science Plan for COAT: Climate-ecological Observatory for Arctic Tundra. Fram Centre Report Series No. 1. Fram Centre, Tromsø. https://www.coat.no/portals/coat/SciencePlanCOAT_web.pdf

Karlsen SR, Anderson HB, van der Wal R, Hansen BB (2018) A new NDVI measure that overcomes data sparsity in cloud-covered regions predicts annual variation in ground-based estimates of high arctic plant productivity. Environ Res Letters 13(2):12. https://doi.org/10.1088/1748-9326/aa9f75

Loe LE, Hansen BB, Stien A, Albon SD, Bischof R, Carlsson A, Irvine RJ, Meland M, Rivrud IM, Ropstad E, Veiberg V, Mysterud A (2016) Behavioral buffering of extreme weather events in a high-Arctic herbivore. Ecosphere 7 (6). https://doi.org/10.1002/ecs2.1374

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

MOSJ (2024) MOSJ Miljøovervåking Svalbard og Jan Mayen. http://www.mosj.no/no/

Mölle JP, Kleiven EF, Ims RA, Soininen EM (2022) Using subnivean camera traps to study Arctic small mammal community dynamics during winter. Arct Sci 8(1):183–199. https://doi.org/10.1139/as-2021-0006

Nater CR, Eide NE, Pedersen AO, Yoccoz NG, Fuglei E (2021) Contributions from terrestrial and marine resources stabilize predator populations in a rapidly changing climate. Ecosphere 12(6). https://doi.org/10.1002/ecs2.3546

Pedersen AO, Soininen EM, Hansen BB, Le Moullec M, Loe LE, Paulsen IMG, Eischeid I, Karlsen SR, Ropstad E, Stien A, Tarroux A, Tommervik H, Ravolainen V (2023) High seasonal overlap in habitat suitability in a non-migratory High Arctic ungulate. Glob Ecol Conserv 45. https://doi.org/10.1016/j.gecco.2023.e02528

Pigeon G, Albon S, Loe LE, Bischof R, Bonenfant C, Forchhammer M, Irvine RJ, Ropstad E, Veiberg V, Stien A (2022) Context-dependent fitness costs of reproduction despite stable body mass costs in an Arctic herbivore. J Ani Ecol 91(1):61–73. https://doi.org/10.1111/1365-2656.13593

Ravolainen V, Soininen EM, Jonsdottir IS, Eischeid I, Forchhammer M, van der Wal R, Pedersen AO (2020) High Arctic ecosystem states: Conceptual models of vegetation change to guide long-term monitoring and research. Ambio 49(3):666–677. https://doi.org/10.1007/s13280-019-01310-x

Trondrud LM, Pigeon G, Król E, Albon S, Evans AL, Arnold W et al (2021). Fat storage influences fasting endurance more than body size in an ungulate. Functional Ecology 35(7):1470–1480. https://doi.org/10.1111/1365-2435.13816

van der Wal R, Stien A (2014) High arctic plants like it hot: a long term investigation of between-year variability in plant biomass across habitats and species. Ecology 95(12):3414–3427. https://doi.org/10.1890/14-0533.1

Veiberg V, Loe LE, Albon SD, Irvine RJ, Tveraa T, Ropstad E, Stien A (2017) Maternal winter body mass and not spring phenology determine annual calf production in an Arctic herbivore. Oikos 126(7):980–987. https://doi.org/10.1111/oik.03815

Understanding and analysing recurrent warm events in Svalbard: a comprehensive review on land cryosphere (AWARE)

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1. Introduction

Over the past decades, the Svalbard climate has experienced a significant transformation associated with Arctic Amplification (Spolaor et al. 2024). The overall rise in regional temperatures has increased the frequency of extreme events marked by persistent warm and moist air masses during summer and, more recently, also during winter (Dahlke and Maturilli 2017; Sobota et al. 2020). Such events are known as "warm spells" or "heatwaves". In winter, they can bring prolonged periods of exceptionally high temperatures, often accompanied by "rain-on-snow" (RoS) events (Wickström et al. 2020). From a meteorological point of view, while warm spells refer to a persistent period of abnormally warm weather at any time during the year, heatwaves are defined in relation to the highest values observed during the year, and in most climates their occurrence is more likely during the warm season.

These events pose numerous challenges to the fragile Svalbard ecosystem and its inhabitants, affecting environmental, ecological, and socioeconomic aspects (Zdanowicz et al. 2023). Sporadic, unpredictable extreme events impact both coastal and inland areas of the Svalbard archipelago (Vickers et al. 2022); they influence the cryosphere and snow-free terrestrial ecosystems by altering the snow-albedo feedback, accelerating the hydrological cycle (Salzano et al. 2023), and increase heat transfer to the permafrost. Assessment of the effects of heatwaves and warm spells throughout the snow's accumulation and melting periods is essential in order to understand their impact on Svalbard's environment. AWARE highlights the key role of multidisciplinary and integrated observation infrastructures and of assessing the impact of extreme events on the terrestrial cryosphere (Christiansen et al. 2024).

2. Overview of existing knowledge

Due to its location in the North Atlantic Ocean, the Svalbard archipelago experiences heatwaves and warm spells which are frequently associated with extraordinary liquid precipitation in winter, i.e., the so-called RoS events (Rennert et al. 2009). In addition, the meridional temperature gradient between the Arctic and the mid-latitudes is gradually evening out, affecting the jet stream structure (Francis and Vavrus 2015). Therefore, cold air reaches lower latitudes, and warm air reaches higher latitudes (Rennert et al. 2009). In this context, elongated masses of humid air travel over the North Atlantic Ocean, making this region one of those most sensitive to intrusions of warmer air masses from mid-latitudes (Isaksen et al. 2016, 2022; Woods and Caballero 2016; Dahlke and Maturilli 2017). Winter heatwaves are characterised by the Eurasian–North American temperature dipole, with higher-than-normal temperatures in the Eurasian Arctic associated with higher index values for the Arctic Oscillation and the North Atlantic Oscillation (Wegmann et al. 2020), which constitute the most dominant atmospheric patterns in the North Atlantic realm. However, due to their major zonal atmospheric flow structure, their impact on Svalbard is debated and has been reported as being only marginal (Winther 2002). On the other hand, meteorological and climatological parameters in Svalbard are strongly influenced by circulation patterns with a meridional flow structure, featuring enhanced southerlies from mid-latitudes towards Svalbard. Such patterns include Scandinavian Blocking, the Arctic Dipole pattern, or the Barents Oscillation. Such atmospheric configurations allow anomalous geostrophic flow from the south towards Svalbard, which often features the advection of anomalously warm and moist air (Dahlke and Maturilli 2017), clouds (Yeo et al. 2018), or even atmospheric rivers (long, narrow streams of air with enhanced water vapour content often associated with extreme weather (Lauer et al. 2023)).

While there is a growing understanding of heatwaves and warm spells in Svalbard and their consequences, significant uncertainties and research gaps remain, particularly in regard to the long-term ecological, environmental and socioeconomic impacts. Knowledge about warm events in Svalbard has expanded significantly in recent years. Scientific research and monitoring programmes (Maturilli et al. 2013; Peeters et al. 2019; Scoto et al. 2023) are crucial for understanding and studying the effect of heatwaves and warm spells in the archipelago, and satellite remote sensing (Vickers et al. 2022), ground-based observations (Peeters et al. 2019; Nowak et al. 2021), and data re-analysis (Rinke et al. 2017), are the essential tools used to observe past, present and future temperature anomalies, precipitation patterns, and changes in ice and snow cover. The occurrence and frequency of these extreme events have been suggested to have increased in the last decade, partly due to reduced sea ice extent (Lapointe et al. 2024) that enhances water evaporation, exerting an impact on atmospheric circulation and leading to more frequent and intense heatwaves and warm spells in Svalbard. Additionally, extreme weather in the Arctic is often related to the occurrence of extreme patterns in atmospheric circulation, such as extreme cyclones. However, analyses of long-term trends in extreme cyclones in the Svalbard region show an unclear scenario, with strong regional differences (Boisvert et al. 2016; Rinke et al. 2017). Several studies document that these events associated with rainfall have negative effects of on herbivores, soil invertebrates, vegetation growth, and on reproduction in some species (Descamps et al. 2017). These events can trigger physiological activity in typically dormant organisms, such as lichens, which are activated even during dark polar winters due to increased heat and water transfer to the snow–ground interface (Keuschnig et al. 2023). Conversely, some ecological components like mosses, which thrive under deep snow cover, become more exposed to cold spells with a thinner, less insulating snowpack. The primary impact of warm events on snow cover is the formation of internal and basal ice layers (in case of the simultaneous occurrence of liquid precipitation), which have serious consequences for reindeer (Serreze et al. 2021), the tourism industry, and local Arctic communities (Forbes et al. 2016). Winter extreme events and RoS disrupt the snow season, affecting snow accumulation, moistening, and ripening processes, as well as triggering water runoff through the snowpack (Sobota et al. 2020; Salzano et al. 2023; Scoto et al. 2023). The presence of water implies state transformations and heat transfer processes at the snow–ground interface, leading to soil warming and potentially to early permafrost thawing. Identifying RoS events is straightforward, although a clear and accepted definition is still missing, but assessing their repercussions on the environment, economy, and local populations requires further investigation and a broad approach that integrates and analysis datasets from multiple disciplines.

2.1. Enhancing the definition of heatwaves and warm spells for the Svalbard region

Researchers need to agree on the definition of a specific climate phenomenon, and align the methods used to explore it in historical datasets. According to the World Meteorological Organization, a heatwave is defined in relation to the highest temperature normally observed during the year and therefore is most likely to occur during the warm season in most climates. Thus, a heatwave can be described as a period of unusually hot weather compared to the 30-day average of the study location, that persists for at least two consecutive days, and that poses a potential threat for the local population. Similarly, a warm spell refers to a period of unseasonably warm weather, typically occurring during the cooler seasons: autumn, winter, or early spring. Warm spells can last for a few days or even longer, and are often caused by unusual atmospheric conditions, such as a high-pressure system trapping warm air over a region. The above definitions have a stronger connection to mid-latitude regions, and for the Arctic as well as for Svalbard, they need to be adjusted. Therefore, in the present work, we propose a set of key definitions, which will be essential for standardising available datasets as well as detecting the occurrence of climate phenomena in the Svalbard archipelago and

assessing how these phenomena have evolved over the past few decades. This terrestrial cryosphere approach targets the impacts of warm events during the snow season, emphasising their role in triggering intense snow melt and their associated environmental consequences rather than focusing on the meteorological intensity of each single event. According to the methodology of Dobricic et al. (2020), the following metrics are defined to facilitate the identification of potential changes in the frequency and intensity of these events:

Cryosphere Warm Spell (CWS): A Svalbard cryosphere warm spell refers to a persistent period of at least 5 days of abnormally warm weather for the time of year, during which the daily average temperature exceeds the 90th percentile threshold of climatological daily average temperatures. This is centred on a 31-day window and based on the decade before the year being investigated.

Cryosphere Heatwave (CHW): A Svalbard cryosphere heatwave refers to a persistent period of at least 2 days (but no more than 4 days) of abnormally warm weather for the time of year, during which the daily average temperature exceeds the 90th percentile threshold of climatological daily average temperatures. This is also centred on a 31-day window and based on the decade before the year being investigated.

Rain-on-Snow events (RoS): RoS events occur when rain falls and freezes onto an area with uninterrupted snowpack, forming an ice crust. Precipitation is considered as rain when the air temperature is equal to or above 1°C (based on Jennings et al. 2018).

Seasonal accumulated Rain (SR): Daily averaged integrated liquid precipitation (defined as the total amount of precipitation at temperatures above 1°C) during the snow season (as defined below).

Days Above Zero (DAZ): The number of days during the snow season when the mean air temperature is above 0°C.

Positive Degree Days (PDD): The sum of the number of degrees by which daily average temperatures exceeded 0°C over a given time period or during the snow season.

Regarding the AWARE SESS report and the determination of temporal changes in the occurrence of CHW and CWS, we define the snow season as extending from 1st October to 31st May of the following year (e.g., 1 Oct 2020 – 31 May 2021). CHW and CWS will be evaluated based on data collected between 1995 and 2023, a period for which time series of meteorological observations from Ny-Ålesund and Hornsund Research Stations are available.

2.2. Frequency of RoS, CHW and CWS in Ny-Ålesund and Hornsund

At least two different data sources can be considered to detect CHW and CWS during each snow season of the investigated period. Meteorological observations are provided by research stations at the selected sites, and datasets are accessible through public web portals such as SEKLIMA or additional data repository like PANGAEA. We considered stations operating since the 1980s in Spitsbergen featuring air temperature and precipitation at least at daily resolution. The available stations on SEKLIMA are Hornsund (SN99754), Ny-Ålesund (SN99910), Isfjord Radio (SN99790) and Svalbard Lufthavn (SN99840). While all these sites had robust scientific observations, snow research activities were limited at Isfjord Radio and Svalbard Lufthavn, and they will be not considered for this review chapter. Additional stations are outside Spitsbergen, located at Hopen (SN99720) and Kongsøya (SN99740). The second data source is based on atmospheric re-analysis, where observations and satellite data are assimilated into a modelled spatial grid (e.g., CARRA, ERA5). For Ny-Ålesund, we considered time series on precipitation and air temperature, supported by MET Norway1 2Our analysis focused on above-zero conditions, potentially leading to rain precipitation. The meteorological data analysis

1 https://seklima.met.no/
2 https://doi.org/10.1594/PANGAEA.914979

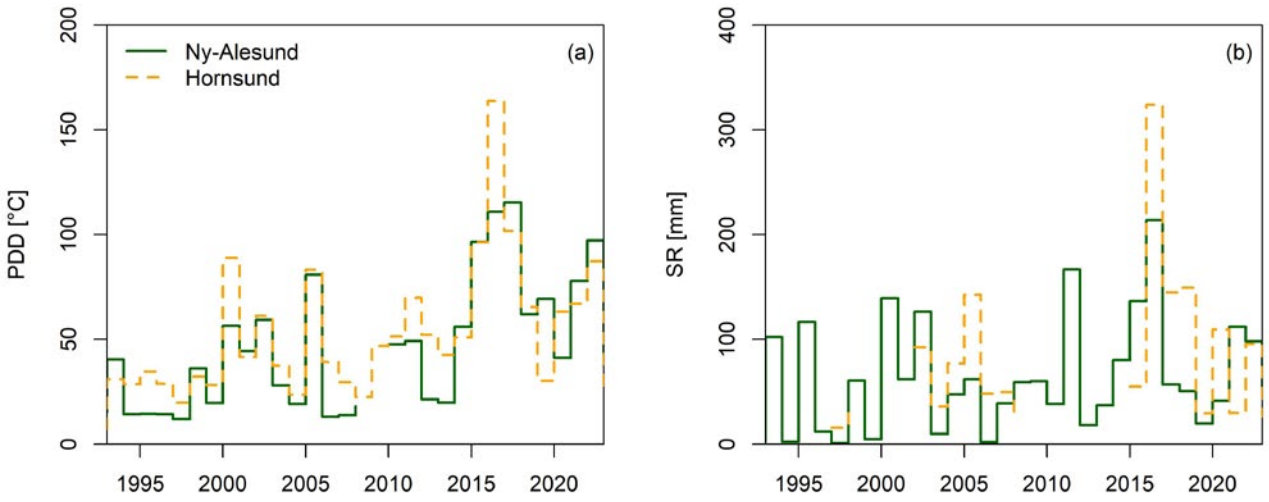

Figure 1: PDD (positive degree day) and SR (Seasonal accumulated Rain) during the snow season for Ny-Ålesund (solid green line) and Hornsund (dashed yellow line) from 1995 to 2023.

showed an increase in above-zero days during the snow season from about 20 days in the 1980s to more than 30 days in the 2020s (Figure 1).

Accordingly, the amount of heat estimated through the Positive Degree Day (PDD) metric also increased, from around 30°C in the 1980s to more than 60°C between 2010 and 2023. Although the number of both CWS and CHW warm events remained relatively stable (between 5 and 10 per year), additional metrics indicated a rise in the duration of these events as well as in the occurrence of rain precipitation: the average PDD per event was around 3°C in the 1980s, but rose to almost 9°C in the last decade, with the duration of individual events almost doubling from 2 days to approximately 4 days. Another noticeable trend is the increase in humidity during these events. This clearly indicates a growing frequency of moist and warm air masses reaching the Arctic site. The same analysis was conducted in Hornsund, using data from IG PAS, which are also available through SEKLIMA and PANGAEA. The number of days above zero (DAZ) during the snow season doubled from 22 days in the 1980s to more than 40 days in the 2020s, increasing the amount of heat estimated through the Positive Degree Day (PDD) metric, which rose from approximately 30°C in the 1980s to over 70°C during the snow season in the last decade. Observations corroborate the trends observed at Ny-Ålesund, though Hornsund showed only a slightly higher recent PDD compared to the past (from 3°C per event in the 1980s to 4.7°C in recent years) and less pronounced increases in the duration of single events (from 2.7 days to 3.1 days). Additionally, the proportion of precipitation that fell as rain at Hornsund increased more than it did in Ny-Ålesund: while Hornsund received about 30% as rain in the 1980s and over 46% more recently; Ny-Ålesund received about 18% as rain in the 1980s and 22% in recent years. Looking at CHW, CWS and RoS events, we reviewed the SEKLIMA datasets in order to gain homogeneous data sources and workflow from 1993 to 2023 (Figure 2). CHW and CWS were computed considering a 30-year reference climatology (1993–2023) both for Hornsund and Ny-Ålesund. The southernmost site highlighted a decadal trend. In 1993–2003, there was about one CHW per season and RoS occurred for about 6 days per season. For the last ten years (2013–2023), the same site showed a lower occurrence of short duration events (CHW) (fewer than 4 events in all), with an increase of more persistent conditions (CWS) and warmer air masses (more than 4 events). There was also evidence of an increased occurrence of moist air masses, with more than 20 days with RoS in the last decade. In northwestern Svalbard, Ny-Ålesund showed a slightly different pattern, with usually less than 4 CHW per season: in fact, between 1993 and 2003, there was often one CWS per season, and RoS occurred on average less than 10 days per season in the whole 30-year period 1993–2023. Over the last ten years (2013–2023), short-duration events (CHW) and persistent conditions (CWS) increased to slightly more than 10 events per season, with

RoS events significantly increased to more than 15 days per season.

The results shown in this SESS report are based on a safe approach using a fixed 30-year climatology (reference window), but this approach might prove not to be the most apt to identify these types of events, since phenomena that were generally considered unusual 30 years ago may be common at the present time. Future analysis will need to consider different approaches, using reference windows and both fixed and moving statistics, thus raising an additional discussion on how to define statistical thresholds for detecting extreme events. Recent warming has notably impacted the 90th percentile threshold used to define these events, especially during winter, when temperatures have increased by up to 4°C. Further analyses are planned to develop investigations specific to the cryosphere.

2.3. Assessing the spatial occurrence of Rain-on-Snow using data re-analysis

One of the primary advantages of re-analysis products is their ability to expand spatial coverage beyond data retrieved solely from automatic weather stations typically associated with research stations. We tested the feasibility of using this type of analysis on above-zero metrics from the Ny-Ålesund site, comparing AWI observations with CARRA outputs, focusing on DAZ and PDD. Comparison of the re-analyses performed with CARRA, and the in-situ data shows significant agreement (Figure 3), laying the groundwork for using re-analysis products to extend the evaluation of CHW, CWS, and RoS across the entire archipelago. Although the scarcity of in-situ data for verification of CARRA results introduces uncertainty, we chose to extrapolate to broader regions. This approach might allow us to assess the extent of the archipelago affected by RoS events and even to produce statistics on their occurrence over longer periods (seasons, years, or decades). These tools would greatly aid in understanding which areas of the archipelago are more susceptible to RoS occurrences. However, re-analysis products are not limited to detecting RoS events but might also be used to evaluate the spatial and temporal evolution of several meteorological parameters and events, such as CHW or CWS. Nevertheless, a common and shared definition, along with a standardised statistical approach, needs to be prepared to unify results derived from both in-situ observations and re-analysis products.

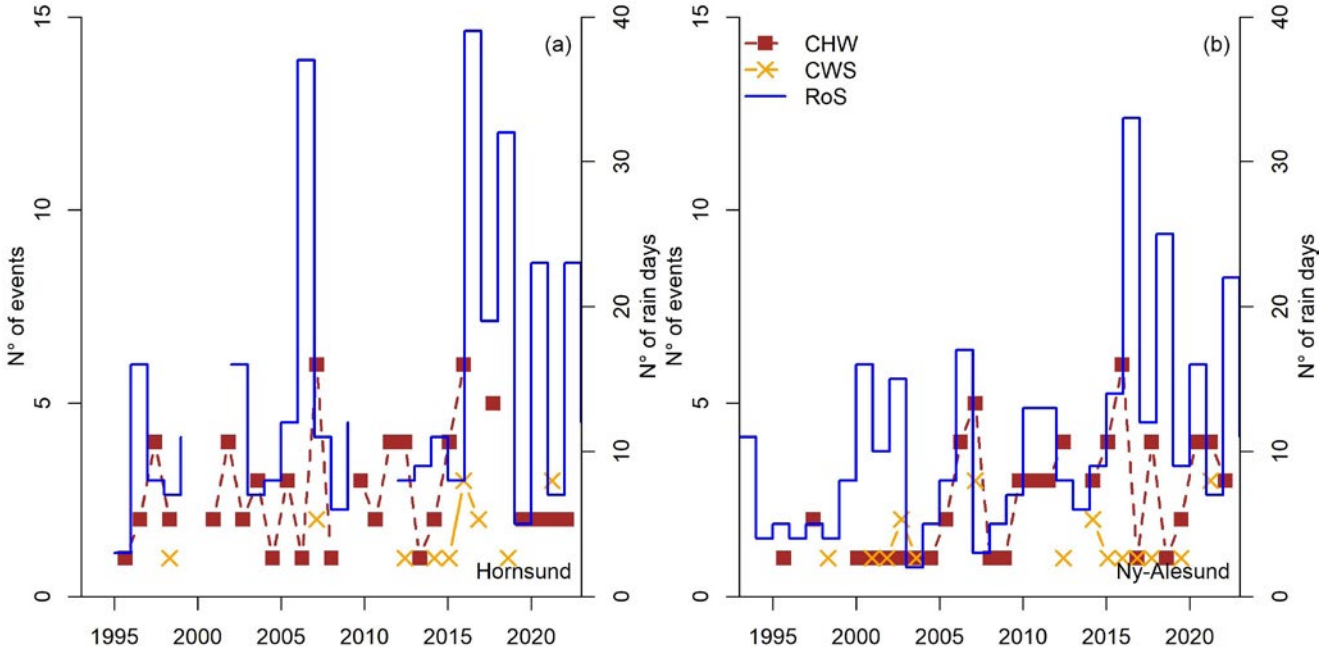

Figure 2: Year CHW (dashed red line), CWS (dashed yellow line) and RoS (Rain-on-snow, blue line) events during the snow season for Hornsund (panel a) and Ny-Ålesund (panel b) from 1995 to 2023.

2.4. Assessing the impact of extreme events using Remote Sensing

Snow cover monitoring in Svalbard is a major challenge, although several technologies support the remote sensing of cryospheric components. An overview of the available monitoring opportunities is given by Zdanowicz et al. (2023) and specific SESS chapters have reviewed different aspects of those techniques (Salzano et al. 2021b; Karlsen et al. 2021). The snow-covered area (SCA) represents the primary feature influenced by extreme events and can be assessed through several products on platforms such as Suomi NPP, POES, Terra/Aqua, Landsat and Sentinel. The seasonality of the snow cover can be approached by integrating sensors with different spatial (from 10 to 500 metres and more) and temporal (daily or weekly) resolutions, but ground-based and airborne remote sensing are key data sources for the identification of critical thresholds related to process triggering. For data on the snow water equivalent (SWE), which is key information for assessing RoS events, various passive microwave sensors have been available since the 1980s. Unfortunately, applications in Svalbard are limited due to the gaps in spatial resolution and to problems related to satellite data processing. L-band SAR technologies will become more available with upcoming missions, such as NISAR (NASA) and ROSE-L (ESA), and their products are bound to offer intriguing opportunities. Although snow depth or height (HS) might constitute a major essential variable, the use of satellite data still presents some difficulties, although attempts have been made to measure HS at a global scale using the ratio between co- and cross-polarization backscatter from Sentinel-1 observations (Lievens et al. 2019). Airborne LiDAR can be a successful tool aimed at obtaining high-resolution snow depth measurements. Nonetheless, limiting issues are to be taken into consideration due to the overflights being infrequent. As for liquid water content (LWC), the identification of wet snow is a valuable parameter for assessing the impact of extreme events in Svalbard: in fact, historical datasets based on scatterometer data were used to detect wet snow on Svalbard using Quikscat at a coarse resolution (2.5 km) (Rotschky

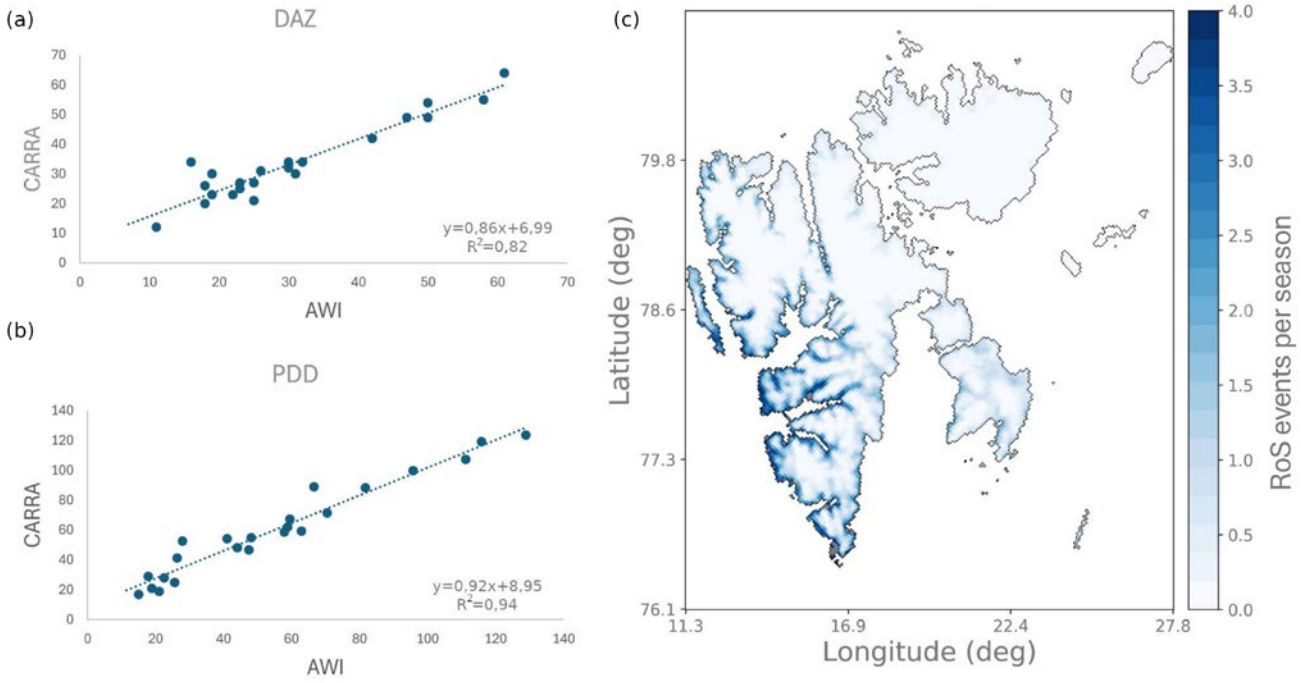

Figure 3: Comparison between the metrics DAZ (days above zero, panel a) and PDD or SPD (Positive degree days or Sum positive degrees, panel b) obtained by using in-situ observations and re-analysis outputs in Ny-Ålesund. Panel c shows the number of RoS events using a threshold at T=1°C for the period 1 November–30 April, averaged for 2000–2020 (adapted from Vickers et al. 2022).

et al. 2011), but Sentinel-1 C-band SAR is also an option in order to map wet snow with a ~100 m resolution (Vickers et al. 2024). Lastly, Sentinel-1 data can be used assess snow avalanche activity in Svalbard thanks to the availability of different mode data providing different specifications for this task. For example, the Sentinel-1 EW mode features a resolution that is considered as too low to detect small to medium-sized snow avalanches (Wesselink et al. 2017), whereas the Sentinel-1 IW mode features sufficient spatial resolution but presents some limitations in terms of overpass timing. Hyperspectral sensors are becoming state-of-the-art tools available in spaceborne (PRISMA, EnMAP) or airborne (SIOS' airborne facility) platforms and their data represent a key asset for monitoring the occurrence of different types of snow cover. In view of this, data collection in the future may offer intriguing new possibilities thanks to novel instruments and next-generation platforms. The next generation of Sentinel-1 satellites will likely feature an improved spatio-temporal resolution, implying improved capabilities for the specific tasks. On a larger scale, the wide range of different data sources will significantly contribute to finally solve the multi-scale gap between satellite observations and in-situ measurements.

2.5. Potential consequences of CHW and CWS on glacier mass balance

Warm spells and Arctic heatwaves significantly impact glacier mass balance in the Svalbard region (Łupikasza et al. 2019). These warm periods lead to temperatures rising above average for extended durations, causing direct winter melting of glacier surfaces, particularly in the lower parts of the glaciers. During these warm spells, precipitation that would normally fall as snow may instead come as rain, which reduces the snow accumulation crucial for maintaining glacier mass. Snow contributes to glacier mass by adding layers of ice over time. When rain falls on snow, especially during RoS events, it can freeze and form an ice crust. This crust reduces the insulating properties of the snow, leading to more melting beneath the surface.

As the annual snowpack melts, it often exposes darker surfaces, such as meltwater pools, debris, and particles, which absorb more sunlight. This can accelerate the melting process during the melting season, from late spring through summer. The meltwater generated during these warm periods also increases surface runoff, contributing to further glacier mass loss. This meltwater can lubricate the glacier's base, particularly in temperate glaciers, potentially speeding up glacier movement and leading to calving of icebergs from glaciers that reach the sea, also during the cold season.

These warm periods can also disrupt the usual seasonal cycles of snow accumulation and melting, pushing the equilibrium line—the point where the glacier gains and loses mass equally—higher. This shift results in a larger glacier area being in the melting zone. The CHW and CWS are usually associated with intense precipitation leading to an imbalance between the higher snow accumulation in the upper portions of the glaciers and less accumulation in the lower parts. If this disproportion persists for extended periods—years to decades—it could eventually modify glacier dynamics and increase its flow speed. In addition, the precipitation associated with warm spells and heatwaves, even if it falls as snow in the upper parts of glaciers, typically occurs at relatively warm temperatures. For example, in 2023, a warm spell from April 6th to April 17th caused intense melting on the western Svalbard coast but resulted in heavy snowfall at the summit of the Holtedalfonna glacier (1100 m a.s.l.). However, the precipitation occurred at temperatures between -3 and -5°C, forming a relatively warm snowpack on the glacier surface with potential impacts on the glacier's thermal properties. Finally, the effects of winter RoS events extend beyond the glaciers themselves. Intense RoS events can cause an influx of fresh meltwater into coastal and marine ecosystems during winter or early spring, potentially altering these environments and affecting marine life and local ecosystems and might hasten the algae bloom in the coastal region.

2.6. Potential consequences of CHW and CWS on snow cover dynamics and the hydrological system

The dynamics of snow cover are significantly influenced by warm spells and heatwaves, largely due to the higher likelihood of RoS events during these times (Gallet et al. 2018; Salzano et al. 2021a). Temperature spikes can alter the internal thermal gradient of the snowpack, changing its physical structure and ultimately also the load of chemical species contained (Scoto et al. 2023). This results in processes like preferential metamorphism, surface melting, and the formation of internal ice layers, usually near the surface, along with a general densification of the snowpack. When RoS events coincide with CWS, their impact is even more pronounced. The snowpack may undergo extensive melting and compaction, warming throughout its depth and becoming isothermal at the melting point (Scoto et al. 2023). When atmospheric temperatures drop after the warming event, the presence of meltwater and/or rainwater can lead to the formation of ice crusts on the snowpack's surface but also of internal ice layers and basal ice. The latter can significantly impact on the local fauna since it seals the ground, limiting access to vegetation beneath the snowpack. Typically, the hydrological system in winter is slowed or inactive due to cold temperatures, but a rise in temperature along with snowmelt and liquid precipitation can reactivate it, particularly in coastal areas (Figure 4). This winter reactivation of the hydrological system has implications for coastal environments, altering the microbiological communities within the snowpack and causing an early release of nutrients and contaminants trapped in the snow. Furthermore, the winter melting can lead to increased permafrost thawing, and although some recent findings suggest only a moderate effect (Magnússon et al. 2024), winter melting may cause increased thawing of permafrost, which can destabilise the ground, leading to landslides and erosion.

Dust and carbonaceous particles, such as black carbon, which are hydrophobic, tend to remain suspended on the surface of the snowpack, decreasing its overall albedo. A lower albedo means that more solar energy is absorbed, leading to further warming, and accelerating the melting process. This feedback loop can intensify the effects of warm spells and heatwaves on snow cover (Bertò et al. 2021). Finally, the formation of internal ice layers within the snowpack (that can contribute to the formation of weak layers in the snowpack if the necessary meteorological conditions follow, e.g., prolonged spells of cold weather with a shallow snowpack), and accelerated melting within the snowpack can make the snow structure unstable. This increases the risk of avalanches, which poses a danger to human life, infrastructure, and wildlife, especially in mountainous regions.

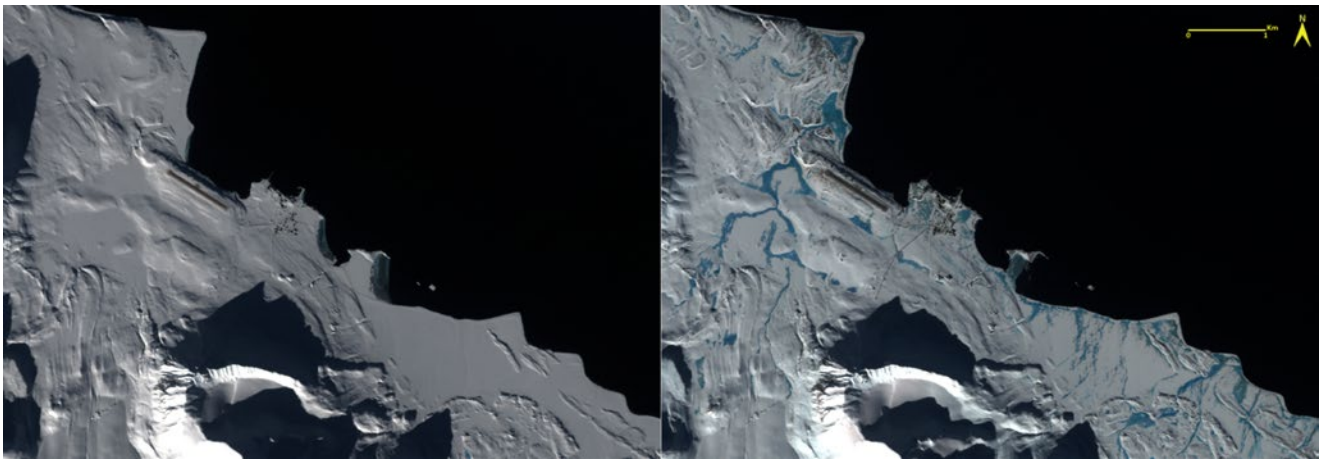

Figure 4: Surface hydrological features observed by Sentinel 2 (a) before and (b) after the RoS event that occurred on 28 April 2024.

In the Kaffiøyra region of NW Spitsbergen, research focused on a detailed analysis of RoS events during the winter season (November–April), specifically on Waldemarbreen and Irenebreen glaciers. The intensity and frequency of RoS events were evaluated, along with their long-term variability from 1976 to 2018. The study identified a relationship between RoS events and the properties of the snow cover on these glaciers, particularly changes in the number and thickness of ice layers and snow density, which significantly influence the winter snowpack and the timing of snowmelt.

This research represents some of the first studies of this type in glacier forefields, exploring changes occurring on glaciers. It also found that the frequency and intensity of RoS events have increased in recent years. The number of days with heavy RoS events—mainly over 15 mm of rainfall, but also under 15 mm—has risen. RoS events affect the formation of ice layers, with heavy RoS events contributing to the development of thicker ice layers. Additionally, the increase in RoS events is associated with a decrease in snow density on glaciers (Sobota et al. 2020).

2.7. Potential consequences of CHW and CWS on the microbial community in snow

Microbial communities, which include bacteria, viruses, fungi, and other microorganisms, play a crucial role in the biogeochemical cycles of polar ecosystems. The relative warmer temperatures associated with heatwaves can lead to melting snow, which alters the physical structure of the snowpack. As the snow melts, liquid water becomes more prevalent within the snowpack, creating conditions that are more conducive to microbial activity (Keuschnig et al. 2023). The presence of liquid water can increase the metabolic rates of microbes, leading to enhanced microbial growth and reproduction. This can cause shifts in the composition and abundance of microbial communities, potentially favouring those species that are more adapted to warmer and wetter conditions (Malard et al. 2021). Additionally, the melting snow can make available nutrients that were previously trapped within the snow grains. These nutrients, such as nitrogen and phosphorus, can provide an additional food source for the microbes, further stimulating their growth. However, the increased availability of nutrients can also lead to the proliferation of specific microbial species, potentially reducing biodiversity and altering the overall balance of the microbial ecosystem. The ice layers formed because of RoS events can create physical barriers within the snow, restricting the movement of microbes and the diffusion of gases and nutrients and reduce the oxygen availability within the snow, leading to anaerobic conditions that favour certain types of microbes, such as those that produce methane. Moreover, the increase in temperature can also disrupt the dormancy patterns of some microorganisms. Many microbes in the Arctic are adapted to survive in a dormant state during the long, cold winter months. However, warm spells can prematurely wake these microbes from dormancy, potentially leading to a mismatch between microbial activity and the availability of nutrients and other resources. This could have downstream effects on the timing and magnitude of microbial processes, such as the decomposition of organic matter. Moreover, the consecutive refreezing at the end of the RoS can also influence the microbiological community by altering water availability and the distribution of nutrients, affecting microbial growth and metabolism as well. Freezing and thawing can also directly increase the mortality of certain species, potentially leading to shifts in diversity and richness, with the selection of more resistant organisms. This has the potential to impact biodiversity and community resilience. The impacts of heatwaves and warm spells on the snow microbiome affect the interactions between microbes and other organisms, such as snow algae and higher trophic levels, potentially altering the entire food web.

2.8. Potential impact of CHW and CWS on the fate of pollutants and impurities in atmosphere and snow

In Svalbard, the occurrence of CHW and CWS events is characterised by specific atmospheric

configurations that promote long-range transport from mid-latitudes into the higher latitudes. As described previously, rapid air mass movements from mid-latitudes to the high north can carry compounds, contaminants, and impurities into the Arctic, increasing their presence in the region. Warm spells and heatwaves could thus have a dual effect on the fate and behaviour of pollutants: they promote long-range transport from mid-latitudes while simultaneously facilitating the release of pollutants from the snowpack into the hydrological system and surrounding environment, including permafrost and coastal ocean waters. These periods of elevated temperature can alter the distribution, concentration, and chemical behaviour of contaminants, impacting their environmental and health effects. In the atmosphere, warm events can increase the volatility of certain pollutants, such as volatile organic compounds, mercury, and persistent organic pollutants. These substances can more readily evaporate and disperse into the air when temperatures rise, leading to their redistribution over large areas. Elevated temperatures can also accelerate photochemical reactions, resulting in the formation of secondary pollutants like ozone and fine particulate matter (PM2.5), which can affect air quality. In the snowpack, CHW and CWS and the likely associated RoS events can lead to melting and early percolation of pollutants trapped in the snow. As the snow melts, contaminants like black carbon, dust, and other impurities that were previously bound within the snowpack can be released or resuspended into the snow surface. Meltwater resulting from the RoS events can carry these pollutants into nearby water bodies where, if a cold spell ensues, they can be trapped again in this terrestrial aquatic environment. This can have ecological consequences, causing an early introduction of harmful substances into aquatic ecosystems, affecting the health of organisms, and potentially entering the food chain. The formation of ice layers after a RoS event can also affect the fate of pollutants. These ice layers can trap impurities within the snowpack, slowing their release into the environment. However, when the ice eventually melts, it can lead to a concentrated release of pollutants, resulting in pulses of contamination that can overwhelm local ecosystems.

2.9. Socioeconomic activities

Warm spells and heatwaves can have profound and multifaceted impacts on socioeconomic activities in Svalbard. In the tourism sector, while warmer temperatures might extend the season for activities such as hiking and sightseeing, which could benefit summer tourism, they could also have adverse effects on winter/spring activities that are vital to the region's economy. Snowmobiling, ski touring, and dog sledding, which are central attractions in Svalbard in the present climate, could face a shortened season or diminished quality due to reduced snow cover. The impact on wildlife due to warmer temperatures can also influence eco-tourism. Changes in animal behaviour and migration patterns might affect the viewing opportunities for tourists and potentially disrupt local ecosystems. For example, if wildlife migrates earlier or shifts its range due to changing temperatures, tourists may not experience the wildlife encounters they expect, reducing the appeal of eco-tourism experiences. Infrastructure is another area significantly affected. Melting ice and snow can damage infrastructures, creating safety hazards and logistical challenges, disrupting both daily life and economic activities. Additionally, thawing permafrost can cause ground subsidence, impacting the stability of roads, buildings, and other structures, including harbours and transportation routes, potentially increasing maintenance and repair costs and requiring costly adaptations. In addition, an intense warm spell associated with elevated liquid precipitation could cause flooding or increase the avalanche risk, which poses a danger to both residents and tourists. Overall, the impacts of warm spells and heatwaves on Svalbard's socioeconomic activities are broad and interconnected. They impact on tourism, infrastructure, and public health, highlighting the need for adaptive strategies to mitigate these effects. Ensuring that infrastructure is resilient to changing conditions, preparing for shifts in wildlife patterns, and addressing public health concerns are crucial for maintaining the well-being of both residents and visitors in Svalbard.

3. Contributions to interdisciplinarity

Svalbard heatwaves and warm spells can have widespread impacts due to their ability to rapidly alter the region's average meteorological and, to some extent, climatological conditions. The goal of the AWARE SESS report is to provide background information on the frequency of these events by analysing long-term monitoring data from Ny-Ålesund and Hornsund. Additionally, this chapter outlines a framework for a comprehensive working model that integrates in-situ observations, remote sensing data, and re-analysis datasets to capture a complete overview of the occurrence and impacts of winter warm spells and RoS events in Svalbard. This integrated approach will serve as the foundation of the study, providing robust scientific evidence to evaluate whether the frequency and intensity of these events are indeed on the rise.

The impact of Svalbard warm spells (CWS), heatwaves (CHW), and associated RoS events is extensive, as they modify the average conditions of the archipelago with broad implications for its environment. This document primarily explores the consequences of these events on snow cover processes. However, additional research is needed from an *ecological* perspective to assess whether these events affect the seasonal migration patterns or habitats of local fauna. Moreover, these events can contribute to the greening phenomenon, accelerating the expansion of vegetation due to early snowmelt and potentially leading to shifts in the vegetal species present in the archipelago. Another aspect to consider is the intensified atmospheric circulation associated with these events, which can increase the transport of pollutants from mid-latitudes. Alien species could potentially also be transported and, given the forecasted increase in temperatures, become established in Svalbard's ecosystems.

Furthermore, these events alter surface air exchange, and could thus alter *atmospheric composition*, affecting chemical reactions and influencing *atmospheric chemistry*. There is also a need to strengthen the connection between the snow community and *oceanographic systems*, as these events could impact surface water composition and lead to an earlier release of debris into the ocean.

Another important aspect to consider is the impact of extreme events on *sea ice*. These events are often associated with strong southward winds, which can break up sea ice formed during the winter and move it away from coastal regions, thus potentially altering the hunting areas of polar bears. While this effect might be secondary compared to the overall reduction of Arctic sea ice and the sea ice around Svalbard, it is still of potential significance for the polar bear population.

4. Unanswered questions

A potential increase in the frequency of atmospheric phenomena that bring warmth to the Arctic raises several scientific questions particularly given the links to other disciplines. At present, we wish to focus on the following:

1. Could Arctic heatwaves increase in frequency and become a normal atmospheric condition in the future, in response to sea ice retreat and Arctic Ocean warming?
2. Could Arctic heatwaves significantly affect the annual load of pollutants transported from mid-latitudes and impact the health of the ecosystem?
3. Could the heatwaves and warm spells associated with RoS events modify the coastal hydrological cycle, with consequences for pollutant and nutrient release into surface ocean waters and phytoplankton blooms?

4. Could warm spells and heatwaves play a significant role in the greening phenomenon of the Svalbard archipelago and in the early release of greenhouse gases from the permafrost?
5. Could warm spells and heatwaves accelerate the cycling of glacier surging, by unbalancing the annual accumulation?

5. Recommendations for the future

- Develop universally accepted definitions, metrics, atmospheric and snowpack parameters, and statistical approaches to identify these events in the Svalbard Archipelago, and, more broadly, in the Arctic (and potentially the Antarctic) regions by an active dialogue with WMO.
- Enhance by equipping existing automatic weather stations with sensors for measuring snow height, snow water equivalent, snow temperature, and liquid water content, in order to better link atmospheric conditions with the cryosphere compartment in relation to rapid warming events.
- Identify three regions in the Svalbard Archipelago for three long-term supersites to establish and support the study of the spatial occurrences and the variability of these phenomena, including their impact on the cryosphere (ideally, these locations could be identified in Ny-Ålesund, Longyearbyen, and Hornsund).
- Expand the study of Svalbard heatwaves and their impacts on the ocean, including their effects on water stratification and sea ice dynamics; on permafrost, particularly early thawing; and on biota, focusing on consequences for local fauna and Arctic greening and engage with the local community to discuss potential repercussions on Svalbard's society.
- Develop a working model to assess the impacts of Cryosphere Heatwaves (CHW) and Cryosphere Warm Spells (CWS) and to potentially predict their occurrence based on meteorological forecasts.

6. Data availability

Dataset	Parameter	Period	Location	Metadata access (URL)	Dataset provider
Air Temperature at Ny-Ålesund	Air T (air temperature)	2023	Ny-Ålesund	https://doi.pangaea.de/10.1594/PANGAEA.914979	AWI
Snow height at the Gruvebadet Snow Research Site (Ny-Ålesund, Svalbard, Norway)	HS (height snow)	2023	Ny-Ålesund	https://metadata.iadc.cnr.it/geonetwork/srv/eng/catalog.search;jsessionid=4996E2ACF102C3992CDD05547C688126#/metadata/319eb7d4-70c8-42b1-8f2b-91da8b42f8df	CNR
Snow Water Equivalent at the Gruvebadet Snow Research Site (Ny-Ålesund, Svalbard, Norway)	SWE (snow water equivalent)	2023	Ny-Ålesund	https://metadata.iadc.cnr.it/geonetwork/srv/eng/catalog.search;jsessionid=E314220977B1BE48C87E8F5CD2B0EE5F#/metadata/73651cf8-a0df-4585-8a8a-131547545e52	CNR
Ensembled terrestrial FSCA in the Bayelva area	FSCA (Fractional snow cover)	2023	Ny-Ålesund	https://metadata.iadc.cnr.it/geonetwork/srv/api/records/236a77a6-58e4-438e-8636-01d466db7037	CNR
Snow height in Hornsund	HS (height snow)	2023	Hornsund	https://zenodo.org/records/13754687	IG PAS
Snow Water Equivalent in Hornsund	SWE (snow water equivalent)	2023	Hornsund	https://zenodo.org/records/13754687	IG PAS

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8. References

Bertò M, Cappelletti D, Barbaro E et al (2021) Variability in black carbon mass concentration in surface snow at Svalbard. Atmos Chem Phys 21:12479–12493. https://doi.org/10.5194/acp-21-12479-2021

Boisvert LN, Petty AA, Stroeve JC (2016) The Impact of the Extreme Winter 2015/16 Arctic Cyclone on the Barents–Kara Seas. Mon Weather Rev 144:4279–4287. https://doi.org/10.1175/MWR-D-16-0234.1

Christiansen HH, Matero ISO, Baddeley L et al (2024) Developing the Svalbard Integrated Arctic Earth Observing System (SIOS). Earth System Dynamics 15:933–946. https://doi.org/10.5194/esd-15-933-2024

Dahlke S, Maturilli M (2017) Contribution of atmospheric advection to the amplified winter warming in the arctic north atlantic region. Advances in meteorology. https://doi.org/10.1155/2017/4928620

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

Dobricic S, Russo S, Pozzoli L et al (2020) Increasing occurrence of heat waves in the terrestrial Arctic. Environmental Research Letters 15:024022. https://doi.org/10.1088/1748-9326/ab6398

Forbes BC, Kumpula T, Meschtyb N et al (2016) Sea ice, rain-on-snow and tundra reindeer nomadism in Arctic Russia. Biol Lett 12:20160466. https://doi.org/10.1098/rsbl.2016.0466

Francis JA, Vavrus SJ (2015) Evidence for a waiver jet stream in response to rapid Arctic warming. Environmental Research Letters 10:014005. https://doi.org/10.1088/1748-9326/10/1/014005

Gallet JC, Björkman MP, Borstad CP, Hodson AJ, Jakobi H-W, Larose C, Luks B, Spolaor A, Schuler TV, Urazgildeeva A, Zdanowicz C (2019) Snow research in Svalbard: current status and knowledge gaps. In: Orr et al. (eds): SESS report 2018. Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 82–107. https://doi.org/10.5281/zenodo.4778366

Isaksen K, Nordli Ø, Førland EJ et al (2016) Recent warming on Spitsbergen—Influence of atmospheric circulation and sea ice cover. Journal of Geophysical Research: Atmospheres 121:11,911–913,931. https://doi.org/10.1002/2016JD025606

Isaksen K, Nordli Ø, Ivanov B et al (2022) Exceptional warming over the Barents area. Sci Rep 12:9371. https://doi.org/10.1038/s41598-022-13568-5

Jennings KS, Winchell TS, Livneh B, Molotch NP (2018) Spatial variation of the rain–snow temperature threshold across the Northern Hemisphere. Nat Commun 9:1148. https://doi.org/10.1038/s41467-018-03629-7

Karlsen SR, Stendardi L, Nilsen L, Malnes E, Eklundh L, Julitta T, Burkart A, Tømmervik H (2020) Sentinel satellite-based mapping of plant productivity in relation to snow duration and time of green-up. In: Van den Heuvel et al. (eds): SESS report 2019, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 42-57. https://doi.org/10.5281/zenodo.4704361

Keuschnig C, Vogel TM, Barbaro E et al (2023) Selection processes of Arctic seasonal glacier snowpack bacterial communities. Microbiome 11:35. https://doi.org/10.1186/s40168-023-01473-6

Lapointe F, Karmalkar A V, Bradley RS et al (2024) Climate extremes in Svalbard over the last two millennia are linked to atmospheric blocking. Nat Commun 15:4432. https://doi.org/10.1038/s41467-024-48603-8

Lauer M, Rinke A, Gorodetskaya I et al (2023) Influence of atmospheric rivers and associated weather systems on precipitation in the Arctic. Atmos Chem Phys 23:8705–8726. https://doi.org/10.5194/acp-23-8705-2023

Lievens H, Demuzere M, Marshall H-P et al (2019) Snow depth variability in the Northern Hemisphere mountains observed from space. Nat Commun 10:4629. https://doi.org/10.1038/s41467-019-12566-y

Łupikasza EB, Ignatiuk D, Grabiec M et al (2019) The Role of Winter Rain in the Glacial System on Svalbard. Water (Basel) 11:334. https://doi.org/10.3390/w11020334

Magnússon RÍ, Schuuring S, Hamm A et al (2024) Limited sensitivity of permafrost soils to heavy rainfall across Svalbard ecosystems. Science of The Total Environment 943:173696. https://doi.org/10.1016/j.scitotenv.2024.173696

Malard LA, Avila-Jimenez M, Convey P et al (2019) Microbial activity monitoring by the Integrated Arctic Earth Observing System In: Orr et al. (eds): SESS report 2018, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 48-81. https://doi.org/10.5281/zenodo.4778348

Maturilli M, Herber A, König-Langlo G (2013) Climatology and time series of surface meteorology in Ny-Ålesund, Svalbard. Earth Syst Sci Data 5:155–163. https://doi.org/10.5194/essd-5-155-2013

Nowak A, Hodgkins R, Nikulina A, Osuch M, Wawrzyniak T, Kavan J, Łepkowska E, Majerska M, Romashova K, Vasilevich I, Sobota I, Rachlewicz, G (2021) From land to fjords: The review of Svalbard hydrology from 1970 to 2019. In: Moreno-Ibáñez et al (eds) SESS report 2020, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 176-200. https://doi.org/10.5281/zenodo.4294063

Peeters B, Pedersen ÅØ, Loe LE et al (2019) Spatiotemporal patterns of rain-on-snow and basal ice in high Arctic Svalbard: detection of a climate-cryosphere regime shift. Environmental Research Letters 14:015002. https://doi.org/10.1088/1748-9326/aaefb3

Rennert KJ, Roe G, Putkonen J, Bitz CM (2009) Soil Thermal and Ecological Impacts of Rain on Snow Events in the Circumpolar Arctic. J Clim 22:2302–2315. https://doi.org/10.1175/2008JCLI2117.1

Rinke A, Maturilli M, Graham RM et al (2017) Extreme cyclone events in the Arctic: Wintertime variability and trends. Environmental Research Letters 12:94006. https://doi.org/10.1088/1748-9326/aa7def

Rotschky G, Vikhamar Schuler T, Haarpaintner J et al (2011) Spatio-temporal variability of snowmelt across Svalbard during the period 2000–08 derived from QuikSCAT/SeaWinds scatterometry. Polar Res 30:5963. https://doi.org/10.3402/polar.v30i0.5963

Salzano R, Cerrato R, Scoto F et al (2023) Detection of Winter Heat Wave Impact on Surface Runoff in a Periglacial Environment (Ny-Ålesund, Svalbard). Remote Sens (Basel) 15:4435. https://doi.org/10.3390/rs15184435

Salzano R, Killie MA, Luks B, Malnes E (2021a) 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 252-256. https://doi.org/10.5281/zenodo.4294092

Scoto F, Pappaccogli G, Mazzola M et al (2023) Automated observation of physical snowpack properties in Ny-Ålesund. Front Earth Sci (Lausanne) 11: https://doi.org/10.3389/feart.2023.1123981

Serreze MC, Gustafson J, Barrett AP et al (2021) Arctic rain on snow events: bridging observations to understand environmental and livelihood impacts. Environmental Research Letters 16:105009. https://doi.org/10.1088/1748-9326/ac269b

Sobota I, Weckwerth P, Grajewski T (2020) Rain-On-Snow (ROS) events and their relations to snowpack and ice layer changes on small glaciers in Svalbard, the high Arctic. J Hydrol (Amst) 590:125279. https://doi.org/10.1016/j.jhydrol.2020.125279

Spolaor A, Scoto F, Larose C et al (2024) Climate change is rapidly deteriorating the climatic signal in Svalbard glaciers. Cryosphere 18:307–320. https://doi.org/10.5194/tc-18-307-2024

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 (Lausanne) 10: https://doi.org/10.3389/feart.2022.868945

Vickers H, Saloranta T, Køltzow M et al (2024) An analysis of winter rain-on-snow climatology in Svalbard. Front Earth Sci (Lausanne) 12: https://doi.org/10.3389/feart.2024.1342731

Wegmann M, Rohrer M, Santolaria-Otín M, Lohmann G (2020) Eurasian autumn snow link to winter North Atlantic Oscillation is strongest for Arctic warming periods, Earth Syst. Dynam., 11:509–524. https://doi.org/10.5194/esd-11-509-2020

Wesselink DS, Malnes E, Eckerstorfer M, Lindenbergh RC (2017) Automatic detection of snow avalanche debris in central Svalbard using C-band SAR data. Polar Res 36:1333236. https://doi.org/10.1080/17518369.2017.1333236

Wickström S, Jonassen MO, Cassano JJ, Vihma T (2020) Present Temperature, Precipitation, and Rain-on-Snow Climate in Svalbard. Journal of Geophysical Research: Atmospheres 125:e2019JD032155. https://doi.org/https://doi.org/10.1029/2019JD032155

Winther J (2002) Surface albedo in Ny-Ålesund, Svalbard: variability and trends during 1981–1997. Glob Planet Change 32:127–139. https://doi.org/10.1016/S0921-8181(01)00103-5

Woods C, Caballero R (2016) The Role of Moist Intrusions in Winter Arctic Warming and Sea Ice Decline. J Clim 29:4473–4485. https://doi.org/10.1175/JCLI-D-15-0773.1

Yeo H, Park S-J, Kim B-M et al (2018) The observed relationship of cloud to surface longwave radiation and air temperature at Ny-Ålesund, Svalbard. Tellus B: Chemical and Physical Meteorology 70:1450589. https://doi.org/10.1080/16000889.2018.1450589

Zdanowicz C, Gallet J-C, Salvatori R et al (2023) An agenda for the future of Arctic snow research: the view from Svalbard. Polar Res 42. https://doi.org/10.33265/polar.v42.8827

Assessing anthropogenic and natural aerosol sources in the Arctic: A baseline to detect changes due to climate change (AAA-Source)

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1. Introduction

Climate change is amplified in the Arctic region (Rantanen et al. 2022) with the strongest signal present in increased near-surface temperature trends. Arctic aerosol composition is influenced by a complex web of environmental and atmospheric feedbacks and socio-economic responses. Moreover, in response to increasing temperature, both the environment and the economy of the Arctic are rapidly changing.

Arctic air receives aerosol both from source regions at mid-latitudes, which are mainly anthropogenic, and local sources that are mainly natural (Schmale et al. 2022). The impact of both sources is influenced by global change, which differs in intensity in different parts of the Arctic: for this reason it is important to have a picture of the available data from the whole Arctic.

Trace gas and aerosol budgets in the Arctic are heavily influenced by natural emissions in the region, including species emitted from sea ice, snow, open water, and land. For example, dimethylsulphide (DMS) emissions from the open ocean/ice edge are oxidised to sulphate in the atmosphere, forming new particles and contributing to growth of existing aerosols (Schmale and Baccarini 2021 and references therein).

As warming of the Arctic continues, sea ice and snow cover retreat, it is expected that biogenic emissions of aerosol precursors both from phytoplankton (Becagli et al. 2019) and terrestrial vegetation will increase (Petäjä et al. 2022; Tobo et al. 2024). This may lead to increased biogenic aerosol concentrations (Pernov et al. 2024; Tobo et al. 2024). It has been shown that new aerosol particles formed from biogenic emission may increase the number of cloud condensation nuclei (CCN) and ice nucleation particles (INPs) (Kulmala et al. 2014; Beck et al. 2021; Tatzelt et al. 2022). CCN play an important role in the formation of clouds, while INPs alter the phase state (frozen or liquid) of cloud droplets, which affects cloud radiative properties (Vergara-Temprado et al. 2018). Furthermore, cloud glaciation influences the precipitation formation and dissipation of clouds (Tatzelt et al. 2022 and references therein). As a consequence, changes in cloud radiative properties and cloud lifetime impact Earth's climate (Murray et al. 2012).

Another consequence of the Arctic sea ice loss is the increased accessibility of the Arctic. As Arctic sea ice thins and retreats, it is expected that new shipping routes within the Arctic Ocean will seasonally open up, substantially decreasing transport distances between Asia, North America, and Europe[1]. A detectable increase in particulate matter concentrations at Resolute Bay on remote Lord Cornwallis Island in Canada has been associated with ship traffic in the newly accessible Northwest Passage (Aliabadi et al. 2015). Similar increases have been associated with cruise ship traffic near Svalbard in the Norwegian Arctic (Eckhardt et al. 2013; Conca et al. 2019) and are evidenced also in northern Greenland (Becagli et al. 2020). In addition, a large portion of the Earth's undiscovered oil and gas is predicted to be under the Arctic Ocean floor and will be increasingly utilised in the future (Peters et al. 2011; Gautier et al. 2009). Population numbers, associated urbanisation, infrastructure development, and mining activities are also expected to increase in the Arctic (Andrew 2014), adding further local emissions of pollutants. The emerging local sources have recently been identified and shown to influence atmospheric composition on local and regional scales (Roiger et al. 2015; Becagli et al. 2020) but are poorly quantified.

Unless compensated by tighter pollutant emission controls, these increasing activities will cause additional local emissions of air pollutants to those transported from mid- and high-latitudes especially in spring (Arctic haze). The Arctic haze phenomenon was evidenced for the first time in the late 1800s (Nordenskiöld 1883; Garrett and Verzella 2008),

1 https://gcaptain.com/chinese-container-ships-take-arctic-shortcut-avoiding-red-sea/

but it was not until the late 1970s that it became possible to determine through chemical analyses that the haze was anthropogenic in origin and was a result of long-range transport from northern hemisphere mid-latitudes, occurring so far mainly in winter and especially in spring, when the low pressure system is strong over the Arctic. It is thought that mid-latitude emissions (from Europe, Asia, and North America) are currently the main source of air pollutants in the Arctic (Stohl 2006; Sharma et al. 2013). However, sources of pollution within the Arctic or the nearby sub-Arctic (defined here as "local") are already important in some regions (e.g., Stohl et al. 2013), and may rapidly become even more so in the future (Peters et al. 2011).

Another effect of Arctic warming is an increase of the extent of land not covered by snow or ice sheet. This can lead to an increase of natural and human-influenced open fires emitting large quantities of trace gases and aerosols within and near the Arctic (e.g., Warneke et al. 2009, 2010). Both the frequency and geographic distribution of these fires is expected to increase in a warming climate (McCarty et al. 2021; Schmale et al. 2022). Wildfires in forest and peatland areas in the Arctic and pan-Arctic region emit a significant amount of organic compounds and black carbon, which have a strong effect on radiation budget. There is a cooling but also a warming component of this aerosol load, which could increase the temperature of the atmosphere (Calì Quaglia et al. 2022) and also change the albedo of snow-covered areas (Kang et al. 2020). The climate impacts of such emissions may result in further warming of the high latitudes, leading to increases in natural fire activity, and a potential but poorly understood climate feedback.

For the above reported reasons, improving the quantification of the relative contributions of different aerosol sources is fundamental to provide a scientific basis for sustainable solutions and adaptive strategies (Schmale et al. 2021).

The understanding of aerosol sources and their temporal evolution in the Arctic will benefit greatly from long-term sustained and repeated sampling and determination of aerosol chemical composition. Such efforts are particularly challenging in the Arctic region due to the difficulty of continuous operation of sophisticated instrumentation in this inaccessible region. Moreover, the cost of maintaining and servicing these instruments is high. For this reason, although several intensive campaigns have been performed since 1980, long-term aerosol chemical measurements in this area remain scarce.

The largest regional temperature increases associated with Arctic warming have been observed in Svalbard (Rantanen et al. 2022), making this a good location for describing impacts of climate change. However, to give a broad picture of the present-day aerosol sources the available data from several sites in the Arctic are considered here and compared to measurements from Svalbard.

In this chapter we collect the existing data on aerosol chemical composition (main and trace components) in recent years (mainly from 2015 to 2023) from sites located in the Arctic and pan-Arctic region. From the chemical composition we retrieve a map of the present-day status of natural and anthropogenic aerosol sources that can be used as a reference point, as the picture will probably change in the future due to global change. Data obtained in future decades can be compared with those described here (and reported in the data set repository) to assess and quantify how aerosol sources and chemical composition in the Arctic have changed. Moreover, we stress the need for enlarge the data sets on aerosol chemical composition both in terms of number of chemical parameters measured and in number of monitored sites in the Arctic and pan-Arctic region.

2. Overview of existing knowledge

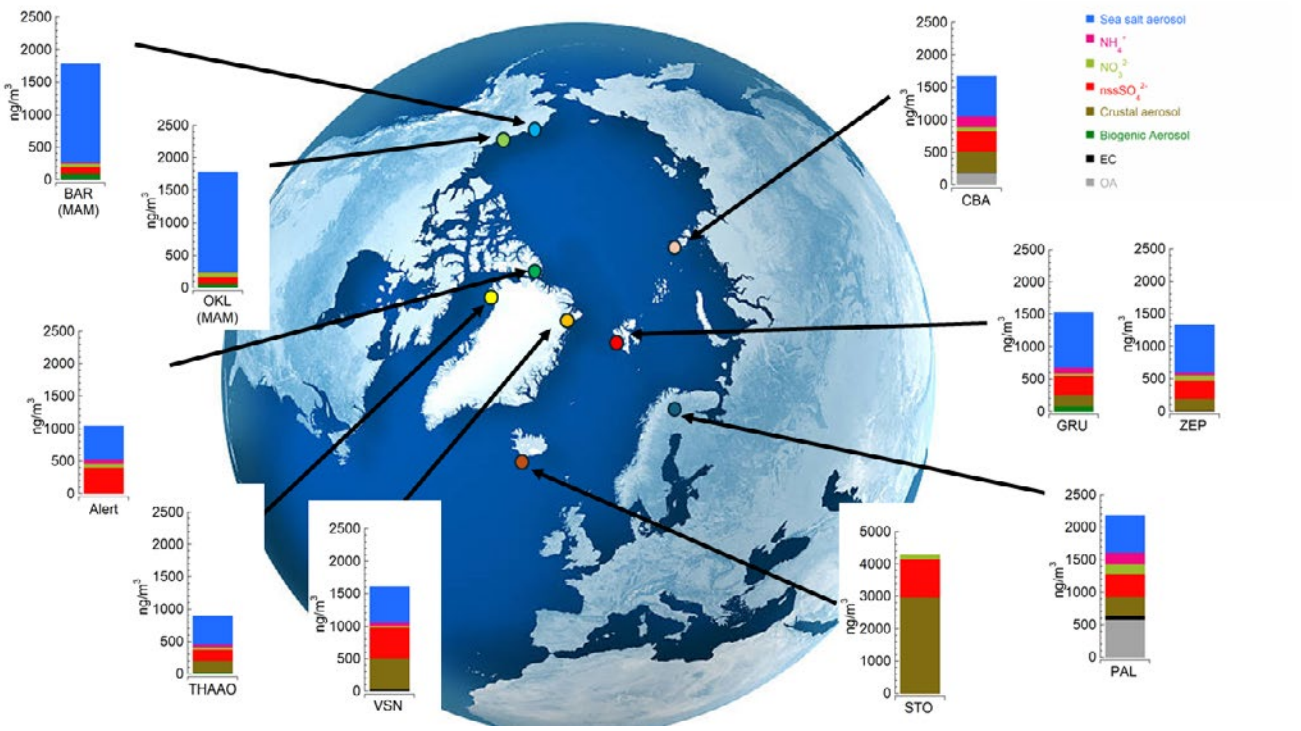

Figure 1: Map of the sampling sites, showing the annually averaged main components of atmospheric aerosol measured at each site. For BAR and OLK only data for springtime (March–April–May, MAM) are available. For STO sea salt aerosol data are not available.

In this review we collect already published chemical data sets of aerosol (Total Suspended Particles – TSP or particles with aerodynamic diameter ≤10 mm – PM10) for Arctic and some pan-Arctic stations reported in Figure 1. Details on the sampling site, aerosol collection and chemical measurements are reported in Table 1 and references therein.

We calculated the sea salt aerosol concentrations as follows:

$$[\text{Sea-salt}] = [Cl^-] + [Na^+] * 1.47 \quad (1)$$

The value 1.47 accounts for the presence of anions and cations (i.e. SO_4^{2-}, K^+, Ca^{2+}, Mg^{2+}) other than Na^+ and Cl^- in sea salt (Moffett et al. 2020).

Crustal aerosol concentration is calculated by the content of Al (or Fe for the site CBA) considering that it is 8% (3%) of the upper continental crust (Henderson and Henderson 2009).

Secondary biogenic aerosol arising from the oxidation of the biogenic DMS is calculated from the methanesulphonic acid (MSA) concentration measured in PM10, as MSA is the univocal tracer for this type of aerosol. In the high latitude regions, the ratio of biogenic aerosol/MSA depends on several factors and can range from 2 to 6; here we use the value of 4 (Becagli et al. 2019) for all the stations where MSA was measured.

Finally, non-sea salt (nss) sulphate is calculated by the equation:

$$[nssSO_4^{2-}] = [SO_4^{2-}] - 0.252 * [Na^+] \quad (2)$$

Where the value of 0.252 represents the mass ratio of sulphate-to-sodium in seawater. Non-salt sulphate ($nssSO_4^{2-}$) represents the sum of crustal, biogenic and anthropogenic sulphate. The use of the value 0.252 to calculate the $nssSO_4^{2-}$ fraction does not account for the possible fractionation

Table 1: Sampling site geographical characteristic, country hosting the station, sampling cut-off, chemical measurements, resolution, considered time range for average calculation. Black carbon and organic aerosol average values are from Moschos et al. 2022a and b. In the analysis column IC is ion chromatography; ICP-MS is Inductively Coupled Plasma Mass Spectrometer; ICP-AES is Inductively Coupled Plasma Atomic Emission Spectrometry; PIXE is Particle Induced X-Ray Emission; XRF is X-Ray Fluorescence; CE is Capillary Electrophoresis

Site	Acr.	Lat. Long.	Alt. m a.s.l.	PM	Analysis	Time interval	Sampling resolution	Methods references and data source
Barrow Atmospheric Baseline Observatory (USA)	BAR	71.323°N 156.615°W	11	TSP	Ions: IC	2015-17 Only Jun-Sep	1 week	Moffet et al. 2020 (data and references therein)
Oliktok point (USA)	OLK	70.495°N 149.886°W	10	TSP	Ions: IC	2015-17 Only Jun-Sep	1 week	Moffet et al. 2020 (data and references therein)
Thule High Arctic Atmospheric Observatory (DK)	THAAO	76.514°N 68.743°W	220	PM10	Ions: IC Metals: ICP-AES	2016-20	2 days	Becagli et al. 2020
Alert (CA)	ALE	82.499°N 62.342°W	210	TSP	Ions: IC Metals: ICP-MS	2015-17 2013-14	1 week	Ioni: EBAS (https://ebas.nilu.no) hosted by NILU Metals: De Vera et al. 2021
Storhofdi (IS)	STO	63.400°N 20.288°W	180	TSP	Metals: ICP-MS	2015-19	2 weeks	EBAS (https://ebas.nilu.no) hosted by NILU
Villum-Station Nord (DK)	VSN	81.600°N 16.667°W	24	TSP	Ions: IC Elements: PIXE.	2008-10 2011-13	7 days	Nguyen et al. 2013 Massling et al. 2015
Ny Alesund-Gruvebadet (NO)	GRU	78.907°N 11.887°E	50	PM10	Ions: IC Metals: ICP-MS	2018-23	1 or 2 days	Amore et al. 2022 Giardi et al. 2018
Ny Alesund-Zeppelin (NO)	ZEP	78.907°N 11.887°E	474	PM10	Ions: IC Metals: ICP-MS	2017-22 2017-20	1 week	EBAS (https://ebas.nilu.no) hosted by NILU
Pallas (FI)	PAL	68.000°N 24.237°E	340	PM10	Ions: IC Metals: ICP-MS	2018-23 2000-06	1 day 1 week	EBAS (https://ebas.nilu.no) hosted by NILU
Cape Baranova (RU)	CBA	79.16°N 101.45°E	30	PM10	Ions: CE Elements: XRF	2015-16	42-72h	Manousakas et al. 2020

effect due to the presence of sea spray aerosol from the so called "frost flowers" over the sea ice surface. "Frost flowers" are crystalline structures formed on the sea ice surface that are depleted of sulphate due to the precipitation of mirabilite (Na_2SO_4) at temperatures below 8°C (Rankin et al. 2000). In presence of frost flower aerosol the correct sulphate-to-sodium ratio is lower than 0.252 (Rankin et al. 2000), therefore the use of 0.252 could lead to incorrect (even negative) values of $nssSO_4^{2-}$ especially in winter. Actually, previous studies showed that at the site GRU the sea spray source represents a minor contribution to total sulphate (13.6% yearly); conversely, the anthropogenic fraction is the dominant contribution to the $nssSO_4^{2-}$ with value ranging from 99% in February to about 66% in June (Amore et al. 2022; Traversi et al. 2024). The crustal contribution to SO_4^{2-} is negligible over the year and the biogenic fraction becomes evident only in spring and summer; therefore, for stations where MSA was not determined we use the $nssSO_4^{2-}$ calculated from the equation to quantify long-range transported pollution.

The measurements of organic aerosol (OA) reported here are described and discussed in detail in Moschos et al. (2022a, b). Measurements are performed with a high-resolution long time-of-flight aerodyne aerosol mass spectrometer (L-ToF-AMS) with electron impact ionisation on the aqueous extract. To derive the total OA mass the AMS OA mass spectra were used as inputs in positive matrix factorisation (PMF) analysis (Moschos et al. 2022a, b).

Elemental and organic carbon are measured (Sunset OC-EC analyser-based) by thermal-optical analysis using the EUSAAR-2 protocol (Cavalli et al. 2010), except at measurement sites ALE (Huang et al. 2021) and BAR (NIOSH 5040 protocol).

2.1. Results

Figure 1 shows the averaged composition of the main atmospheric aerosol types at the 10 considered sites. It is evident that in the nine sites where Na is measured and sea salt aerosol is quantified (i.e., excluding STO), sea salt is the main source of aerosol; this source can be considered local due to the proximity of the sea at all the sites. The second most important aerosol type is nssSO_4^{2-} arising mainly from long-range transport. The third most abundant type is crustal aerosol, from both local and long-range sources, as will be described later.

The average sea salt aerosol concentrations at different sites and seasons are reported in Figure 2. The averaged concentrations of sea salt are quite constant over the Arctic region; differences are related to the altitude of the site, with lower concentration and, especially, smaller variability as altitude increases. The standard deviation of measured sea salt concentrations in each season is high due to sporadic but intense events which are typical for this wind-driven aerosol source. Strong winter storms can explain also the generally highest averaged values in winter (December,

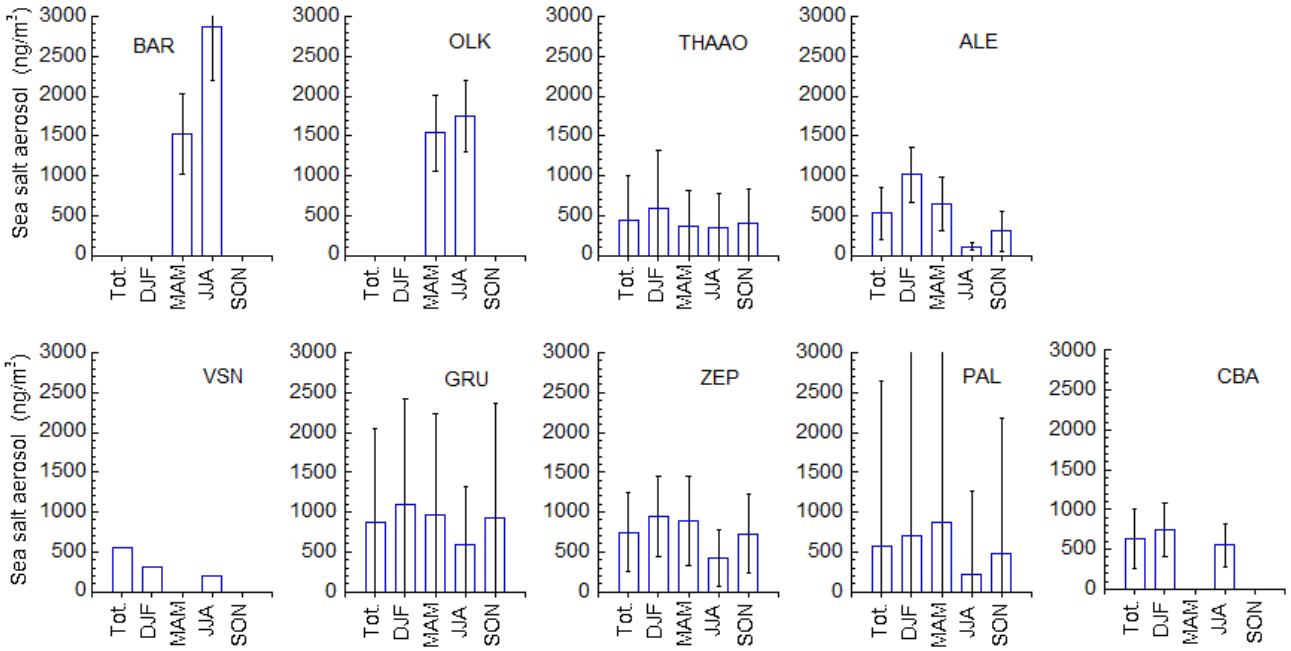

Figure 2: Sea salt aerosol total and seasonal average (December, January, February – DJF, winter; March, April, May – MAM, spring; June, July, August – JJA, summer; September, October, November – SON, fall) concentration in the Arctic sites reported in Table 1 where data on Na and Cl are available. Vertical bars represent the standard deviation of the respective seasonal and total mean values. For VSN the averaged values are from Nguyen et al. (2013) where standard deviation was not reported.

January, February – DJF) when the open sea (i.e., the source area) is far from the sampling site due to the presence of more sea ice.

Aerosol import from southerly latitudes is largely facilitated by the presence of low-pressure weather systems extending from mid-latitudes up over the Arctic in winter and spring (Stohl 2006). Recent studies based on both in-situ vertical profile measurements and modelling have demonstrated enhanced pollutant layers in the Arctic troposphere. Northern Eurasian sources dominate the layer near the surface, whereas in the mid- and upper troposphere, import from mid-latitude North America and Asia dominates (e.g., Sharma et al. 2013; Stohl et al. 2013; Law et al. 2014; Monks et al. 2015). These different source sensitivities in the vertical result from pseudo-isentropic transport pathways that bring mid-latitude emissions to the Arctic, combined with suppressed vertical mixing due to the high vertical stability of the Arctic troposphere (e.g., Stohl 2006).

The main component of long-range transported aerosol is anthropogenic sulphate (i.e., most of the $nssSO_4^{2-}$), but long-range transported aerosol also contains heavy metals, especially Pb, Cd, Co, and As. Metals are present in lower concentrations than $nssSO_4^{2-}$ but they are good tracers of long-range transport aerosol. Moreover, some metals have a strong impact on public health and European legislation has established a target maximum value for the concentration of arsenic, cadmium, and nickel in ambient air to prevent or reduce harmful effects of these metals on human health and the environment as a whole (Directive 2004/107/EC of the European Parliament and of the Council of 15 December 2004). Figures 3 and 4 show the average concentration of these compounds at the monitored Arctic stations. So far, the concentrations of toxic metals are below the European targets, but continued monitoring is necessary to assess the air quality in the Arctic.

Apart from the sites at lower latitudes (STO and PAL), most sites show the highest concentration of $nssSO_4^{2-}$, as expected, in spring due to the Arctic haze phenomenon. Another important observation is that sites in the European–Asian sector of the Arctic present $nssSO_4^{2-}$ concentrations higher than sites in the American–Canadian sector (BAR, OLK and THAAO). This evidence highlights that surface sites in the European–Asian sector are more sensitive to transport of pollution from mid-

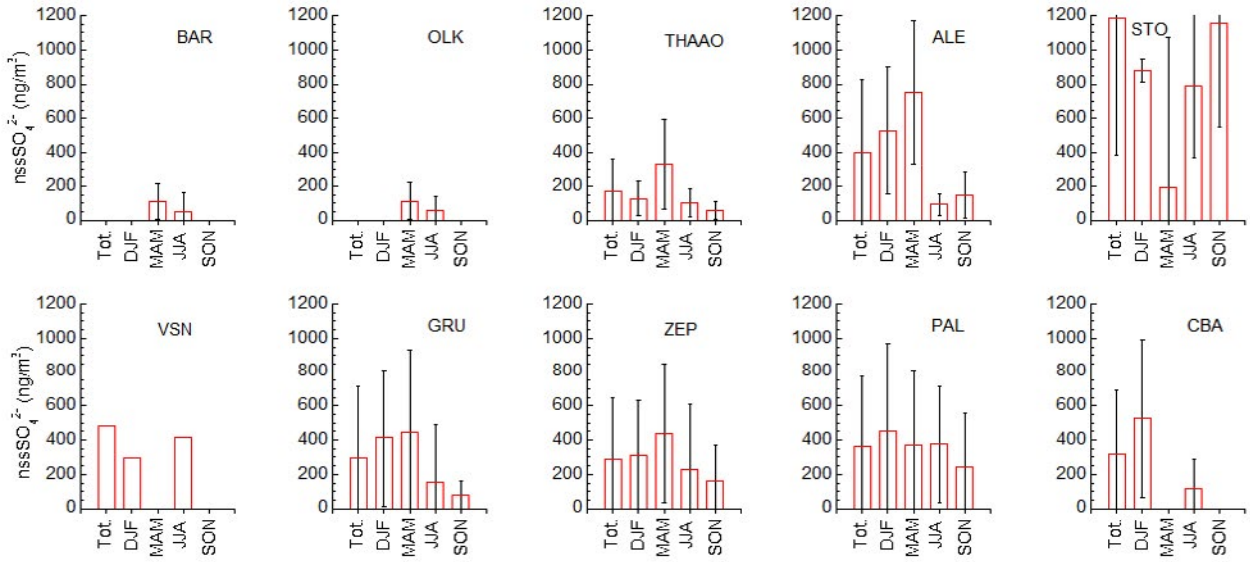

Figure 3: $nssSO_4^{2-}$ total and seasonal average (December, January, February – DJF, winter; March, April, May – MAM, spring; June, July, August – JJA, summer; September, October, November – SON, fall) concentration in the Arctic sites reported in Table 1. Vertical bars represent the standard deviation of total and seasonal mean values. For VSN the averaged values are from Nguyen et al. (2013) where standard deviation was not reported.

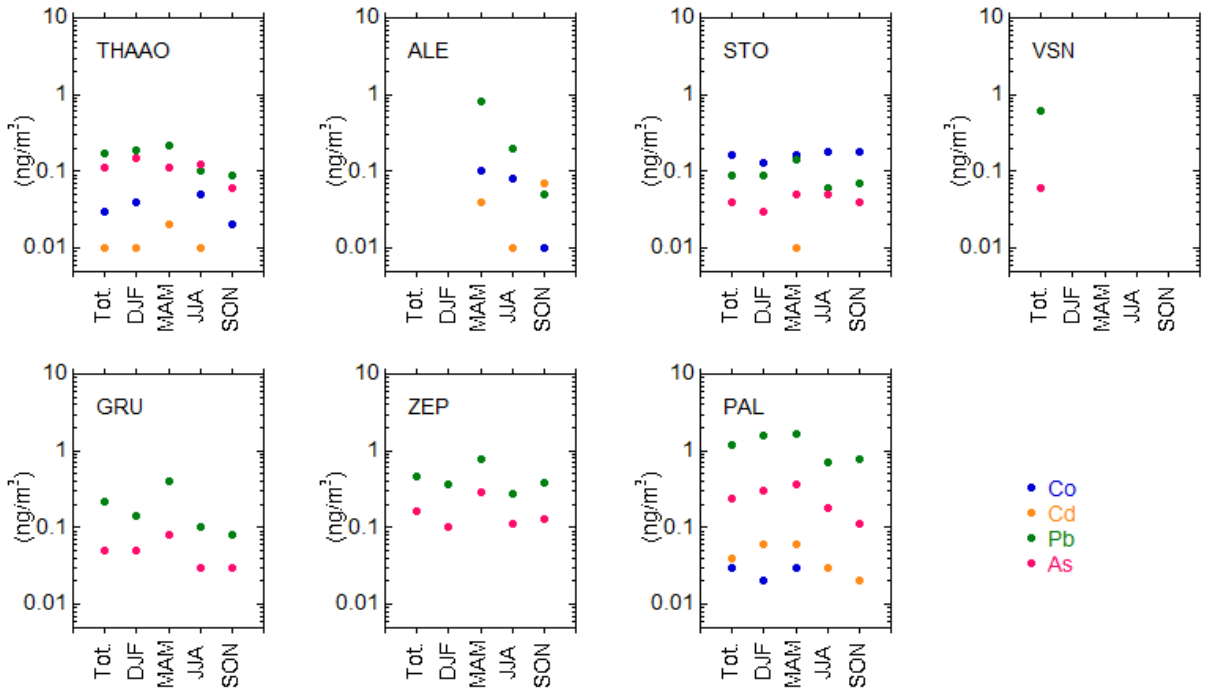

Figure 4: Co, Cd, Pb, As total and seasonal average (December, January, February – DJF, winter; March, April, May – MAM, spring; June, July, August – JJA, summer; September, October, November – SON, fall) concentration in the Arctic sites reported in Table 1 where they are measured.

latitude. STO and PAL present a different seasonal pattern likely due to the impact of anthropogenic local sources. For STO the presence of $nssSO_4^{2-}$ from SO_2 in volcanic emissions in the proximity can explain the elevated SO_4^{2-} concentrations.

Pb, Cd, As and Co typically show a maximum value in spring (March, April, May – MAM) demonstrating that they originate from long-range transport, similarly to anthropogenic $nssSO_4^{2-}$. This pattern, with maximum values in spring, is visible also at the more southerly sites of PAL and STO, highlighting that also these sites are affected by anthropogenic aerosol transported from mid-latitudes.

Previous studies have demonstrated that changes in mid-latitude emissions caused reductions in concentrations of pollutants in the Arctic. For instance, Sharma et al. (2019) found a decline SO_4^{2-} and black carbon (BC) at Alert, Barrow, and Ny-Ålesund during the mid-1990s. The reduction was associated with declines in SOx and BC emissions from Eurasia between 1990 and 1995 rather than changed transport. More recently, the decreasing trend of anthropogenic $nssSO_4^{2-}$ has been less pronounced (Sharma et al. 2019; Amore et al. 2022; Traversi et al. 2021, 2024). A recent study demonstrates that the decreasing trend in long-range transported aerosol could also be due to changes in precipitation scavenging efficiency (Heslin-Rees et al. 2024).

There is also evidence of decreasing concentrations of Pb and Cd in the 1980s and 1990s, followed by relatively stable levels for the last couple of decades (De Vera et al. 2021).

It is now demonstrated that the fast warming of the Arctic region reduces the strength of the low-pressure system over the Arctic (e.g., Kim et al. 2014) and leads to heat waves in the Arctic and cold waves at mid-latitudes. It will be challenging to study how this change in low-pressure systems will influence the efficiency of pollutant transport processes from mid-latitude to the Arctic. It will be interesting to study in the coming decades how and to what extent the climate-driven changes in transport processes coupled with the increasing local emissions will shift the relative contribution of local vs. long-range transported pollutants.

Organic aerosol is difficult to monitor in Arctic sites;

data are scarce and related to sporadic campaigns (Moschos et al. 2022b). A recent study conducted over several Arctic sites reveals an overall nearly equal annual abundance of summed anthropogenic-dominated and summed natural-dominated organic aerosol. The anthropogenic source dominates in winter, the natural one in summer (Moschos et al. 2022a).

Black carbon (BC) presents quite low concentration in the Arctic, but these light-absorbing particles have a strong climatic effect both in the atmosphere and once deposited on snow (Kang et al. 2020). Due to its climatic relevance, a SESS report chapter on this topic was published (Gilardoni et al. 2020).

Flaring of excess natural gas during oil extraction in the Russian Arctic has been estimated to be the dominant contributor to black carbon (BC) concentrations in the atmosphere and surface snow in this portion of the Arctic (Stohl et al. 2013). There was also evidence for an increasing use of wood for household heating in past decades (Pearson et al. 2013) producing absorbing and non-absorbing particles. The BC emissions from the above reported sources are only partially quantified.

Since 2005, measurements of the aerosol absorption coefficient, used to estimate BC, have been conducted at the Zeppelin Observatory. BC, a major climate forcer, varies by source and region across seasons and its levels are primarily influenced by episodic long-range transport from areas with extreme background levels. In winter, emissions from flaring and domestic heating in Eurasian high latitudes are common, while summer measurements often capture wildfire emissions (Stohl et al. 2006).

BC concentrations in the Arctic have generally declined since the 1990s, primarily due to emission reduction policies (AMAP 2021). But wildfires, including those at high latitudes, have increased (McCarty et al. 2021). When comparing the Arctic aerosol absorption coefficient during Arctic haze (winter–spring) vs non-Arctic haze (summer) periods, distinct trends appear: we see a clear decrease in BC levels during winter–spring, but not in summer. This difference is especially evident when one studies the 80th percentile of the data, which captures pollution episodes rather than average concentrations (Figure 5).

Decreases in snow cover over land play a fundamental role in the amplification of warming in the Arctic due to huge decreases of albedo. Moreover, land not covered by snow is a prime area for crustal aerosol production. Therefore, the impact of locally produced crustal aerosol is expected to increase as the Arctic warms (Meinander et al. 2022 and references therein).

Figure 6 reports the concentrations of crustal aerosol, which are quite homogeneous among the sites excluding ALE, PAL and STO. These higher concentrations are likely related to the proximity to

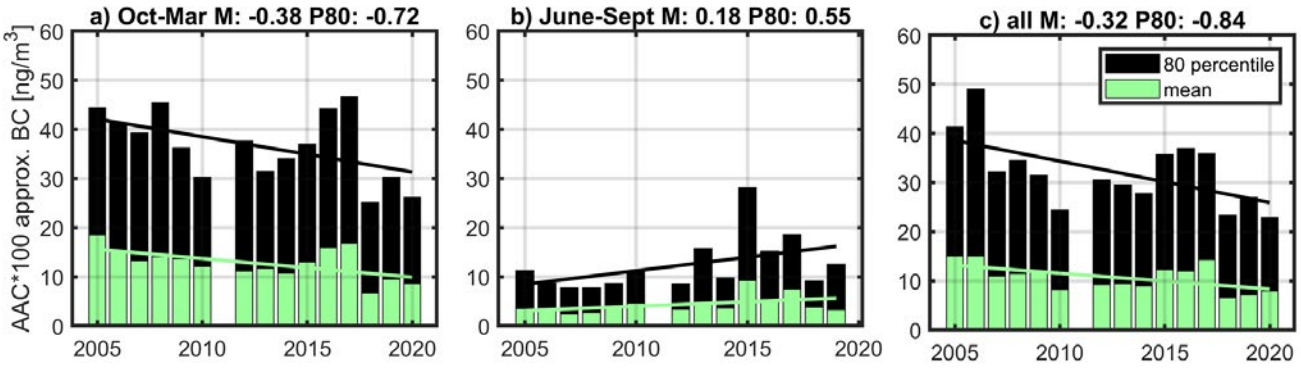

Figure 5: Aerosol absorption coefficient (GR05L_aethalometer_AE31, Eleftheriadis et al. 2009) based on three-hourly observations at Zeppelin from 2005 to 2020. Mean values (black bars) and 80th percentiles (green bars) for different periods: October to March in panel a), June to September in panel b), and for the entire year in panel c). The green and black lines represent the linear trends for the mean and 80th percentile values, respectively. The title above each panel indicates the trends as 100 times the aerosol absorption coefficient per year.

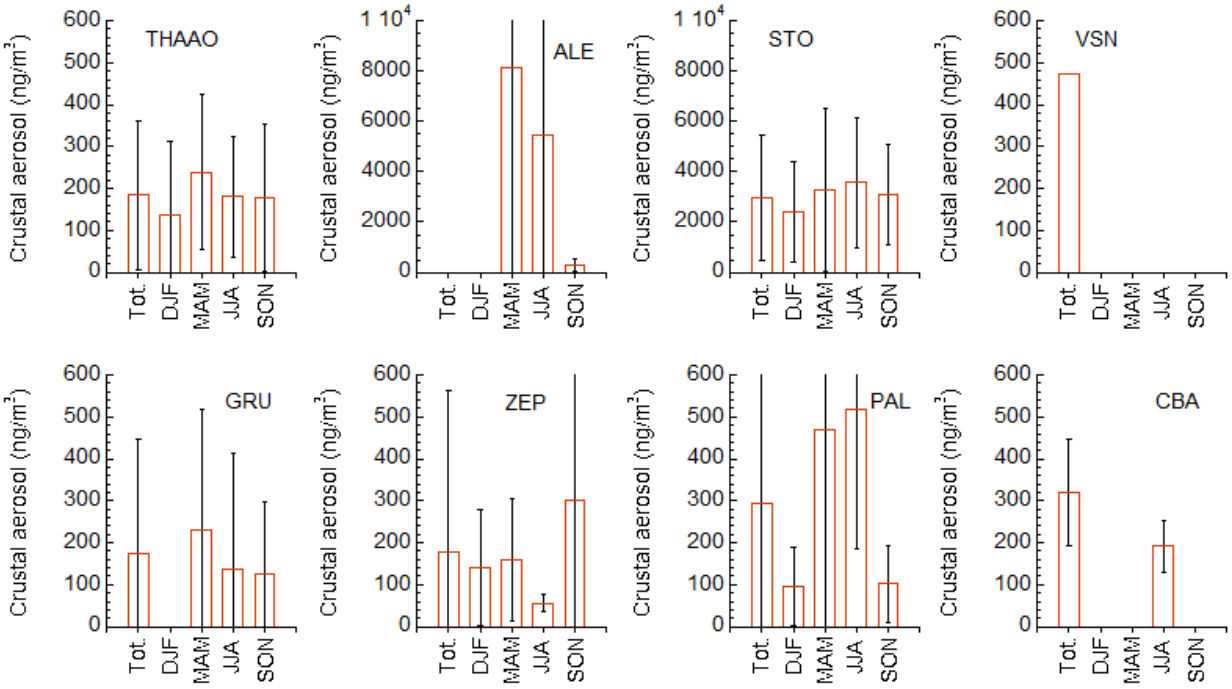

Figure 6: Crustal aerosol total and seasonal averaged (December, January, February – DJF, winter; March, April, May – MAM, spring; June, July, August – JJA, summer; September, October, November – SON fall) concentration in the Arctic sites reported in Table 1 where they are measured. Crustal aerosol was calculated as above reported by Al concentration. Vertical bars represent the standard deviation of the total and seasonal mean values.

dusty land not covered by snow. Iceland represents one of the major sources of high latitude dust, due to its extensive desert surface where fine volcanic sediments are present (Blechschmidt et al. 2012). An Icelandic storm can lead to a dust concentration similar to Saharan conditions (Dagsson-Waldhauserova et al. 2019) giving a concentration of crustal aerosol more than one order of magnitude higher than at the other Arctic sites. Regarding the seasonal pattern we observe a maximum value in spring, but high concentration still remains in summer and fall seasons. The spring maxima are more related to long-range transported dust (together with pollutants), whereas summer and fall dust is more related to local sources (Meinander et al. 2022).

Other elements present in dusty aerosol are Fe, Ti and Mn (Figure 7). The seasonal trend conforms with those observed for crustal aerosol content due to their dominant source from dust. Enhanced knowledge about the atmospheric concentration of Fe is highly recommended in studies regarding biogeochemical nutrient cycling, as the role of atmospheric deposition of this micronutrient over ocean and its fertilisation effects are still being debated (De Vera et al. 2021).

Among the metals, V, Cr, Ni, Cu are of particular interest (Figure 8) as these elements are generally considered to originate from anthropogenic sources. They do not show a clear maximum in spring (MAM) as observed for Pb, Cd and As, but their seasonal pattern is more similar to those of crustal aerosol. Especially at THAAO a maximum in summer (June, July, August – JJA) is observed for Ni and V. For these elements we can hypothesise mineral dust as a prevailing source. Indeed, soil in some polar regions is particularly rich in these elements (Becagli et al. 2020).

Figure 9 shows the concentration of biogenic aerosol estimated by the concentration of MSA at the Arctic sites where it is measured. Data on MSA and biogenic aerosol are scarce over the Arctic region, but from Figure 9 we observe that concentrations measured at GRU (Svalbard) are higher than those measured at BAR, OLK and

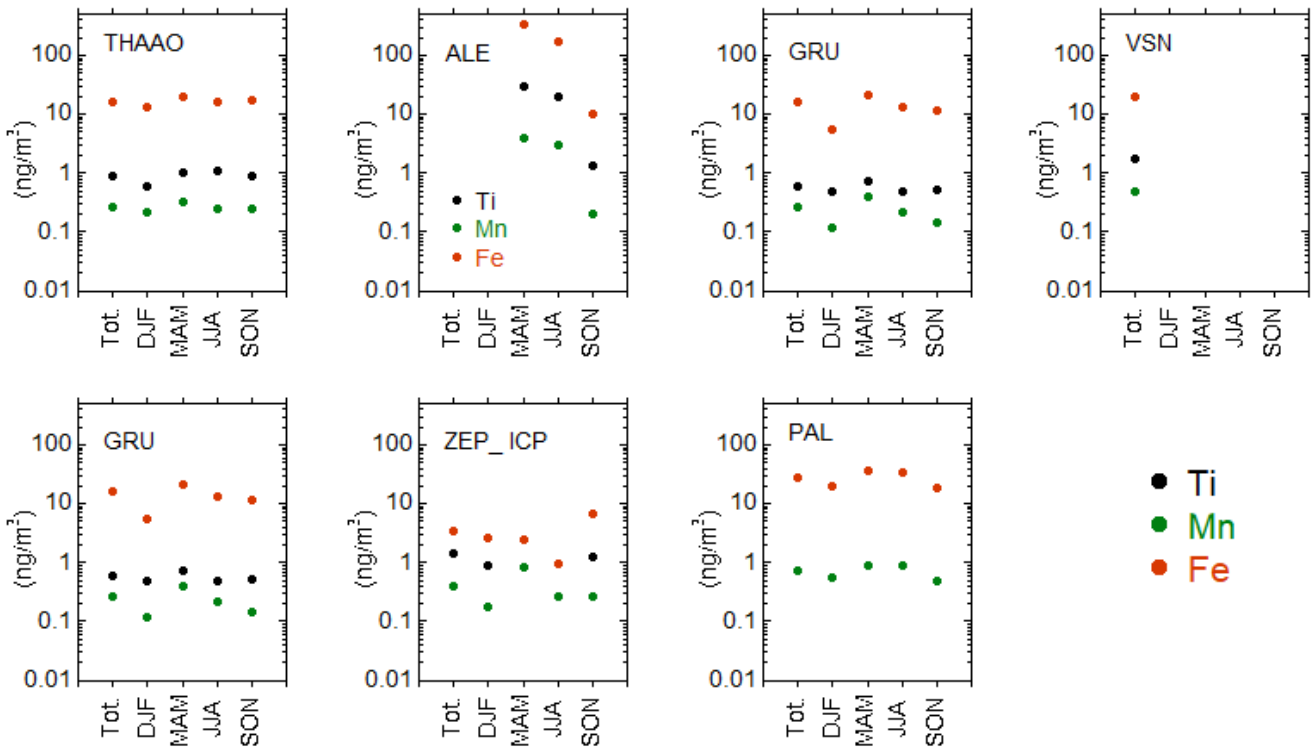

Figure 7: Fe, Mn, Ti total and seasonal average (December, January, February – DJF, winter; March, April, May – MAM, spring; June, July, August – JJA, summer; September, October, November – SON, fall) concentration in the Arctic sites reported in Table 1 where they are measured.

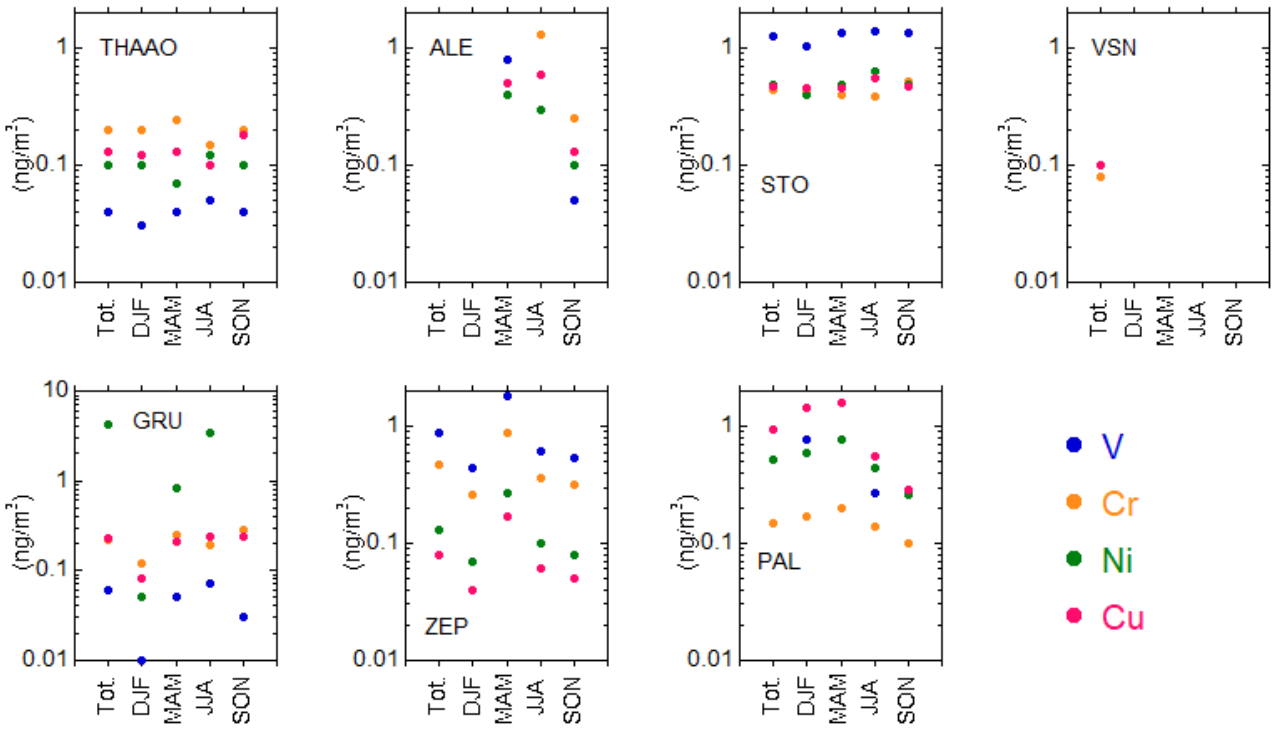

Figure 8: V, Cr, Ni, Cu total and seasonal average (December, January, February – DJF, winter; March, April, May – MAM, spring; June, July, August – JJA, summer; September, October, November – SON, fall) concentration in the Arctic sites reported in Table 1 where they are measured.

THAAO adjacent to the western Arctic Ocean, confirming data reported by Sharma et al. (2012) for the previous decade.

The seasonality with summer maxima of biogenic aerosol production is well known and it is the same over the whole Arctic (Becagli et al. 2016; Sharma et al. 2012; Schmale et al. 2022). What is not yet known is the possible change in seasonality and the impact of biogenic aerosol in the Arctic related to early melting of sea ice. Besides, it is important to know the effect of Arctic Ocean atlantification on biogenic aerosol production. In this context the Svalbard archipelago is in one of the areas more sensitive to atlantification, as extensively reported by Bensi et al. (2025). It is of particular relevance to study the effect of this oceanic phenomenon on the atmosphere to better understand ocean–atmosphere feedback processes in a global change scenario.

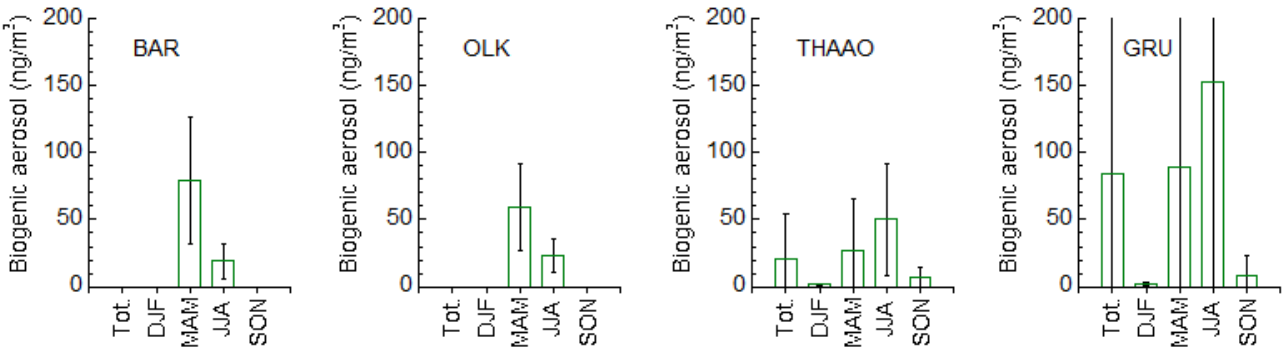

Figure 9: Biogenic aerosol total and seasonal average (December, January, February – DJF, winter; March, April, May – MAM, spring; June, July, August – JJA, summer; September, October, November – SON, fall) concentration in the Arctic sites reported in Table 1. Biogenic aerosol is calculated from the MSA concentration, as described above. Vertical bars represent the standard deviation of the values.

3. Contributions to interdisciplinarity

This chapter offers several points of contact with other disciplines, and is strongly connected with SESS report chapters published previously and in this issue.

Biogenic aerosol formation is correlated with oceanic parameters able to promote phytoplanktonic activity such as temperature, sea ice extent and nutrient availability. Therefore, the knowledge about the impact of atlantification, especially in the western Greenland Sea as reported in the chapter ARiS by Bensi et al. (2025) is of particular relevance to explain the increase of biogenic aerosol formation observed at Svalbard. Moreover, as these processes are related to global warming, the occurrence of warm events reported in the chapter AWARE by Spolaor et al. (2025) will give further input to explain the processes. Warm events are also related to change in the strength of the polar vortex; therefore, changes in atmospheric circulation processes may influence the impact of aerosol transported from distant sources.

Another important interdisciplinary connection concerns knowledge of the local crustal aerosol fingerprint. As snow cover retreats, the importance of local crust as an aerosol source is expected to increase. To distinguish between local and long-range transported crustal aerosol and to quantify both, it is necessary to know the geology and composition of Svalbard soil as reported in the chapter about SVALGEO by Senger et al. (2025).

This chapter is obviously related to previously published chapters in the SESS report presenting trends of sulphate and black carbon in the atmosphere: HAZECLIC and HAZECLIC 2 (Traversi et al. 2021, 2024) and ABC Svalbard (Gilardoni et al. 2020).

4. Unanswered questions

Is it possible to quantify the local anthropogenic sources of aerosol in the Arctic?

At some sites there is some evidence of local anthropogenic sources, but more parameters must be measured to perform a rigorous source apportionment for these minor sources. To identify and quantify local sources of aerosol it is necessary to measure at least: PM10 (or TSP), Al, Ti, Fe, Cr, As, Cd, Pb, Ni, V and organic carbon. In addition, measurement of methanesulphonate and levoglucosan is desirable to quantify the impact of biogenic aerosol and biomass burning aerosols, respectively.

Do we know enough about organic aerosol to study its impact?

The roles of Arctic aerosols as ice-nucleating particles remain poorly understood, even though their effects on cloud microphysics are crucial for assessing the climate sensitivity of Arctic mixed-phase clouds and predicting their response to Arctic warming. Studies on new particles or ice particle formation show that organic aerosol produced by both marine and terrestrial biota has a crucial role especially in remote and Arctic regions (Beck et al. 2021). Besides, a recent study suggests that highly active organic ice-nucleating particles could be actively released from Arctic natural sources in response to surface warming (Tobo et al. 2024). To assess the impact of organic aerosol on new particle formation we must first measure organic aerosol. Such measurements are difficult and existing data are scarce. Few measuring campaigns have been done, and they cover only short time periods.

Organic carbon measurements are relatively easy to obtain and could cover the whole year with a temporal resolution of 1 or 2 weeks. From these measurements the total concentration of organic aerosol could be obtained for long time periods, but without any chemical speciation. Such measurements should therefore be coupled with chemical speciation measurements (such as those made in Moschos et al. 2022a) that require more complex instrumentation, but that could be done in targeted measurement campaigns.

5. Recommendations for the future

The rapid pace of Arctic environmental change puts high priority on improving our understanding of processes controlling the sources and fate of Arctic air pollutants that negatively impact Arctic communities. Deficiencies in our predictive capability due to the lack of long-term observations at high latitudes, makes reliable near- and long-term projections of Arctic environmental change challenging.

An important goal of this chapter is to furnish to policymakers and Arctic residents, basic information on the risks and benefits global warming poses for Arctic communities.

The data set we have collected here gives an overview of the present-day Arctic aerosol composition, not least in Svalbard, which is a particularly climate-sensitive area. In addition, this work should promote new collaborations among observational and modelling groups, social science researchers, and local Arctic communities.

From the results shown in this chapter the following recommendations for the future can be given:

- Continue and promote long-term monitoring and regular intensive field observations, both at the surface and throughout the troposphere (in-situ, remote sensing, and satellite observations). We emphasise the need for a network of state-of-the-art research infrastructures in the Arctic

region for ground-based observations to supplement the existing stations. In addition, we stress that it is important to measure a large number of markers to identify processes and sources that could be neglected by only observing main tracers. Long-term surface observations provide the main source of information on the seasonality and trends of Arctic air pollution. Additional community-based monitoring could enhance the spatial and temporal coverage of surface observations while engaging local populations in science and decision-making.

- Use a trans-disciplinary approach. This should exploit collaborative platforms for observations across linked aspects of the Earth system (atmosphere, cryosphere, ocean, land surface, society), considering of societal and economic drivers and responses to Arctic change impacting climate, air quality and ecosystems. It should be carried in a collaborative framework linking to existing and planned programmes.
- Improved predictive capability is needed across a range of scales to diagnose wider impacts of Arctic aerosol on regional and global climate and the Earth system, and on local air quality and ecosystems. Modelling efforts should also exploit new capabilities in Earth system modelling, particularly regarding the interactions between atmospheric composition/climate and the biosphere/ocean.
- Train the new generation of scientists in setting up and maintaining new techniques of instrumentation and chemical analysis to monitor the atmosphere (but also, snow, water and soil). Raising the awareness of budding scientists about this issue, for example through regular training schools organised and supported by SIOS, is of particular importance. These young people will be in charge of monitoring and possibly trying to find solutions to mitigate disadvantageous trends.

6. Data availability

Dataset	Parameter	Period	Location	Metadata access (URL)	Dataset provider
Main trace chemical markers concentrations in the aerosol (bulk and PM10)	Sea salt aerosol, NH4, NO3, nssSO4, Al, Crustal aerosol, MSA, Biogenic Aerosol, Black Carbon, Organic aerosol, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Cd, Pb, As, Ba, Mo, Si.	Annually and seasonally averaged concentration. Covered period: from 2015 to 2023, with few exceptions as specified in metadata.	Arctic and pan-Arctic region	https://metadata.iadc.cnr.it/geonetwork/srv/api/records/73b59bc8-f025-4b2d-ac30-8bfb358069ff	Silvia Becagli silvia.becagli@unifi.it

7. Acknowledgements

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8. References

Aliabadi AA, Staebler RM, Sharma S (2015) Air quality monitoring in communities of the Canadian Arctic during the high shipping season with a focus on local and marine pollution. Atmos Chem Phys 15: 2651–2673. https://doi.org/10.5194/acp-15-2651-2015

AMAP (2021) AMAP Assessment 2021: Impacts of Short-lived Climate Forcers on Arctic Climate, Air Quality, and Human Health. Arctic Monitoring and Assessment Programme (AMAP), Tromsø, Norway. x + 375pp

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). Atmos Environ 270:118890. https://doi.org/10.1016/j.atmosenv.2021.118890

Andrew R (2014) Socio-Economic Drivers of Change in the Arctic. *AMAP Technical Report No. 9*. Norway: Arctic Monitoring and Assessment Programme (AMAP). http://www.amap.no/documents/doc/Socio-Economic-Driversof-Change-in-the-Arctic/1115

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 P, 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

Becagli S, Lazzara L, Marchese C, Dayan U, Ascanius SE, Cacciani M, Caiazzo L, Di Biagio C, Di Iorio T, di Sarra A, Eriksen P, Fani F, Giardi F, Meloni D, Muscari G, Pace G, Severi M, Traversi R, Udisti R (2016) Relationships linking primary production, sea ice melting, and biogenic aerosol in the Arctic. Atmos Environ 136:1-15. http://dx.doi.org/10.1016/j.atmosenv.2016.04.002

Becagli S, Caiazzo L, Di Iorio T, di Sarra A, Meloni D, Muscari G, Pace G, Severi M, Traversi R (2020) New insights on metals in the Arctic aerosol in a climate changing world. Science of the Total Environment 741:140511. https://doi.org/10.1016/j.scitotenv.2020.140511

Beck LJ, Sarnela N, Junninen H, Hoppe CJM, Garmash O, Bianchi F et al (2021) Differing mechanisms of new particle formation at two Arctic sites. Geophysical Research Letters 48, e2020GL091334. https://doi.org/10.1029/2020GL091334

Bensi M, Nilsen F, Ferré B, Skogseth R, Moskalik M, Korhonen M et al (2025) The atlantification process in Svalbard: a broad view from the SIOS Marine Infrastructure Network. In: Runge et al (eds) SESS report 2024, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 228-245. https://doi.org/10.5281/zenodo.14425673

Blechschmidt A-M, Kristjánsson JE, Ólafsson H, Burkhart JF, Hodnebrog Ø, Rosenberg PD (2012) Aircraft-based observations and high-resolution simulations of an Icelandic dust storm. Atmos Chem Phys 12:10649–10666. https://doi.org/10.5194/acp-12-10649-2012

Calì Quaglia F, Meloni D, Muscari G, Di Iorio T, Ciardini V, Pace G, Becagli S, Di Bernardino et al (2022) On the Radiative Impact of Biomass-Burning Aerosols in the Arctic: The August 2017 Case Study. Remote Sens 14:313. https://doi.org/10.3390/rs14020313

Cavalli F, Viana M, Yttri KE, Genberg J, Putaud J-P (2010) Toward a standardised thermal-optical protocol for measuring atmospheric organic and elemental carbon: the EUSAAR protocol Atmos Meas Tech 3:79–89. https://doi.org/10.5194/amt-3-79-2010

Conca E, Abollino O, Giacomino A, Buoso S, Traversi R, Becagli S, Grotti M, Malandrino M (2019) Source identification and temporal evolution of trace elements in PM10 collected near to Ny-Alesund (Norwegian Arctic) Atmos Environ 203:153–165. https://doi.org/10.1016/j.atmosenv.2019.02.001

Dagsson-Waldhauserova P, Renard JB, Olafsson H et al (2019) Vertical distribution of aerosols in dust storms during the Arctic winter. Sci Rep 9:16122. https://doi.org/10.1038/s41598-019-51764-y

De Vera J, Chandan P, Landing WM, Stupple GW, Steffen A, Bergquist BA (2021) Amount, sources, and dissolution of aerosol trace elements in the Canadian Arctic. ACS Earth Space Chem 5:2686–2699. http://dx.doi.org/10.1021/acsearthspacechem.1c00132

Eckhardt S, Hermansen O, Grythe H, Fiebig M, Stebel K et al (2013) The influence of cruise ship emissions on air pollution in Svalbard – a harbinger of a more polluted Arctic? Atmos Chem Phys 13: 8401–8409. https://doi.org/10.5194/acp-13-8401-2013

Eleftheriadis K, Vratolis S, Nyeki S (2009) Aerosol black carbon in the European Arctic: Measurements at Zeppelin station Ny-Ålesund, Svalbard from 1998–2007. Geophys Res Lett 36:L02809. https://doi.org/10.1029/2008GL035741

Garrett TJ, Verzella LL (2008) An evolving history of Arctic aerosols. B Am Meteorol Soc 89:299–302.

Gautier DL, Bird KJ, Charpentier RR, Grantz A, Houseknecht DW et al (2009) Assessment of undiscovered oil and gas in the Arctic. Science 324:1175–1179. https://doi:10.1126/science.1169467

Giardi F, Traversi R, Becagli S, Severi M, Caiazzo L, Ancillotti C, Udisti R (2018) Determination of Rare Earth Elements in multi-year high-resolution Arctic aerosol record by double focusing Inductively Coupled Plasma Mass Spectrometry with desolvation nebulizer inlet system. Sci of the Total Environ 613–614:1284–1294. https://doi.org/10.1016/j.scitotenv.2017.09.247

Gilardoni S, Lupi A, Mazzola M, Cappelletti DM, Moroni B, Ferrero L, Markuszewski P, Rozwadowska A, Krecji R, Zieger P, Tunved P, Karlsson L, Vratolis S, Eleftheriadis K, Viola AP (2020) Atmospheric black carbon in Svalbard. In: Van den Heuvel et al (eds) SESS report 2019, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 236–249. https://doi.org/10.5281/zenodo.4707201

Henderson P, Henderson GM (2009) The Cambridge Handbook of Earth Science Data, Cambridge, University Press, Cambridge, 42–44

Heslin-Rees D, Tunved P, Ström J, Cremer R, Zieger P, Riipinen I, Ekman AML, Eleftheriadis K, Krejci R (2024) Increase in precipitation scavenging contributes to long-term reductions of light-absorbing aerosol in the Arctic. Atmos Chem Phys 24:2059–2075. https://doi.org/10.5194/acp-24-2059-2024

Huang L, Zhang W, Santos GM, Rodríguez BT, Holden SR, Vetro V, Czimczik CI (2021) Application of the ECT9 protocol for radiocarbon-based source apportionment of carbonaceous aerosols Atmos Meas Tech 14:3481–500. https://doi.org/10.5194/amt-14-3481-2021

Kang SC, Zhang YL, Qian Y, Wang HL (2020) A review of black carbon in snow and ice and its impact on the cryosphere. Earth-Science Reviews 210. https://doi.org/10.1016/j.earscirev.2020.103346

Kim BM et al. (2014) Weakening of the stratospheric polar vortex by Arctic sea-ice loss. Nat Commun 5:4646. https://doi.org/10.1038/ncomms5646

Kulmala M, Petäjä T, Ehn M, Thornton J, Sipilä M, Worsnop DR, Kerminen V-M (2014) Chemistry of atmospheric nucleation: on the recent advances on precursor characterization and atmospheric cluster composition in connection with atmospheric new particle formation Annu Rev Phys Chem 65:21–37. https://doi.org/10.1146/annurev-physchem-040412-110014

Law KS, Stohl A, Quinn PK, Brock C, Burkhart J et al (2014) Arctic Air Pollution: New Insights from POLARCAT-IPY. Bull Am Meteorol Soc 95:1873–1895. https://doi.org/10.1175/BAMS-D-13-00017.1

Manousakas M, Popovicheva O, Evangeliou N, Diapouli E, Sitnikov N, Shonija N, Eleftheriadis K (2020) Aerosol carbonaceous, elemental and ionic composition variability and origin at the Siberian High Arctic, Cape Baranova, Tellus B: Chemical and Physical Meteorology 72:1-14. https://doi.org/10.1080/16000889.2020.1803708

Massling A, Nielsen IE, Kristensen D, Christensen JH, Sorensen LL, Jensen B et al (2015) Atmospheric black carbon and sulfate concentrations in Northeast Greenland. Atmospheric Chemistry and Physics 15(16):9681–9692. https://doi.org/10.5194/acp-15-9681-2015

McCarty JL, Aalto J, Paunu VV, Arnold SR, Eckhardt S, Klimont Z, Fain JJ, Evangeliou N, Venalainen A, Tchebakova NM, Parfenova EI, Kupiainen K, Soja AJ, Huang L, Wilson S (2021) Reviews and syntheses: Arctic fire regimes and emissions in the 21st century. Biogeosciences 18:5053-5083. https://doi.org/10.5194/bg-18-5053-2021

Meinander O, Dagsson-Waldhauserova P, Amosov P, Aseyeva E, Atkins C, Baklanov A, Baldo C et al (2022) Newly identified climatically and environmentally significant high-latitude dust sources. Atmos Chem Phys 22:11889–11930. https://doi.org/10.5194/acp-22-11889-2022

Moffett CE, Barrett TE, Liu J, Gunsch M J, Upchurch LM, Quinn PK et al (2020) Long-term trends for marine sulfur aerosol in the Alaskan Arctic and relationships with temperature. Journal of Geophysical Research: Atmospheres 125:e2020JD033225. https://doi.org/10.1029/2020JD033225

Monks SA, Arnold SR, Emmons LK, Law KS, Turquety S et al (2015) Multi-model study of chemical and physical controls on transport of anthropogenic and biomass burning pollution to the Arctic. Atmos Chem Phys 15:3575–3603. https://doi.org/10.5194/acp-15-3575-2015

Moschos V, Dzepina K, Bhattu D et al (2022a) Equal abundance of summertime natural and wintertime anthropogenic Arctic organic aerosols. Nat Geosci 15:196–202. https://doi.org/10.1038/s41561-021-00891-1

Moschos V, Schmale J, Aas W, Becagli S et al (2022b) Elucidating the present-day chemical composition, seasonality and source regions of climate-relevant aerosols across the Arctic land surface. Environ Res Lett 17:034032. https://doi.org/10.1088/1748-9326/ac444b

Murray BJ, O'Sullivan D, Atkinson JD, Webb ME (2012) Ice nucleation by particles immersed in supercooled cloud droplets. Chemical Society Reviews 41(19):6519–6554. https://doi.org/10.1039/C2CS35200A

Nguyen QT, Skov H, Sørensen LL, Jensen BJ, Grube AG, Massling A, Glasius M, Nøjgaard JK (2013) Source apportionment of particles at Station Nord, North East Greenland during 2008–2010 using COPREM and PMF analysis Atmos Chem Phys 13:35–49. https://doi.org/10.5194/acp-13-35-2013

Nordenskiöld AE (1883) Nordenskiöld on the inland ice of Greenland. Science 2:732–739. https://doi.org/10.1126/science.ns-2.44.732

Pearson P, Bodin S, Nordberg L, Pettus A (2013) On Thin Ice: How Cutting Pollution can Slow Warming and Wave Lives, Vol. 1. Washington DC: World Bank. Accessed 9 November 2015. http://documents.worldbank.org/curated/en/2013/10/18496924/thin-ice-cutting-pollution-can-slowwarming-save-lives-vol-1-2-main-report

Pernov JB, Harris E, Volpi M et al (2024) Pan-Arctic methanesulfonic acid aerosol: source regions, atmospheric drivers, and future projections. npj Clim Atmos Sci 7:166. https://doi.org/10.1038/s41612-024-00712-3

Petäjä T, Tabakova K, Manninen A et al (2022) Influence of biogenic emissions from boreal forests on aerosol–cloud interactions. Nat Geosci 15:42–47. https://doi.org/10.1038/s41561-021-00876-0

Peters G, Nilssen T, Lindholt L, Eide M, Glomsrød S, Eide LI, Fuglestvedt JS (2011) Future emissions from shipping and petroleum activities in the Arctic. Atmos Chem Phys 11:5305–5320. https://doi.org/10.5194/acp-11-5305-2011

Rankin AM, Wolff EW, Auld V (2000) Frost Flowers as a source of fractionated sea salt aerosol in the polar regions. Geophys Res Lett 27:3469–3472. https://doi.org/10.1029/2000GL011771

Rantanen M, Karpechko AY, Lipponen A et al (2022) The Arctic has warmed nearly four times faster than the globe since 1979. Commun Earth Environ 3:168. https://doi.org/10.1038/s43247-022-00498-3

Roiger A, Thomas J-L, Schlager H, Law KS, Kim J et al (2015) Quantifying emerging local anthropogenic emissions in the Arctic region: The ACCESS aircraft campaign experiment. Bull Am Meteorol Soc 96:441–460. https://doi.org/10.1175/BAMS-D-13-00169.1

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

Schmale J, Baccarini A (2021) Progress in unraveling atmospheric new particle formation and growth across the Arctic. Geophysical Research Letters 48(14):e2021GL094198. https://doi.org/10.1029/2021GL094198

Schmale J, Sharma S, Decesari S, Pernov J, Massling A, Hansson H-C, von Salzen K, Skov H, Andrews E, Quinn PK, Upchurch LM, Eleftheriadis K, Traversi R, Gilardoni S, Mazzola M, Laing J, Hopke P (2022) Pan-Arctic seasonal cycles and long-term trends of aerosol properties from 10 observatories. Atmos Chem Phys 22:3067–3096. https://doi.org/10.5194/acp-22-3067-2022

Senger K, Ammerlaan F, Betlem P, Dumais M-A, Eagles G, Foster W et al (2025) Geology of Svalbard: Deep-time and Deep-Earth. In: Runge et al (eds) SESS report 2024, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 52-83. https://doi.org/10.5281/zenodo.14425478

Sharma S, Barrie LA, Magnusson E, Brattström 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. Journal of Geophysical Research: Atmospheres 124(14):133–14,161. https://doi.org/10.1029/2019JD030844

Sharma S, Ishizawa M, Chan D, Lavoue D, Andrews E et al (2013) 16-year simulation of Arctic black carbon: Transport, source contribution, and sensitivity analysis on deposition. J Geophys Res 118(2):943–964. https://doi.org/10.1029/2012JD017774

Sharma S, Chan E, Ishizawa M, Toom-Sauntry D, Gong SL, Li SMD, Tarasick W, Leaitch WR, Norman A, Quinn PK, Bates TS, Levasseur M, Barrie LA, Maenhaut W (2012) Influence of transport and ocean ice extent on biogenic aerosol sulfur in the Arctic atmosphere. J Geophys Res 117:D12209. http://dx.doi.org/10.1029/2011JD017074

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-Science Reviews 210:103346. https://doi.org/10.1016/j.earscirev.2020.103346

Spolaor A, Salzano R, Scoto F, Barbaro E, Luks B, Laska M et al 2025) Understanding and analyzing recurrent warm events in Svalbard: a comprehensive review on land cryosphere. In: Runge et al (eds) SESS report 2024, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 212-227. https://doi.org/10.5281/zenodo.14425903

Stohl A (2006) Characteristics of atmospheric transport into the Arctic troposphere. J Geophys Res 111:D11306. https://doi.org/10.1029/2005JD006888

Stohl A, Klimont Z, Eckhardt S, Kupiainen K, Shevchenko VP et al (2013) Black carbon in the Arctic: The underestimated role of gas flaring and residential combustion emissions. Atmos Chem Phys 13:8833–8855. https://doi.org/10.5194/acp-13-8833-2013

Stohl A, Andrews E, Burkhart JF, Forster C, Herber A, Hoch SW, Kowal D, Lunder C, Mefford T, Ogren JA, Sharma S, Spichtinger N, Stebel K, Stone R, Strom J, Torseth K, Wehrli C, Yttri KE (2006) Pan-Arctic enhancements of light absorbing aerosol concentrations due to North American boreal forest fires during summer 2004. Journal of Geophysical Research: Atmospheres 111:D22214. https://doi.org/10.1029/2006JD007216

Tatzelt C, Henning S, Welti A, Baccarini A, Hartmann M, Gysel-Beer M, van Pinxteren M, Modini RL, Schmale J, Stratmann F (2022) Circum-Antarctic abundance and properties of CCN and INPs. Atmos Chem Phys 22:9721–9745. https://doi.org/10.5194/acp-22-9721-2022

Traversi R, Becagli S, Severi M, Mazzola M, Lupi A, Fiebig M, Hermansen O, Krejci R (2024) Arctic haze in a climate changing world: the 2010–2022 trend. In: Verret et al (eds) SESS report 2023, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 64-73. https://doi.org/10.5281/zenodo.10254992

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

Tobo Y, Adachi K, Kawai K. *et al.* (2024) Surface warming in Svalbard may have led to increases in highly active ice-nucleating particles. Commun Earth Environ 5, 516. https://doi.org/10.1038/s43247-024-01677-0

Vergara-Temprado J, Miltenberger AK, Furtado K, Grosvenor DP, Shipway BJ, Hill AA, Wilkinson JM, Field PR, Murray BJ, Carslaw KS (2018) Strong control of Southern Ocean cloud reflectivity by ice-nucleating particles. PNAS 115(11):2687–2692. https://doi.org/10.1073/pnas.1721627115

Warneke C, Bahreini R, Brioude J, Brock CA, de Gouw JA et al (2009) Biomass burning in Siberia and Kazakhstan as an important source for haze over the Alaskan Arctic in April 2008. Geophys Res Lett 36(2):L02813. https://doi.org/10.1029/2008GL036194

Warneke C, Froyd KD, Brioude J, Bahreini R, Brock CA et al (2010) An important contribution to springtime Arctic aerosol from biomass burning in Russia. Geophys Res Lett 37(1):L01801. https://doi.org/10.1029/2009GL041816

Towards an integrated data-driven infrastructure (InfraNor)

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1. Introduction

The Arctic is warming almost four times faster compared to the rest of the world (Rantanen et al. 2022). Svalbard and its surroundings have warmed faster than most of the Arctic (Cai et al. 2021; Isaksen et al. 2022). The Svalbard archipelago also shows large temperature variations from south to north and east to west (Østby et al. 2017). Svalbard has good infrastructure, logistics and communications (airport, port, laboratories), and excellent possibilities for data transfer. This makes Svalbard and its surroundings an attractive living natural laboratory for long-term and campaign-based Arctic studies.

Svalbard Integrated Arctic Earth Observing System (SIOS) is a Norwegian-initiated international cooperation to exploit Svalbard's research infrastructure for the purpose of increasing knowledge about global climate and environmental changes through long-term monitoring (Christiansen et al. 2024). It currently includes 29 member institutions from 10 different countries with a research focus relevant to interdisciplinary earth system studies in and around Svalbard. These studies explore the complex interrelationships between ocean currents, atmospheric and geological conditions, the extent of ice and snow, and terrestrial food webs of plants and animals. Within SIOS, researchers collaborate by sharing and integrating data and research infrastructure to build an efficient observing system that focuses on long-term monitoring of parameters that are important for understanding the Arctic in the context of global environmental change.

The research infrastructures[1] in Svalbard have mainly been established as independent activities by projects or research stations. The existing environmental monitoring and observation infrastructures in Svalbard are generally maintained at a high standard and are state-of-the-art. While the individual observations and research infrastructures might be of good quality, they are not optimised and the gathered data are not harmonised, except for e.g., in COAT (Pedersen et al 2025). SIOS utilises existing infrastructure, as well as new infrastructure, instigated by considerations and deliberations of the working groups coordinated by the central hub, SIOS-Knowledge Centre.

SIOS-InfraNor is a regional distributed observing system utilising versatile infrastructure from in situ to satellite remote sensing observations (Figure 1). The project, funded jointly by the Research Council of Norway and the Norwegian Space Agency (NoSA), strengthens SIOS with a coordinated and state-of-the-art observation network for marine, terrestrial and atmospheric research. This network, which provides data in accordance with the FAIR principles (Wikinson et al. 2016), is implemented and operated in and around Svalbard. The InfraNor project, as a prioritised infrastructure initiative identified through a gap analysis study, provides new and upgraded research facilities to support addressing Earth System Science (ESS) questions on global environment change. SIOS offers a single point of access to infrastructure, data, tools and services owned or operated by its members.

InfraNor is a response to the ongoing effort to optimise the SIOS observing system. This effort builds on the SIOS Strategy for Optimisation, and draws on work conducted through the SIOS Science Optimisation Service[2] (as described in the SIOS current state document[3]). The focus is on observational measurements to address regional issues and offer an opportunity for much more comprehensive monitoring of ESS-relevant variables throughout the region as articulated in the SIOS Infrastructure Optimisation Report[4]. The report targets vertical and horizontal interactions, cryosphere–geosphere dynamics, and climate change impacts on biodiversity and ecosystems.

1 https://research-and-innovation.ec.europa.eu/strategy/strategy-research-and-innovation/our-digital-future/european-research-infrastructures_en
2 https://sios-svalbard.org/Optimisation
3 https://sios-svalbard.org/sites/sios-svalbard.org/files/documents/2024-09/20240909_sios_currentstate.pdf
4 https://sios-svalbard.org/system/files/common/Documents/D3.4_SIOSInfrastructureOptimisationreport_PP.pdf

In order to be consistent with the thematic division in the Norwegian SIOS prioritisation report (Mehlum et al. 2013), we divided SIOS-InfraNor into 6 modules: Modules 1-4 contain scientific infrastructure priorities related to studies of atmosphere, land, ocean, and interdisciplinary research, Module 5 deals with data management, and Module 6 with project management.

The aim of this chapter is to present the main components of each module's implemented InfraNor monitoring system. It highlights the key items, outlines their characteristics, provides specimens of the collected datasets, along with references to selected novel scientific results published thanks to this infrastructure.

Furthermore, it explains how the system integrates data into a distributed coherent observing system that is addressing the needs of ESS as outlined in the SIOS Strategy for Optimisation, the SIOS Vision and the SIOS Strategy. A key component of this integration is the SIOS Data Management System[5] (SDMS), which acts as a bridge between the various science components of the Earth System through standardised and harmonised exposure of the collected data. The combined effect of this approach facilitates interdisciplinary science and enhances collaboration.

A list of acronyms used in this chapter is provided in Appendix 1.

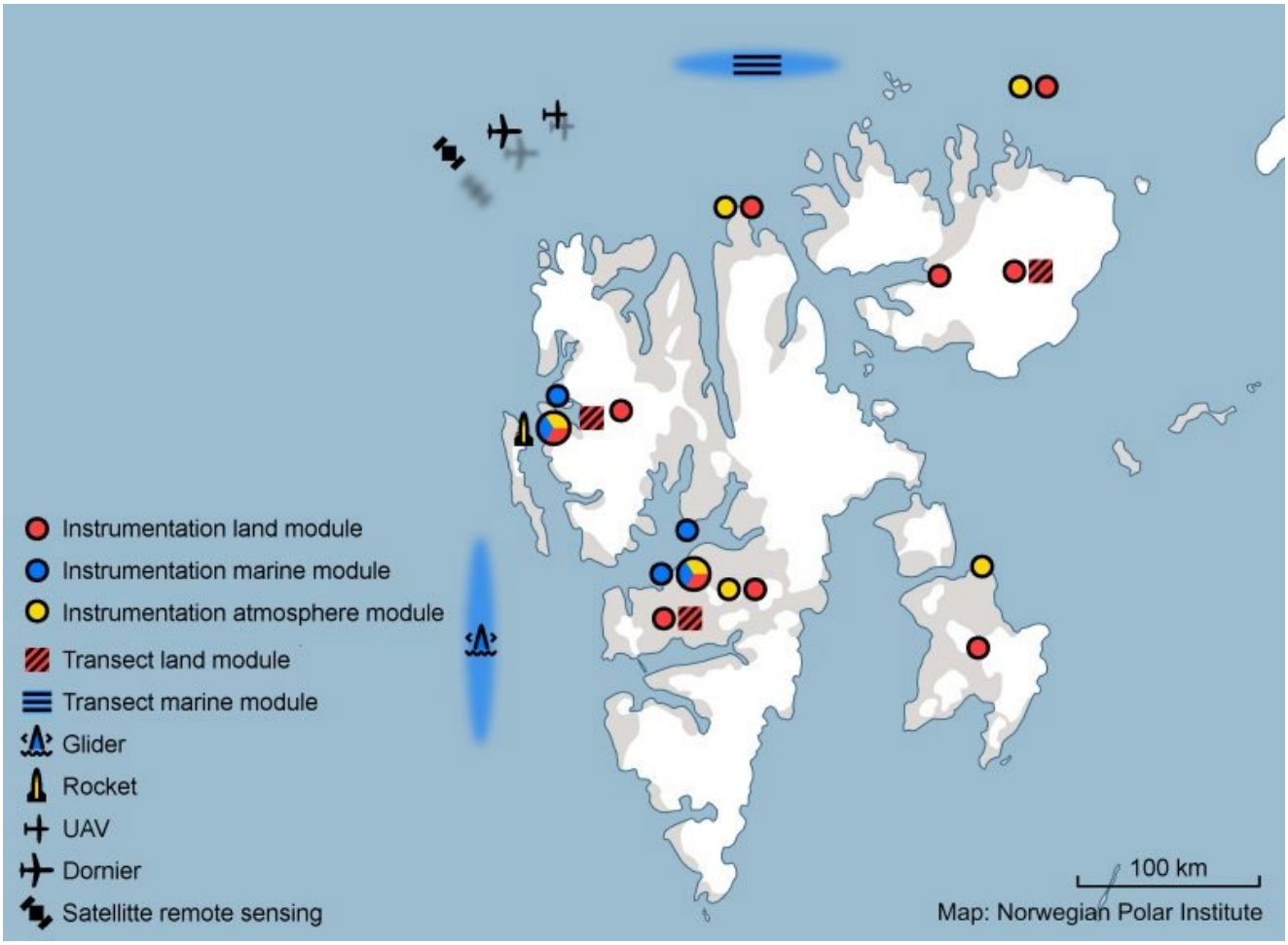

Figure 1: The InfraNor distributed installations within the atmosphere, terrestrial, ocean and common modules. Map by Anders Skoglund (NPI).

5 https://sios-svalbard.org/Data

2. Overview of the modules and their achievements

2.1. Module 1 – Atmosphere

This module focuses on enhancing and expanding observations of meteorology, climate, surface energy/radiation processes, and trace gas and aerosol characteristics. It also addresses air pollution transport to the Arctic and aims to improve understanding of the coupling between space and the upper and lower atmosphere, particularly in the polar region. Meteorological observations are essential parameters for other modules, supporting studies of land and ocean–atmosphere interactions and aiding in the assessment of climate impacts across the Arctic environment.

The module includes: 1) upgrading of the automatic weather stations (AWS) at Verlegenhuken and Edgeøya with radiation and snow depth measurements, combined with permafrost boreholes of Module 2; 2) upgrading the SOUSY Svalbard Radar in Adventdalen to continue the time series on polar mesospheric summer echoes (PMSE) and tropopause height; 3) resuming ionospheric soundings in Ny-Ålesund with a CADI-ionosonde to monitor the ionosphere for space weather and radio propagation conditions; 4) installing an Aerodynamic Particle Sizer (APS) at Zeppelin station to measure coarse (dust) aerosols; 5) installing and upgrading a Lunar Precision Filter Radiometer (PFR) instrument that measures the aerosol optical depth (AOD) making use of the moonlight methodology (Mazzola et al. 2024); 6) installing a Pandora instrument measuring atmospheric columns of trace gases, the two latter both at the Sverdrup station. The upgrades and installations of the atmospheric infrastructure took place from 2018 to 2021, and all the instruments have been operational for several years. Data are openly available in various international repositories and linked to the SIOS Data Management System (SDMS).

The observations enabled by InfraNor have proven to be valuable in several areas, including:

- The upgrade of the AWS provides important new data on surface–atmosphere energy exchanges at 80°N, at the northernmost point of Spitsbergen, Svalbard (Isaksen et al. 2022).
- The upgrade of the SOUSY radar continues one of the longest time series (since 1998) on PMSE (Hall et al. 2020) and in Feb. 2024, polar mesospheric winter echoes (PMWE) were observed for the first time. As a biproduct of the upgrade, the radar is now also capable of measuring vertical winds in the troposphere.
- The CADI ionosonde data are extensively used in both space weather applications and ionospheric research and for diagnosing high frequency (HF) radio conditions.
- The study of vertical coupling processes in the atmosphere, from the ground to space, includes not only data from the SOUSY radar and CADI ionosonde, but also rocket-borne process research from the CGI-cusp initiative. Data from CGI-cusp is being integrated with InfraNor data within the SDMS to address knowledge gaps in the SIOS initiative related to energy transport through the atmosphere (Moen et al. 2019).
- The APS has increased the size range in the size distribution measurements, making it possible to detect larger aerosols especially important during the arctic haze period and for detecting dust episodes (Platt et al. 2023).
- The lunar PFR has enabled measurements during the polar night, allowing for the analysis of annual cycles and year-round trends in AOD in the Arctic, which is rarely done (Platt et al. 2023).
- The Pandora instrument is fully operational in validating the ESA Sentinel-5P satellite (Compernolle et al. 2024). The validation of NO_2 has significantly improved due to parallel instrumentation. For O_3, measurements can now be taken year-round, whereas older instruments often stopped at lower azimuth levels (Svendby et al. 2024).

An example of a data product available from module 1 is shown in Figure 2.

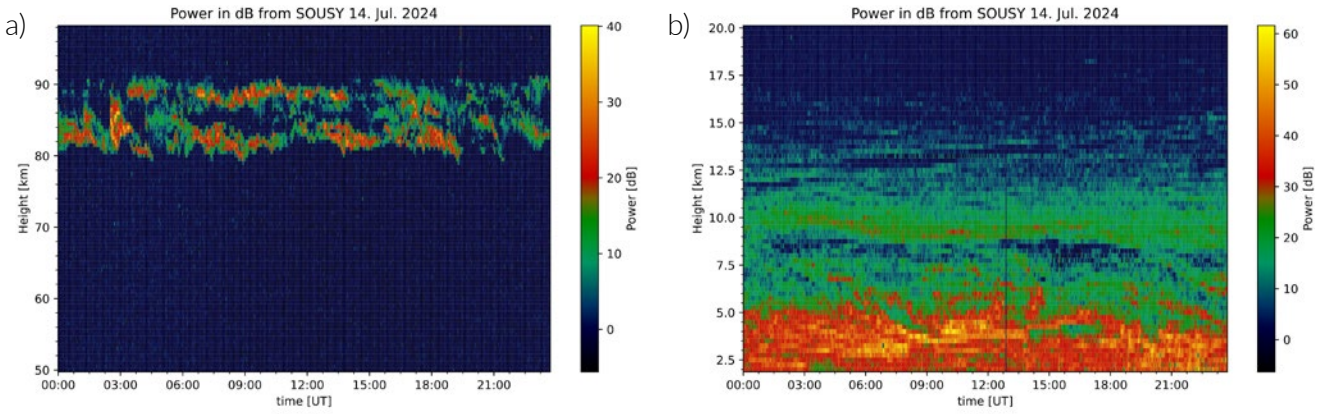

Figure 2: Raw backscatter signals in dB from the SOUSY Mesosphere Stratosphere Troposphere (MST) radar in Adventdalen from 14 July 2024. (Njål Gulbrandsen). **a)** Polar Mesospheric Summer Echos (PMSE), a strong radar backscatter in the mesosphere due to charged dust and ice particles that only happens in the summer when the temperatures in the mesosphere are low enough for ice formation. **b)** Radar backscatter from the troposphere due to dust, fluctuating temperature and humidity, and turbulence. Especially visible is the tropopause seen around 10 km. The radar is also capable of measuring vertical wind in the troposphere.

2.2. Module 2: Land

2.2.1. The SIOS terrestrial module

The SIOS land module implements an ecosystem and landscape-based observatory that focuses on key components of both predictor and driver targets. The monitoring covers different parts of the Svalbard landscape in the cryosphere, hydrosphere, and biosphere to enable real-time detection, documentation, understanding and prediction of climate impacts on Arctic tundra ecosystems. The infrastructures are implemented through a suite of instruments and study designs (Figure 3 and Pedersen at al. 2025). The module incorporates the *Climate-ecological Observatory for Arctic Tundra* (COAT; see Pedersen et al. 2025; Ims et al. 2013, Ims and Yoccoz 2017) and 15 separate instruments/infrastructures across eight institutions. This infrastructure provides detailed data for coupled process modelling at relevant temporal and spatial scales for the terrestrial ecosystem, as well as observations from the climatic gradients in Svalbard for larger scale studies and Earth System models. The implemented research infrastructure has both expanded and strengthened existing monitoring programmes, such as the Environmental Monitoring of Svalbard and Jan Mayen and the Global Terrestrial Network on Permafrost (GTN-P). Additionally, it provides new time-series and research infrastructure for focal ecosystem components and drivers that were previously lacking, such as snow monitoring.

Glaciology

Glaciers cover about 60% of the Svalbard archipelago and have lost significant mass over the last few decades. In situ measurements of mass balance are labour-intensive and thus limited to a few glaciers. Nevertheless, such direct measurements are essential to constrain and evaluate remote sensing products (e.g., Morris et al. 2022; Gray et al. 2015) and model simulations (e.g., Schmidt et al. 2023; Van Pelt et al. 2019; Østby et al. 2017) that are used to assess the state of balance of Svalbard glaciers on a regional scale (pan-Svalbard, Schuler et al. 2020). The infrastructure investments made by InfraNor and related SIOS-optimisation services permit now close-to-real-time records of glacier mass balance components, snow depth, snow and firn temperature profiles and surface flow velocity. Some of these essential variables related to the cryosphere are already accessible as quality-controlled datasets through the SIOS data portal; for the remaining records, such data publication currently is prepared or in progress. (Schuler et al. 2022; NPI-UiO, 2023). Near-surface measurements of meteorological variables (e.g., Schuler et al. 2013) also play an

important role in filling the gaps in otherwise data-sparse regions, outside the coverage of operational weather-forecasting networks.

Snow

Snow is a critical component for Arctic climate and ecosystems, particularly in Svalbard, with a strong oceanic influence. The land module has established Svalbard as a much-needed (Christensen et al. 2023) super-site for calibration–validation of Arctic snow monitoring by implementing infrastructures on the ground and maintaining time-series of satellite remote sensing of snow parameters and field measurements. Several new automatic stations for snow depth measurements distributed across Svalbard and the COAT climate monitoring network significantly contribute to understanding the distribution of snow (cross reference to COAT chapter). SIOS has also established new relations between modellers and observers. The results of decadal intercomparisons have been documented in several scientific papers and in SESS reports (Vickers et al. 2020, 2022).

The land module has established field monitoring of the most important snow–climate variables, snow cover fraction (cameras), snow depth and snow water equivalent (ground penetrating radar). In addition, we have also established long term remote sensing time-series of additional parameters, such as snow wetness and avalanche activity. These parameters are crucial for understanding the effects of climate change in Svalbard. This infrastructure, together with extensive field campaigns during the years 2018–2023 has provided a significantly enhanced snow observation regime in Svalbard that has been documented as FAIR data in the SIOS Database.

Hydrology

The land module has established one new discharge station in the outlet of Linnévatnet lake, on the coast of Nordenskiöld Land; the Bayelva station, at the west coast close to Ny-Ålesund Research Station, has been reestablished because the old station was damaged due to the thawing of permafrost; and the De Geer station, in Nordenskiöld Land close to Longyearbyen, has been upgraded to improve data quality. The upgraded station is important in the continuation of the long-term hydrological monitoring series. The new station contributes to the Kapp Linné Environmental Observatory (KLEO) (Retelle et al. 2019). With the establishment, we have ensured that accurate discharge measurements continue from existing gauging stations, as well as from a new station. The continuation of the existing long-term discharge series and the establishment of new ones are critical for monitoring hydrological changes, as highlighted by Nowak et al. 2020. Data from all SIOS InfraNOR discharge stations are submitted to the Norwegian Water and Energy Directorate's Hydra 2 database and published in near real-time[6]also be included in the SIOS data management system, adhering to the FAIR principles.

Permafrost

Permafrost in Svalbard is widespread and traditionally classified as continuous, except under the larger glaciers. It is the warmest this far north in the Arctic (Romanovsky et al. 2010) and the longest existing record (from the Janssonhaugen permafrost monitoring site in Adventdalen, close to Longyearbyen) shows a distinct warming trend (Isaksen et al. 2022). The thermal state of permafrost in different landforms has only been monitored since the International Polar Year in 2008, and mainly in central Svalbard and only in the top layers of the permafrost typically down to 10 m depth. Very little data had been collected on the amounts and types of ice in the permafrost (cryostratigraphic studies), despite this being crucial to understanding the potential effects of climate change on the different parts of the Svalbard landscape. To be able to monitor the thermal conditions below the depth of the annual thermal variation, we have drilled 218 m in 8 boreholes, all with temperature observations down to 20 m depth in the Adventdalen area, in different landforms. The infrastructure in each borehole consists of a 20 m thermistor string with 25 sensors installed in a 21

6 https://sildre.nve.no

m long PVC casing. Also, a borehole that almost penetrates the permafrost in Adventdalen reaches down to 101 m (Figure 3) (Christiansen 2024). Boreholes have also been drilled at more remote locations: at Verlegenhuken, the northernmost point of Spitsbergen, and at Edgeøya - Kapp Heuglin in eastern Svalbard in connection with the operational automatic weather stations run by MET Norway. Co-locating these stations increases the value of permafrost data for researchers, model developers, and other users who require the most recent data, as it links directly to a national weather station that allows for quick and easy access (Isaksen et al. 2022). Data transfer occurs every 6 hours through the GSM mobile network or Iridium satellite communication directly to MET Norway in Oslo or downloaded annually if outside mobile and satellite phone coverage. Data is available in near real time in the cryo-web portal[7] and is under integration with SDMS following the FAIR guiding principles and the standards required for SIOS Core Data.

Permafrost cores have been obtained from fine-grained sediment to diamict with large clasts in blockfields from all of the boreholes, which have provided information on the ice content, type and age of the permafrost in different parts of the Svalbard landscape (Christiansen et al. 2021). These cores have been obtained using the UNIS medium-sized permafrost drill rig (Figure 3), which has been upgraded to be able to drill in these various sediment types that exist in Svalbard, including coarse-grained slope sediments that could not be cored previously.

With the extended boreholes the depth of zero annual amplitude (ZAA ≤ 0.1°C) has been reached at all borehole sites. The geothermal gradient varies in the 100 m deep borehole in Endalen from 0°C/m from the depth of ZAA down to 50 m depth (Figure 4), and below there increases to a maximum of 0.037°C/m from 90 to 100 m depth. This shows very clearly that the ongoing warming has reached a depth of around 50 m at that site.

Biosphere

A key to predicting Svalbard tundra ecosystem responses to drivers of change is a thorough understanding of the functioning of food webs (Legagneux et al. 2012, Mellard et al. 2021). The *Climate-ecological Observatory for Arctic Tundra* (COAT), a core of the SIOS biosphere monitoring, has implemented research infrastructure to facilitate data-driven causal analyses and short-term predictions (see chapter 7 – cross-ref to COAT chapter). One major outcome obtained from the

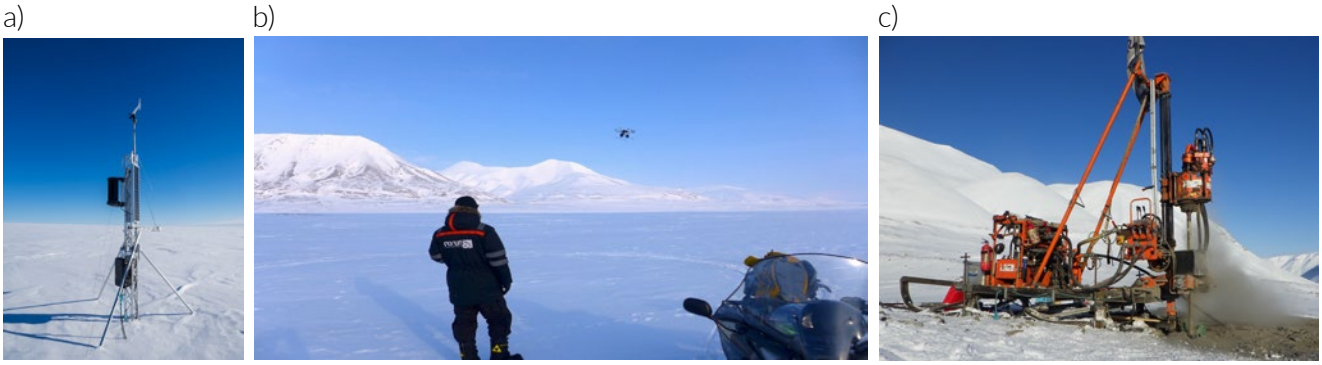

Figure 3: The land module contains infrastructure established by the Climate-ecological Observatory for Arctic Tundra plus 15 separate instruments/infrastructures across eight institutions. A few examples are shown here. **a)** Automatic weather station operated on Etonbreen, Austfonna recording near-surface temperature, relative humidity, wind direction and speed, radiative fluxes, as well as snow height and air temperature. These are transmitted to University of Oslo for quality-control and analysis. Solar panels and a wind-turbine provide sustainable energy to power the recording and transmission systems. (Photo: Thorben Dunse). **b)** Field campaign in Adventdalen using drone with ground penetrating radar to measure snow depth over extended areas. (Photo: Eirik Malnes). **c)** The InfraNor upgraded UNIS medium-sized 3 m high permafrost drill rig (Photo: Ullrich Neumann / Kolibri GeoServices).

7 https://cryo.met.no

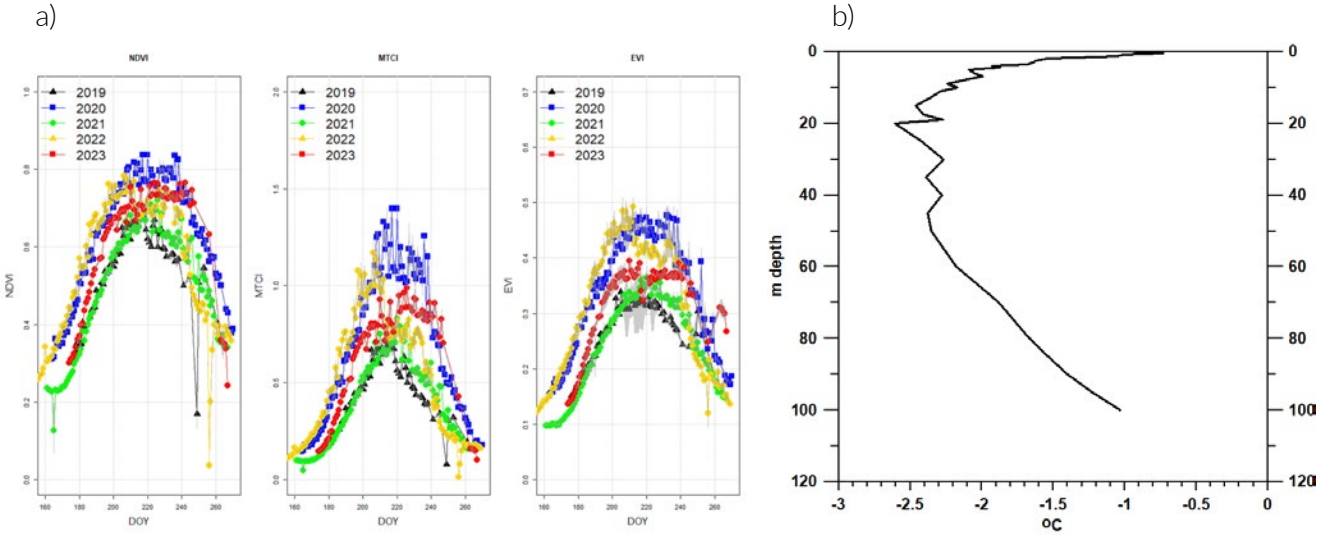

Figure 4: The land module has resulted in numerous scientific results, exemplified here by two important aspects of climate warming, namely Arctic greening and permafrost thawing. **a)** Annual Measurements of different greening-related parameters (NDVI, MTCI [MERIS Terrestrial Chlorophyll Index], and EVI [Enhanced Vegetation Index]) extracted from the hyperspectral FLoX (i.e., hyperspectral field sensor) system for the growing seasons of 2019–2023. The MERIS terrestrial chlorophyll index (MTCI) is sensitive to chlorophyll content (Tømmervik 2024). **b)** Average ground temperature showing the geothermal gradient down the 100 m deep borehole in Endalen. Data from the period November 2021 to November 2023 (Christiansen 2024).

pool of data from the module, was the evaluation of the high-Arctic tundra ecosystem conditions (Pedersen et al. 2021) where one of the main findings is that while the cryosphere and climate have undergone clear changes, the biosphere responses are less pronounced, and biological change may be lagging behind the climatic changes.

Karlsen et al. (2024) report a recent rapid and strong increase for Svalbard tundra productivity (MaxNDVI, Normalised Difference Vegetation Index) strongly related to the recent air temperature increase during the growth season. The high tundra productivity observed in 2022 through remote sensing methods is corroborated by in-situ hyperspectral measurements (Tømmervik et al. 2023; Figure 1). Trends noted through monitoring by near-surface NDVI and hyperspectral sensors in the period 2015–2023 (Karlsen et al. 2021; Parmentier et al. 2021; Karlsen et al. 2022; Tømmervik et al. 2023) were similar to those reported by Karlsen et al. (2024).

2.2.2. Module 3: Ocean

This module focuses on enhancing the marine infrastructure needed for better temporal and spatial coverage around Svalbard to capture the rapidly changing Arctic marine environment. The network of ocean observatories combines fixed observatories with mobile autonomous vehicles to record long-term time series for monitoring climate change and long-term trends, and short-term, high-resolution spatial studies. The observatories monitor areas like the Arctic Ocean inflow west and north of Svalbard and shelf-fjord regions along the West Spitsbergen coast, including physical and biological oceanographic coupling; structure and variability of ocean currents; ocean nutrients and pollutants (horizontally, vertically and through the food chain); and ecosystem resilience to climate seasonal variability and long-term change.

The module includes: 1) Long-term monitoring of the Atlantic Water inflow to the Arctic Ocean and onto the continental shelf and fjord areas through the A-TWAIN mooring array north of Svalbard (NPI/IMR) and the oceanographic mooring in Kongsfjorden (UiT), respectively; 2) Monitoring of changes of temperature, salinity, and circulation pattern in Isfjorden and Adventfjorden through the UNIS Online mooring (Figure 5a) and the NIVA mooring, respectively; 3) Improved spatial coverage of ocean observations by using gliders (Figure 5b) ranging from deep waters, over the continental slope, to the shelf, to understand the dynamics

and variability of the current carrying warm Atlantic water toward the Arctic Ocean and the exchange mechanisms important for Atlantic Water intrusion towards the Arctic fjords; 4) Tracking methane release and other greenhouse gas exchanges from the seafloor (continental shelf) to the sea surface using observatories such as the K-Lander system; and 5) Attaining better understanding of physical and biological coupling by adding biological and biogeochemical instrumentation to the infrastructures listed in 1)-4).

The upgrades of existing marine infrastructure, and the purchase and deployment of new observation platforms, took place from 2018 to 2023. All infrastructures have provided data (except the K-Lander) and been operational for several years. Data are openly available in various international repositories, linked to the SIOS Data Management System (SDMS), and have been used in several publications.

The observations enabled by InfraNor Module 3 have proven to be valuable in several areas, including:

- The upgraded sensors on the mooring array north of Svalbard to measure Arctic Ocean inflow have provided data of physical, biochemical and biological relevance (Sundfjord et al. 2022).
- Moorings in Kongsfjorden (which have produced the longest marine time series in Svalbard) were upgraded and new moorings were acquired to collect data in Isfjorden (southern side close to the Svalbard airport) and Adventfjorden (close to the Adventfjorden river delta) for physical, biochemical, and biological time series studies (e.g., Hop et al. 2019; Cottier et al. 2018, 2021; Skogseth et al. 2020).
- An online mooring was installed in Isfjorden. Although the acoustic transfer of ocean data to a surface buoy was unsuccessful, the surface buoy gave valuable real-time observations of sea surface temperature, sea surface salinity, ocean waves, and meteorological parameters (wind speed and direction, air pressure, relative humidity, dew point temperature).
- Complementary measurements of bio-geochemical parameters in the fjord close to the Adventfjorden river delta and from the river delta upstream (old Aurora station in Adventdalen) increased our understanding of land–ocean interaction processes.
- A new ocean glider, a 1000-m rated Teledyne Webb Slocum electric glider equipped with a pumped CTD system, was acquired and integrated into the glider pool and operations of the NorGlider facility coordinated by the University of Bergen. These gliders collected temperature and salinity profiles in waters around Svalbard.
- The SIOS InfraNor glider infrastructure has been available to the SIOS Access call since 2023 and was used by UNIS in 2023 and 2024 through the SIOS Access project "Spitsbergen Ocean Front Transect (SOFT)", providing valuable temperature and salinity profiles to study fjord circulation.

Scientific results from the InfraNor fixed mooring infrastructures (A-TWAIN, Kongsforden and Isfjorden) have been summarised in the ARiS chapter (Bensi et al. 2025). The integration of stationary fixed observatories with mobile autonomous vehicles provides unique insights into the factors that influence the dynamics of the marine environment around Svalbard. These insights include physical and biological oceanographic coupling, the structure and variability of ocean currents, ocean nutrients and pollutants (horizontally, vertically, and through the food chain); and ecosystem resilience to climate seasonal variability and long-term change.

Here we showcase the glider infrastructure. The glider is integrated into the glider pool and operations of the Norglider facility coordinated by the University of Bergen. This integration allows any available glider (Slocum or Seaglider) in the facility to be utilised for target transects or projects. The glider has been used to collect data in the West Spitsbergen Current off-shelf west of Svalbard as well as in Isfjorden (SIOS access project 2023 – SOFT_2023[8]) and the Barents Sea, supporting

8 https://sios-svalbard.org/SOFT_2023

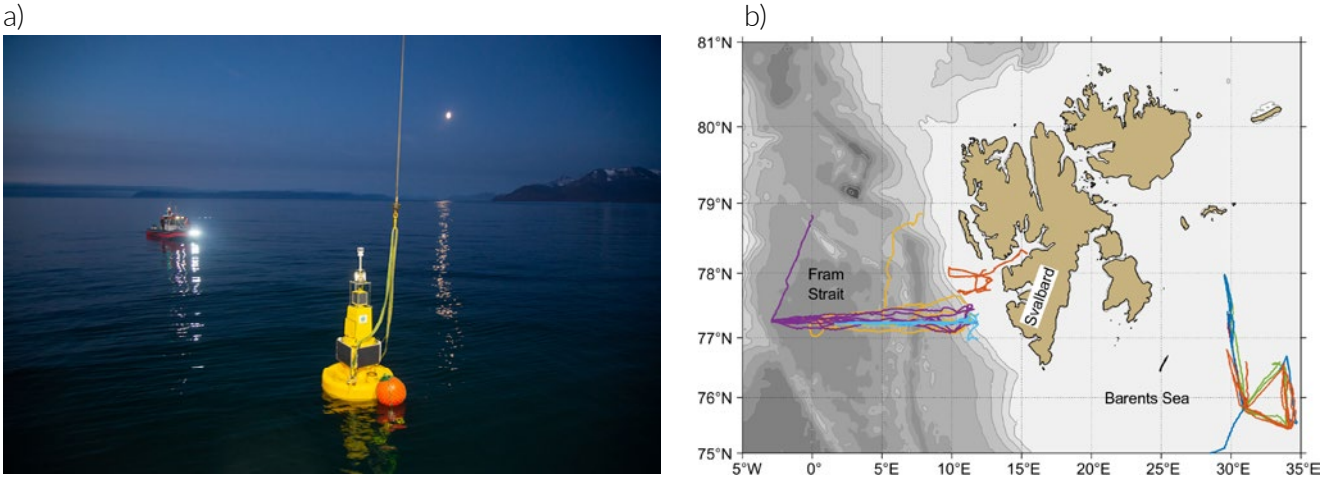

Figure 5: (a) UNIS Online Mooring in Isjorden. (Photo: Eva Falck) **(b)** Glider mission tracks in Fram Strait, Isfjorden and in the Barents Sea. Each coloured track represents a different mission. In Fram Strait, 3 missions repeatedly sampled the West Spitsbergens Current, and in the Barents Sea, 6 missions repeatedly sampled selected transects in the region. (Figure: Ilker Fer)

the Nansen Legacy activity. Data from these missions are available from Fer et al. (2021), Kolås et al.(2022), and Fer et al. (2024). The scientific results are reported in Kolås et al. (2020) and Kolås et al. (2024). The glider will continue to be available based on rentals and other financed activities.

Four successful deployments were made west of Spitsbergen, including one in Isfjorden. Since October 2018, the glider has conducted a total 518 science days (out of 537 total mission days) resulting in 2390 profiles. During these missions, 22 transects were obtained across the West Spitsbergen Current, between the prime meridian and the 400-m isobath at about 12°E. This dataset is presently being analysed to study the dynamics and variability of the current carrying warm Atlantic water toward the Arctic Ocean. Excluding targeted missions with microstructure probes in the Barents Sea polar front region, 6 standard glider missions were made in the Barents Sea between summer 2019 and fall 2022, with 403 days of science sampling returning more than 6000 profiles. Using the observations from the gliders, combined with observations from scientific cruises and a historical dataset compiled by UNIS (Skogseth et al. 2019), Kolås et al. (2024) presented detailed circulation pathways in the northwestern Barents Sea, and quantified that half of the Atlantic Water inflow through the Barents Sea opening between Svalbard and Norway reaches the Hopen Trench, and then subducts under polar waters and continues northward, steered by topography. Compared to 1980, the average Atlantic Water temperature in this region increased by 0.7°C and freshened by 0.1 g/kg, with implications for poleward transport of warm water.

2.2.3. Module 4: Common Infrastructure

In this module, we introduced new interdisciplinary research infrastructure that contributes unique capacities through collection of new data time series. The fact that the infrastructure and sensor capacities have applications in multiple domains lead to the creation of the Common Infrastructure Module.

Specific remote sensing products are identified as one of the common infrastructures of the SIOS-InfraNor project. Daily CMOD5 (for neutral winds) processing of high-resolution Sentinel-1 SAR wind fields was set up at the Nansen Centre. The wind fields were estimated from VV polarised medium resolution (40 m) SAR normalised radar cross section (NRCS) combined with wind directions from the AROME-Arctic forecast model, available from the Norwegian ground segment and the Norwegian Meteorological Institute. The wind fields for 2019 and 2020 are made available to SIOS via the OPeNDAP protocol on the THREDDS server at the Nansen Centre and are expected to

be incorporated in the SIOS data catalogue.

A Svalbard-wide vegetation map has been generated as a common infrastructure using Sentinel-2 data. The Multispectral Instrument (MSI) onboard the satellites provide images with a resolution of 10, 20 and 60 metres. In this product Sentinel-2 A/B 14 images from the dates 2 August 2017 and 31 July 2017 are used in the map creation process. The final map is not yet available but is expected to be made available on SIOS data portal.

The main investment of this module was the establishment of the Dornier DO228 aircraft instrument pod, permanently stationed in Longyearbyen. This unique capability is a collaboration with Lufttransport AS whereby one of the firm's aircraft carries a permanently attached instrument pod housing state of the art sensors. This gives low-cost access throughout the year as there are no ferrying costs. The broadband long range communication system in the pod has allowed us to use the aircraft as a datamule transferring gigabytes of data from buoys within a 1000 km range. This is much more efficient than using an ice-breaker, reducing the environmental footprint of the research in addition to offering the possibility of real time data transfers to scientists in the field.

Key capabilities of the Dornier research Aircraft instrument pod[9]:

- Optical Imaging Sensors: The aircraft is fitted with hyperspectral sensors that capture data across 186 spectral bands in the range of 400–1000 nm and a 50 Mpix aerial RGB camera.
- High Resolution: The sensors provide a ground resolution of approximately 30 cm for the hyperspectral camera and 10 cm for the aerial RGB camera from an altitude of 1000 metres, covering about 600 metres across track.
- Georeferencing: With proper post-processing, the navigational data can achieve direct georeferencing with an accuracy of up to 0.5 pixels.
- Operational Flexibility: The aircraft is used for regular flights in the Svalbard region and can be chartered for specific research missions year-round.
- Future Expansion: There are plans to potentially include additional sensors such as a hyperspectral imager (SWIR 900-2500 nm), SAR sensor, thermal camera, and laser scanner.

There have been several campaigns where data have been collected since the platform became operational in 2020, supporting a wide range of studies within glaciology, vegetation and marine and coastal studies. Flight tracks for hyperspectral data capture are shown in Figure 6a. An example of use of the airborne data is presented by Błaszczyk et al. 2022, where the aerial data are combined with terrestrial laser scanning data to study geomorphological changes in the Hornsund area. Jawak et al. 2021 describes how the SIOS aircraft data products helped fill the data gaps caused by the Covid-19 pandemic travel restrictions and lack of in situ data acquisition in 2020.

Drone services are also part of the SIOS Research Infrastructure Access Programme. One example of how these services can be applied is collection of data on snow water equivalents using a drone mounted UWB radar (Eckerstorfer et al. 2018); another is use of a vertical take-off and landing (VTOL) drone to scout for icebergs from RV Kronprins Haakon in support of the SFI CIRFA cruise (Dierking et al. 2022). The drones are well suited for carrying custom sensor packages as they are based on open-source software which makes it easy to interface the data flow to the drone system and provide and inject essential metadata from the drone to the dataset, such as position, orientation and data from other sensors carried onboard. The multirotor drone currently available can carry up to 20 kg payload and has a flight time of between 10 and 45 minutes depending on payload weight. The VTOL drone can carry 2 kg payload for up to 2 hours and cover 100 km in a flight.

2.2.4. Module 5: Data management

The SIOS Data Policy promotes free and open

9 https://sios-svalbard.org/aerialRSplatforms

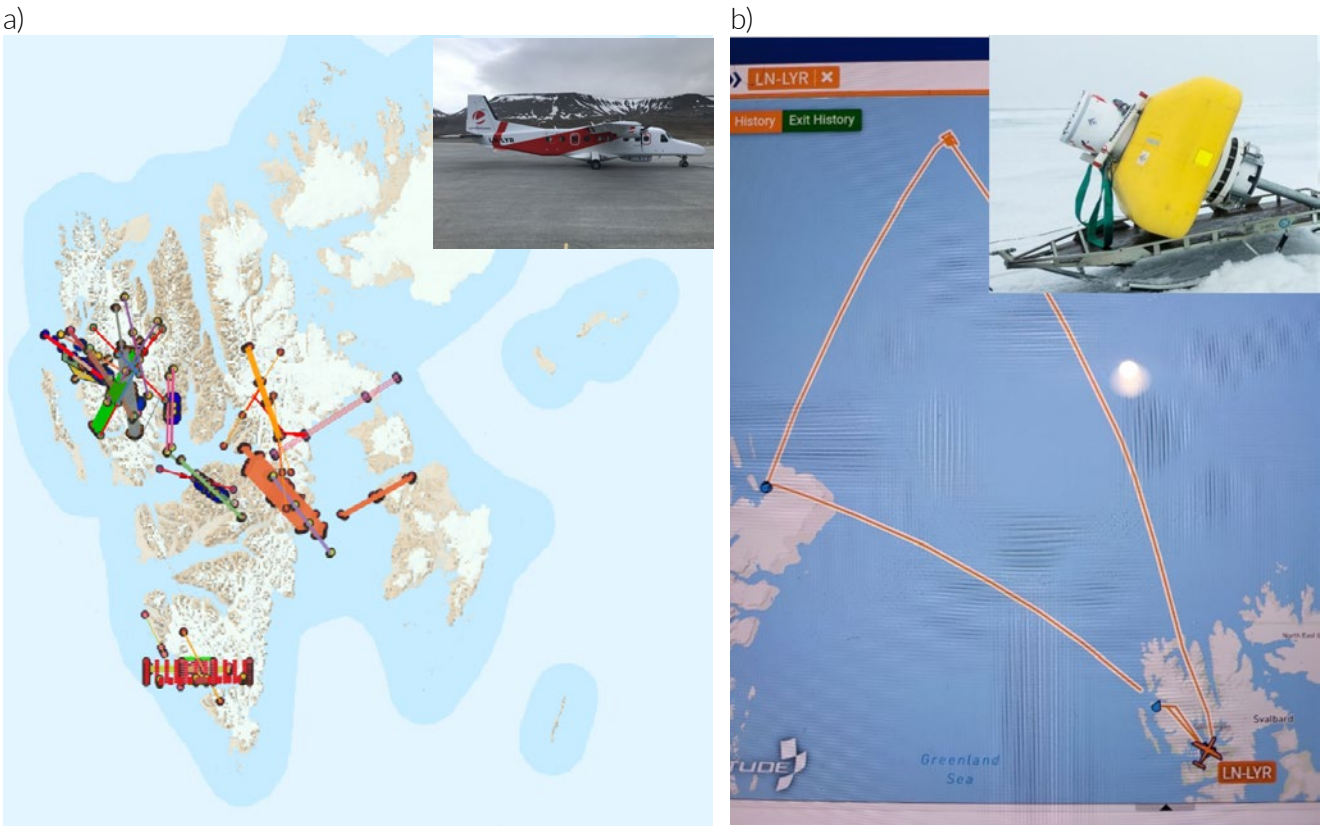

Figure 6: a) Flight tracks for Dornier hyperspectral data collection. (Photo: Agnar Sivertsen) **b)** Dornier as a datamule for the ArcticABC project. (Photo: Pedro de la Torre)

access to data. It is a requirement that scientists and projects utilising the SIOS Infrastructure also adhere to the SIOS Data Policy and deposit data in a data centre contributing to the SIOS Data Management System[10] (SDMS).

The main focus of SIOS-InfraNor data management has been to ensure that the data generated by the instrumentation funded are properly taken care of and shared through SDMS. SDMS is a physically distributed data management system where data are not hosted in a centralised location, but rather integrated through integration of data centres contributing to SIOS. Thus, to ensure a functional system, SIOS relies on agreed standards for documentation of and access to data. Utilisation of standards allows integration with discipline-specific (e.g., WMO Information System) and regional (e.g., Copernicus Marine Environmental Monitoring Service) data management systems. Development of the SDMS technical infrastructure is aligned with current efforts of, e.g., the combined SAON/IASC Data Committee and builds on the experience of distributed data management during the most recent International Polar Year.

SDMS is a physically distributed data management system tied together by discovery and harvest of metadata, which is similar to index cards in libraries, documenting what is measured, by whom, where, when and how it can be accessed. Sub-systems that do not comply with the agreed interoperability standards cannot be integrated. The lowest level of integration is unified data discovery. For this to be useful, harmonised terminology is essential for description of what is measured, and for identification of standardised data access mechanisms and documentation at the use level. If the latter parts are properly done by data centres contributing, it is possible to do on the fly visualisation, subsetting and transformation of datasets. An example of on-the-fly visualisation of data is provided in Figure 7 which shows the information from an automatic weather station on Etonbreen. Data are stored according to CF-NetCDF convention and served through an OPeNDAP server. This implies that the visualisation application can be operated by one data centre

10 https://sios-svalbard.org/Data

and the data served by another data centre. The user can choose if data are to be downloaded as NetCDF format or other formats (e.g., CSV for easy analysis).

Given the framework described above, the main emphasis during the project has been to improve integration of selected partner data centres and ensure proper documentation and publication of the datasets generated. All data collected during the project are supposed to qualify as SIOS Core Data and thus implicitly should be published in harmonised form using CF-NetCDF or Darwin Core Archives. This ensures that data easily and with the help of computers can be combined.

While proper documentation has been achieved for most of the datasets, some work is still pending in order to fully integrate all data through the data repositories handling them. When it comes to interoperability interfaces at partner data repositories, no major advances have been made during the project; interfaces are primarily as they were before the project started, with interoperability primarily achieved at the discovery level. This has been a challenge in SIOS since the start and in order to circumvent this, some datasets with a higher potential for integration across providers and with other data, and that have greater potential for reuse in community-wide services (e.g., EOSC and BlueCloud 2026) have been routed to data centres that have all interfaces in place. In addition, some already published datasets have been cached by these data centres in order to improve functionality. On a general basis there is a lack of understanding of what is needed of data management harmonisation in order to establish a coordinated network of observations (e.g., World Meteorological Organization, Global Biodiversity Information Facility) as opposed to the normally fragmented data documentation used in scientific communities.

While there have been challenges with harmonising data documentation for several datasets, this has succeeded for ocean data. The same applies to information from weather and permafrost stations as well as remote sensing data. Many of these datasets are documented using the standards required and are served through interfaces that allow integration into decision support systems or further processing. When it comes to biodiversity data – in this context essentially the ecosystem-based data of the Climate Ecological Observatory for Arctic Tundra (COAT) – only interoperability at the discovery level has been achieved, leaving no interoperability at the use level. For these datasets a human in the loop is required to understand the data collected and no services like on the fly visualisation can be offered.

Data generated by drones or the Dornier instrument pod have been a major challenge which is now addressed by data transformation tools allowing representation of point clouds in multiple forms, including CF-NetCDF as required by the SDMS Interoperability Guidelines. These data will be published as CF-NetCDF but users will have the ability to download data in other formats (as is supported, e.g., for timeseries).

Although there was a strong emphasis at management level on data management in the project, this focus, with a few exceptions, was not fully understood nor adopted at the instrument implementation level. The understanding of what the FAIR guiding principles imply is weak in the community. One potential cause could be that many observational scientists are more interested in their own data than in combining these with other data. The situation is quite different among scientists within remote sensing and numerical simulation as these often use data provided by others and see the benefit in harmonised documentation standards. Another explanation could be that the knowledge and skills to create good datasets are lacking. This could be compensated by training activities, which was not covered well in the project. This will of course only help if data providers understand the need for harmonised documentation in order to integrate data across data providers.

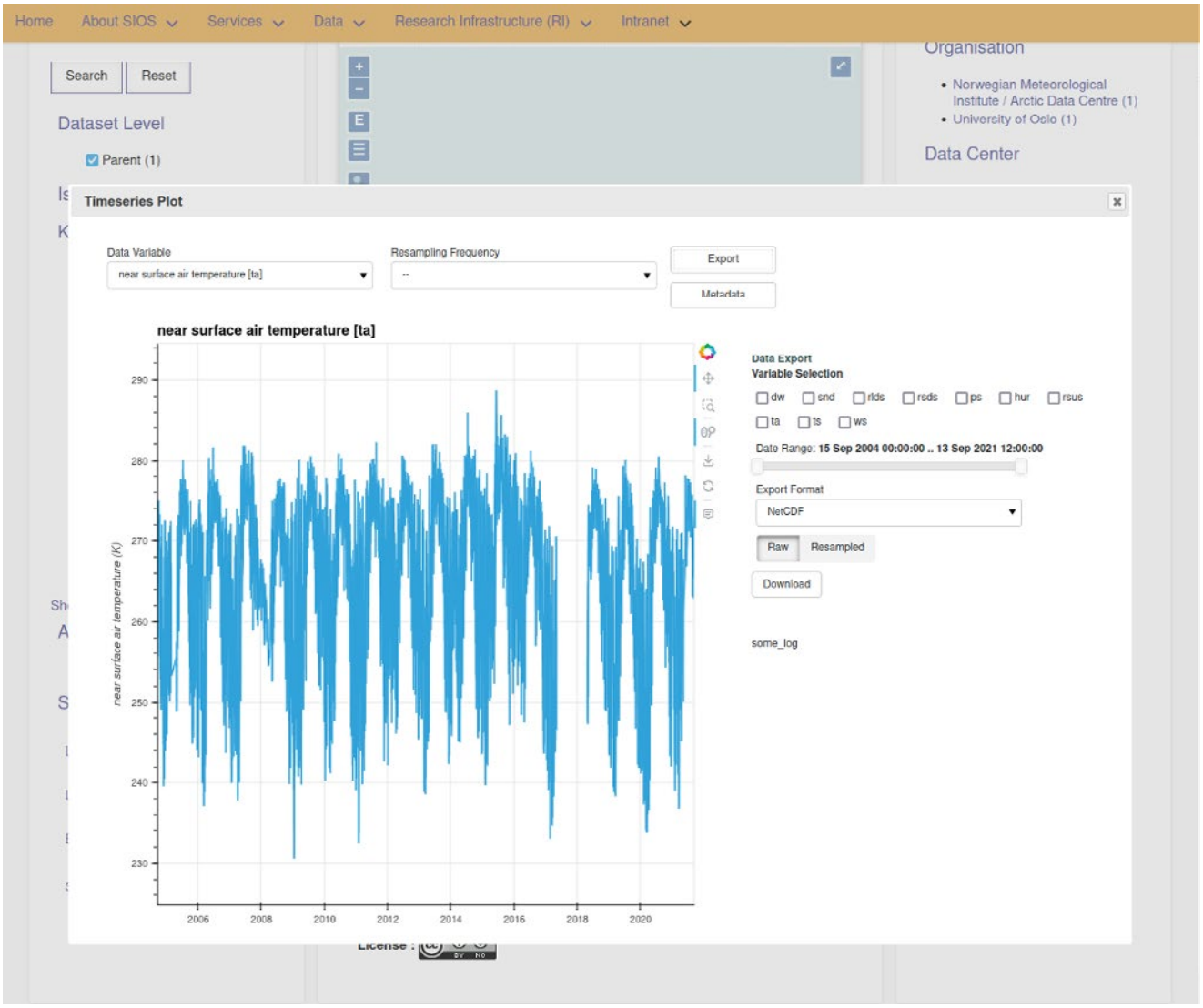

Figure 7: Screen dump of a dataset collected using an automatic weather station at Etonbreen. This is the visualisation available in the data portal if data are published in the appropriate form.

3. Contributions to interdisciplinarity

InfraNor's multidisciplinary nature enables interdisciplinary capabilities by combining co-located and distributed infrastructures, with their data integrated into the SDMS, thereby facilitating a holistic approach enhancing the understanding of Earth System Science. The SDMS links all the components, creating interconnections within the multidomain research infrastructure and paves the way for interdisciplinary studies.

Examples of interdisciplinarity can be found in all modules of InfraNor. A specific example is COAT (Pedersen et al 2025) within the land module, which is an adaptive ecosystem-based programme combining ecology and geophysics (e.g., meteorology, snow geophysics, climate-related monitoring, etc...), and thus contributing to conservation and management of climate-sensitive components of Norwegian Arctic ecosystems.

Permafrost boreholes have been established at remote COAT weather stations in Svalbard, forming an integrated monitoring system that provides daily updated data essential for examining and tracking

current conditions, trends, and effects of extreme climate events on active layer thickness and permafrost temperatures.

The observation programme has been expanded to include measurements of soil moisture, near-surface soil temperature, snow depth, and surface irradiance. This approach fosters consistency and collaboration across national and international initiatives, reduces the environmental impact of the installation, and maximises the value of new stations.

As a result, permafrost data are better integrated and more accessible to climate, snow, and permafrost modelling communities, as well as remote sensing communities for calibration and validation (Isaksen et al. 2022).

The strategy also optimises MET Norway's operational value chain, enabling rapid and efficient data access.

The Common Infrastructure Module provides infrastructure and sensor capacities having applications in multiple domains to support cross-disciplinary priorities. Some infrastructures of the Ocean Module have been used for other projects such as the Nansen Legacy project (Fer et al. 2021, 2024; Kolås et al. 2022).

The multidisciplinarity that is conferred by the InfraNor multidisciplinary research infrastructure and the SDMS together with other projects that have made use of InfraNor has been treated in various previous SESS reports. This is presented in reverse chronological order in the following SESS chapters: SNOW 23 (Malnes et al. 2024); SATMODSNOW 2 (Vickers et al. 2024); SATS (Haaland et al. 2024, 2023); LOAD-RIS (Hansen et al. 2023); SCD (Matero et al. 2022); COAT (Pedersen et al. 2025, 2022, 2020); PermaSval (Christiansen et al. 2021, 2020, 2019); GROWTH (Karlsen et al. 2020); PASSES (Salzano et al. 2021); iMOP (Cottier et al. 2022, 2019); GCI Cusp (Moen et al. 2019).

4. Analysis of achievements

The recent upgrades and installation of advanced instrumentation have significantly enhanced long-term monitoring programmes, elevating the quality and sensitivity of these critical observations, further filling some critical observational gaps. The openly accessible data are utilised by numerous national and international organisations for informed policymaking and by scientists conducting in-depth analysis and research.

COAT has successfully demonstrated the use of the ecosystem-based data as a basis for evaluation of ecosystem condition of high Arctic tundra in Svalbard (Pedersen et al. 2021). COAT has successfully implemented research infrastructure for monitoring of five biotic food web modules and a climate monitoring network, consisting of eight full-scale automatic weather stations and more than 300 ground temperature loggers.

The remote sensing products have been produced for a defined/limited time-series: if extended further they will provide essential data for understanding long-term changes in Svalbard. The data produced by different modules should be fully exploited to address cross-disciplinary questions.

The Dornier platform is a powerful tool to gather vast amounts of hyperspectral and RGB aerial data, with extremely high resolution and position accuracy. That in itself is also a challenge when it comes to distributing and analysing the data. We are still working on improving accessibility on both points. The other challenge is to increase the use of the platform: costs associated with chartering the aircraft and user co-pay requirements limit its use. During the Covid-19 period the aircraft was one of few ways to gather data during lockdown and travel restrictions, and we saw increased use (Jawak et al. 2021). The model of combining passenger aircraft,

logistics and science has made this an extremely cost-efficient tool available year-round as it is based in Longyearbyen. The drone infrastructure also has capacity for more use, the main challenge here as well is the need for co-funding by users.

Tremendous amounts of hyperspectral data collected by the instruments on the Dornier aircraft have made Svalbard one of the hyperspectral-rich data regions on our planet. The lessons learned from use of common infrastructure can be an example for Arctic observing systems on continuation of data series during natural calamities such as pandemic. Common infrastructure also inspired collaboration between scientists working in Svalbard.

A sharper focus on data management early in the process would be advisable. None of the universities in Norway has infrastructure in place to deliver data through SDMS (even after the project is finished). That makes it almost impossible to fulfil the demands of SIOS without a lot of ad-hoc solutions. The available national infrastructure is also missing this functionality. In many contexts, data centres have placed more emphasis on Findable and Accessible, than Interoperable and Re-useable, which is where the real benefit of data management lies. Work is in progress to compensate for part of this at some data centres, but these processes take much time. Mitigation through direction of data submission to data centres that fulfil SIOS requirements would solve the issue while other data centres improve their interfaces.

5. Recommendations for the future

- To monitor rapid climate shifts and their impacts in the Arctic, it is vital to secure long-term funding for Svalbard's observatories and ensure open, accessible, and well-documented data to foster collaboration and wider research use.
- Enhanced use of different levels of remote sensing (e.g., satellites, aircraft, drones) could be supported by various funding tools, e.g., transnational access support from EU, SIOS access programme. Higher-level product development and user training workshops would lower user barriers.
- The data produced by SIOS and supported by projects like SIOS-InfraNor should be evaluated against Copernicus service requirements in cross-disciplinary working group meetings. The recently published Copernicus Polar Roadmap 2024 highlights the evolution of these services.
- In reference to the updated Copernicus Roadmap and its recommendations, a re-analysis of observation gaps is strongly recommended.
- Further synergies should be sought by integrating SIOS InfraNor data (e.g., vegetation and snow data) as drivers of ecosystem change, particularly related to the long-term ecosystem-based monitoring done by COAT and other SIOS-related projects.

6. Data availability

See Appendix 2.

7. Acknowledgements

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8. References

Błaszczyk M, Laska M, Sivertsen A, Jawak SD (2022) Combined Use of Aerial Photogrammetry and Terrestrial Laser Scanning for Detecting Geomorphological Changes in Hornsund, Svalbard. Remote Sensing 14(3):601. https://doi.org/10.3390/rs14030601

Bensi M, Nilsen F, Ferré B, Skogseth R, Moskalik M, Korhonen M, Vogedes D, Kovacevic V, Paladini F, Ingrosso G, Langone L, Giordano P, Inali M, Mano B, Sundfjord A, Bailey A, Foss Ø, Daase M, Castro de la Guardia L, David DT, Renner A, Dumont E, Glowacki O, Ogg F, Olsen H, Dølven KO, Jones E (2025) The atlantification process in Svalbard: a broad view from the SIOS Marine Infrastructure Network. In: Runge et al (eds) SESS report 2024, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 138-151. https://doi.org/10.5281/zenodo.14425673

Cai Q, Wang J, Beletsky D, Overland J, Ikeda M, Wan L (2021) Accelerated decline of summer Arctic sea ice during 1850–2017 and the amplified Arctic warming during the recent decades. Environ Res Lett 16(3):034015. https://doi.org/10.1088/1748-9326/abdb5f

Christiansen HH, Matero ISO, Baddeley L, Holmén K, Hoppe CJ, Loonen MJJE, Storvold R, Vitale V, Zaborska A, Lihavainen H (2024) Developing the Svalbard Integrated Arctic Earth Observing System–SIOS. Earth System Dynamics 15(4):933–946. https://doi.org/10.5194/esd-15-933-2024

Christiansen HH (2024) Upgraded permafrost observations across periglacial landforms around Longyearbyen, Svalbard. Proceedings Volume II, Extended abstracts for the International Conference on Permafrost, ICOP 2024, pp 210–211. https://www.permafrost.org/wp-content/uploads/ICOP2024-Proceedings-Volume-II-Extended-Abstracts.pdf

Christiansen HH, Gilbert G, Demidov N, Guglielmin M, Isaksen K, Osuch M, Boike J (2019) Permafrost thermal snapshot and active-layer thickness in Svalbard 2016–2017. In: Orr et al. (eds): SESS report 2018, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 26–47. https://doi.org/10.5281/zenodo.4777825

Christiansen HH, Gilbert G, Demidov N, Guglielmin M, Isaksen K, Osuch M, Boike J (2020) Permafrost temperatures and active layer thickness in Svalbard during 2017/2018. In: Van den Heuvel et al. (eds): SESS report 2019, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 236–249. https://doi.org/10.5281/zenodo.4777728

Christiansen HH, Gilbert GL, Neumann U, Demidov N, Guglielmin M, Isaksen K, Osuch M, Boike, J (2021) Ground ice content, drilling methods and equipment and permafrost dynamics in Svalbard 2016-2019. In: Moreno-Ibáñez et al. (eds) SESS report 2020, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 258–275. https://doi.org/10.5281/zenodo.4294095

Compernolle S, Eichmann K-U, de Graaf M et al (2024) Copernicus Atmospheric Mission Performance Cluster Service. Quarterly Validation Report of the Copernicus Sentinel-5 Precursor Operational Data Products #23: April 2018 – May 2024. 211 pp. Keppens A, Lambert JC (eds) https://s5p-mpc-vdaf.aeronomie.be/ProjectDir/reports//pdf/S5P-MPC-IASB-ROCVR-23.00.00_FINAL_signed.pdf

Cottier F, Skogseth R, David D, Berge J (2019) Temperature time-series in Svalbard fjords. A contribution from the integrated marine observatory partnership (iMOP). In: Orr et al. (eds): SESS report 2018, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 108–118. https://doi.org/10.5281/zenodo.4778378

Cottier F, Skogseth R, David D, De Rovere F, Vogedes D, Daase M, Berge J (2022) Temperature and salinity time series in Svalbard fjords – Integrated Marine Observatory Partnership. In: Feldner et al. (eds) SESS report 2021, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 26–36. https://doi.org/10.5281/zenodo.5751717

Eckerstorfer M, Jenssen ROR, Kjellstrup, Storvold R, Malnes E, Jacobsen SK. UAV-BORNE UWB RADAR FOR SNOWPACK SURVEYS. (8/2018). Norut; 2018. 13 p. https://hdl.handle.net/11250/2649630

Dierking W, Schneider A., Torbjørn Eltoft, & Sebastian Gerland. (2022). CIRFA Cruise 2022. Cruise report. https://doi.org/10.5281/zenodo.7314066

Frost GV, Macander MJ, Bhatt US, Berner LT, Bjerke JW, Epstein HE, Forbes BC, Lara MJ, Magnússon RÍ, Montesano PM, Phoenix GK, Serbin SP, Tømmervik H, Waigl C, Walker DA, Yang D (2023) NOAA Arctic Report Card 2023: Tundra Greenness. NOAA technical report OAR ARC; 23-09. https://doi.org/10.25923/s86a-jn24

Gray L, Burgess D, Copland L, Demuth MN, Dunse T, Langley K, Schuler TV (2015) CryoSat-2 delivers monthly and inter-annual surface elevation change for Arctic ice caps. The

Cryosphere 9:1895–1913. https://doi.org/10.5194/tc-9-1895-2015

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

Haaland S, van Schaik B, Radlwimmer A, Schillings A, Bjoland L, Skogseth R (2024) Seasonal asymmetries and long-term trends in atmospheric and ionospheric temperatures in polar regions: an update. In: Verret et al. (eds) SESS report 2023, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 24–33. https://doi.org/10.5281/zenodo.10255532

Hall C, Adami C, Tsutsumi M (2020) First observations of Polar Mesospheric Echoes at both 31 MHz and 53.5 MHz over Svalbard (78.2°N 15.1°E). Experimental Results 1:1–7. https://doi.org/10.1017/exp.2020.51

Hansen G, Kouremeti N, Gilardoni S, Stebel K, Evangeliou N, Ritter C, Zielinski T, Herrero S, Kazadzis S, Mateos D, Mazzola M, Pakszys P, Eleftheriadis K (2023) Long-term observations of aerosol optical depth and their relation to in-situ aerosol properties in the Svalbard region. In: Gevers et al. (eds) SESS report 2022, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 44–61. https://doi.org/10.5281/zenodo.7376140

Hop H, Cottier F, Berge J (2019) Autonomous Marine Observatories in Kongsfjorden, Svalbard. In: Hop H, Wiencke C (eds) The Ecosystem of Kongsfjorden, Svalbard. Advances in Polar Ecology, vol 2. Springer, Cham. https://doi.org/10.1007/978-3-319-46425-1_13

Isaksen K, Lutz J, Sørensen A, Godøy Ø, Ferrighi L, Eastwood S, Aaboe S (2022) Advances in operational permafrost monitoring on Svalbard and in Norway. Environ Res Lett 17(9):095012 https://iopscience.iop.org/article/10.1088/1748-9326/ac8e1c

Isaksen K, Nordli Ø, Ivanov B, Køltzow MAØ, 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

Ims RA, Jepsen JU, Stien A, Yoccoz NG (2013) Science Plan for COAT: Climate-ecological Observatory for Arctic Tundra. Fram Centre, Tromsø. https://www.coat.no/Portals/coat/SciencePlanCOAT_web.pdf

Ims RA, Yoccoz NG (2017) Ecosystem-based monitoring in the age of rapid climate change and new technologies. Current Opinion in Environmental Sustainability 29:170–176. https://doi.org/10.1016/j.cosust.2018.01.003

Karlsen SR, Elvebakk A, Stendardi L, Høgda KA, Macias-Fauria M (2024) Greening of Svalbard. Science of The Total Environment 945. https://doi.org/10.1016/j.scitotenv.2024.174130

Karlsen SR, Elvebakk A, Tømmervik H, Belda S, Stendardi L (2022) Changes in Onset of Vegetation Growth on Svalbard, 2000–2020. Remote Sens 14(24):6346. https://doi.org/10.3390/rs14246346

Karlsen SR, Stendardi L, Nilsen L, Malnes E, Eklundh L, Julitta T, Burkart A, Tømmervik H (2020) Sentinel satellite-based mapping of plant productivity in relation to snow duration and time of green-up. In: Van den Heuvel et al. (eds): SESS report 2019, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 42–57. https://doi.org/10.5281/zenodo.4704361

Karlsen SR, Stendardi L, Tømmervik H, Nilsen L, Arntzen I, Cooper EJ (2021) Time-Series of Cloud-Free Sentinel-2 NDVI Data Used in Mapping the Onset of Growth of Central Spitsbergen, Svalbard. Remote Sens 13(15):3031. https://doi.org/10.3390/rs13153031

Kolås EH, Baumann TM, Skogseth R, Koenig Z, Fer I (2024) Circulation and Hydrography in the Northwestern Barents Sea: Insights From Recent Observations and Historical Data (1950–2022), J Geophys Res 129(8):. https://doi.org/10.1029/2023JC020211

Kolås EH, Koenig Z, Fer I, Nilsen F, Marnela M (2020). Structure and transport of Atlantic Water north of Svalbard from observations in summer and fall 2018. J Geophys Res Oceans 125(9). https://doi.org/10.1029/2020JC016174

Isaksen K, Nordli Ø, Ivanov B et al (2022) Exceptional warming over the Barents area. Sci Rep 12:9371. https://doi.org/10.1038/s41598-022-13568-5

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

Macias-Fauria M, Karlsen SR, Forbes BC (2017) Disentangling the coupling between sea ice and tundra productivity in Svalbard. Scientific Reports 7:8586. https://doi.org/10.1038/s41598-017-06218-8

Malnes E, Vickers H, Ricker R, Salzano R, Killie MA, Luks B, Gallet J-C, Rinne E (2024) A holistic approach to snow observations and models in Svalbard. In: Verret et al (eds) SESS report 2023, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 34–43. https://doi.org/10.5281/zenodo.10257050

Matero I, Ignatiuk D, Godøy Ø, Luks B, Neuber R, Vitale V, Jawak S, Hübner C, Jennings I, Lihavainen H (2022) SIOS Core Data. In: Feldner et al (eds) SESS report 2021, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 88–93. https://doi.org/10.5281/zenodo.5751970

Mazzola M, Stone RS, Kouremeti N, Vitale V, Gröbner J, Stebel K, Hansen GH, Stone TC, Ritter C, Pulimeno S (2024) Monitoring Aerosol Optical Depth during the Arctic Night: instrument development and first results. Atmospheric Research, in revision, 2024.

Mehlum F, Misund O-A, Moen J, Jansen E, Holmén K, Ørbæk JB (2013) Svalbard Integrated Arctic Observing System – SIOS – Anbefalinger fra prioriteringsgruppen for nasjonal forskningsinfrastruktur i SIOS. https://sios-svalbard.org/sites/

www.sios-svalbard.org/files/common/MehlumEtAl2013.pdf

Moen J, Spicher A, Rowland DE, Kletzing C, LaBelle J (2019) Grand Challenge Initiative – Cusp: rockets to explore solar wind-driven dynamics of the top side polar atmosphere. In: Orr et al (eds): SESS report 2018, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 184–204. https://doi.org/10.5281/zenodo.4778500

Morris A, Moholdt G, Gray L, Schuler TV, Eiken T (2022) CryoSat-2 Interferometric Mode Calibration and Validation: A Case Study from the Austfonna Ice Cap, Svalbard. Remote Sensing of the Environment 269:. https://doi.org/10.1016/j.rse.2021.112805

Muhammed GH, Colombo R, Middelton EM et al (2019) Remote sensing of solar-induced chlorophyll fluorescence (SIF) in vegetation: 50 years of progress. Remote Sens Environ 213:. https://doi.org/10.1016/j.rse.2019.04.030

Musche M, Adamescu M, Angelstam P et al (2019) Research questions to facilitate the future development of European long-term ecosystem research infrastructures: A horizon scanning exercise. Journal of Environmental Management 250:109479. https://doi.org/10.1016/j.jenvman.2019.109479

Nordli Ø, Wyszyński P, Gjelten HM, Isaksen K, Łupikasza E, Niedźwiedź T, Przybylak R (2020) Revisiting the extended Svalbard Airport monthly temperature series, and the compiled corresponding daily series 1898–2018. Polar Research 39:. https://doi.org/10.33265/polar.v39.3614

Nowak A, Hodgkins R, Nikulina A, Osuch M, Wawrzyniak T, Kavan J, Łepkowska E, Majerska M, Romashova K, Vasilevich I, Sobota I, Rachlewicz, G (2021) From land to fjords: The review of Svalbard hydrology from 1970 to 2019. In: Moreno-Ibáñez et al (eds) SESS report 2020, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 176-200. https://doi.org/10.5281/zenodo.4294063

NPI-UiO (2023) Etonbreen (Austfonna) mass balance. Environmental monitoring of Svalbard and Jan Mayen (MOSJ). https://mosj.no/en/indikator/climate/land/mass-balance-for-glaciers-in-svalbard/

Østby TI, Schuler TV, Hagen JO, Hock R, Kohler J, Reijmer CH (2017) Diagnosing the decline in climatic mass balance of glaciers in Svalbard over 1957–2014. The Cryosphere 11:191–215. https://doi.org/10.5194/tc-11-191-2017

Parmentier F-JW, Nilsen L, Tømmervik H, Cooper EJ (2021) A distributed time-lapse camera network to track vegetation phenology with high temporal detail and at varying scales. Earth Syst Sci Data 13:3593–3606. https://doi.org/10.5194/essd-13-3593-2021

Pedersen ÅØ, Jepsen JU, Paulsen IMG, Fuglei E, Mosbacher JB, Ravolainen V (2021) Norwegian Arctic Tundra: a Panel-based Assessment of Ecosystem Condition. Norwegian Polar Institute, Report Series 153. https://hdl.handle.net/11250/2754696

Pedersen ÅØ, Stien J, Albon S, Fuglei E, Isaksen K, Liston G, Jepsen JU, Madsen J, Ravolainen VT, Reinking AK, Soininen EM, Stien A, van der Wal R, Yoccoz NG, Ims RA (2020) Climate-Ecological Observatory for Arctic Tundra. In: Van den Heuvel et al. (eds): SESS report 2019, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 58–83. https://doi.org/10.5281/zenodo.4704475

Pedersen ÅØ, Albon S, Beumer LT, Fuglei E, Isaksen K, Liston G, Jepsen JU, Madsen J, Mosbacher J, Paulsen IMG, Pedersen ST, Ravolainen VT, Reinking AK, Soininen EM, Stien A, Stien J, van der Wal R, Yoccoz NG, Ims RA (2022) Climate-Ecological Observatory for Arctic Tundra (COAT) – Adaptive system for long-term terrestrial monitoring. In: Feldner et al (eds) SESS report 2021, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 38–55. https://doi.org/10.5281/zenodo.5751761

Pedersen ÅØ, Albon S, Beumer ST, Fuglei E, Isaksen K, Madsen J, Paulsen IMG, Pedersen ST, Ravolainen VT, Soininen EM, Van der Wal R, Yoccoz NG (2025) Operationalisation of COAT in SIOS – an example of adaptive ecosystem-based monitoring in practice. In: Runge et al (eds) SESS report 2024, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 198-211. https://doi.org/10.5281/zenodo.14425871

Platt SM, Svendby T, Hermansen O, Lunder C, Fiebig M, Fjæraa AM, Myhre CL, Stebel K (2023) Monitoring of greenhouse gases and aerosols at Svalbard and Birkenes in 2022. Kjeller: NILU. 24/2023. https://hdl.handle.net/11250/3107693

Pramanik A, Kohler J, Schuler TV, van Pelt W, Cohen L (2019) Comparison of snow accumulation events on two High-Arctic glaciers to model-derived and observed precipitation. Polar Research 38:. https://doi.org/10.33265/polar.v38.3364

Retelle M, Christiansen H, Hodson A, Nikulina A, Osuch M, Poleshuk K, Romashova K, Roof S, Rouyet L, Strand SM, Vasilevich I, Wawrzyniak T (2020) Environmental Monitoring in the Kapp Linné-Grønfjorden Region. In: Van den Heuvel et al. (eds): SESS report 2019, Svalbard Integrated Arctic Earth Observing System, Longyearbyen, pp 84–107. https://doi.org/10.5281/zenodo.4704557

Romanovsky VE, Smith SL, Christiansen HH (2010) Permafrost Thermal State in the Polar Northern Hemisphere during the International Polar Year 2007-2009: a Synthesis. Permafrost and Periglacial Processes 21(2):106–116. https://doi.org/10.1002/ppp.689

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(7):2941–2963. https://doi.org/10.5194/tc-17-2941-2023

Schuler TV, Hult J, Filhol S (2022) Automatic weather station on Etonbreen/ Austfonna glacier. Norwegian Meteorological Institute. https://doi.org/10.21343/9hez-nz67

Schuler TV, Kohler J, Elagina N, Hagen JOM, Hodson AJ,

Jania JA, Kääb AM, Luks B, Malecki J, Moholdt G, Pohjola VA, Sobota I, Van Pelt WJJ (2020) Reconciling Svalbard glacier mass balance. Front Earth Sci 8:. https://doi.org/10.3389/feart.2020.00156

Skogseth R, Ellingsen P, Berge J et al (2019) UNIS hydrographic database. Norwegian Polar Institute. https://doi.org/10.21334/unis-hydrography

Sundfjord A, Lundesgaard Ø, Renner AH (2022) A-TWAIN mooring data 2019-2020. Norwegian Polar Institute. https://doi.org/10.21334/npolar.2022.d3a5adc2

Svendby TM, Fjæraa AM, Schulze D, Bäcklund A, Johnsen B (2024) Monitoring of the atmospheric ozone layer and natural ultraviolet radiation. Annual Report 2023. Kjeller: NILU. 20/2024. https://hdl.handle.net/11250/3153213

Tømmervik H, Nilsen L (2023) SIOS instrument #49 - Hyperspectral measurements including sun-induced fluorescence (SIF) in Adventdalen. Norwegian Meteorological Institute. https://doi.org/10.21343/ZDM7-JD72

Tømmervik H, Julitta T, Nilsen L, Park T, Burkart A, Ostopowic K, Karlsen SR, Parmentier F-JW, Pirk N, Bjerke JW (2023) The Northernmost Hyperspectral Flox Sensor Dataset for Monitoring of High-Arctic Tundra Vegetation Phenology and Sun-Induced Fluorescence (SIF). Data in Brief 50:109591. https://doi.org/10.1016/j.dib.2023.109581

van Pelt W, Pohjola V, 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, 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

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, Cryospheric Sciences 10:. https://doi.org/10.3389/feart.2022.868945

Vickers H, Høgda KA, Solbø SR, Karlsen SR, Tømmervik H, Aanes R, Hansen BB (2016) Changes in greening in the high Arctic: insights from a 30 year AVHRR max NDVI dataset for Svalbard. Environ Res Lett 11(10):105004. https://doi.org/10.1088/1748-9326/11/10/105004

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

Wilkinson MD, Dumontier M, Aalbersberg IJJ et al (2016) The FAIR Guiding Principles for scientific data management and stewardship. Sci Data 3:160018. https://doi.org/10.1038/sdata.2016.18

Appendix 1: List of acronyms

AOD – Aerosol Optical Depth

API – Application Programming Interface

APS – Aerodynamic Particle Sizer

A-TWAIN[11] – Long-term variability and trends in the Atlantic Water inflow region

AWS – Automatic Weather Station

BlueCloud[12] – the Open Science platform for collaborative marine research

CADI – Canadian Advanced Digital Ionosonde

CF-NetCDF – Network Common Data Format (NetCDF) with Climate and Forecast (CF) standard naming convention

CGI-cusp – the Grand Challenge Initiative (GCI) Cusp initiative

CMOD5[13] – geophysical MODel function for ERS C-band scatterometry

COAT – Climate Ecological Observatory for Arctic Tundra

CTD – Conductivity, Temperature, and Depth (oceanographic measurement instrument)

EOSC – the European Open Science Cloud

ERS – European Remote Sensing Satellites

ESA – the European Space Agency

ESS – Earth System Science

EVI – Enhanced Vegetation Index

FAIR – Findable Accessible Interoperable Reusable

FloX[14] – Fluorescence boX (chlorophyll fluorescence observation instrument)

GSM – Global System for Mobile Communications

GTN-P – Global Terrestrial Network on Permafrost

IASC – the International Arctic Science Committee

ICI-5 – Investigation of Cusp Irregularities 5th mission

IMR – the Norwegian Institute of Marine Research

K-Lander[15] – Kongsberg Seabed Observatory

KLEO – Kapp Linné Environmental Observatory

MET – the Norwegian Meteorological Institute

MSI – Multispectral Instrument

MST – Mesosphere Stratosphere Troposphere

MTCI – MERIS Terrestrial Chlorophyll Index

NDVI – Normalised Difference Vegetation Index

NIVA – the Norwegian Institute for Water Research

NPI – the Norwegian Polar Institute

NRCS – SAR Normalised Radar Cross Section,

OPeNDAP – Open-source Project for a Network Data Access Protocol

PFR – Lunar Precision Filter Radiometer

11 https://www.npolar.no/en/projects/a-twain/
12 https://blue-cloud.org/
13 https://www.ecmwf.int/en/elibrary/74789-cmod5-improved-geophysical-model-function-ers-c-band-scatterometry
14 https://www.jb-hyperspectral.com/products/flox/
15 https://www.kongsberg.com/maritime/news-and-events/news-archive/2016/innovation-meets-new-modular-design-the-kongsberg-k-lander-mk2-seabed/

PMSE – Polar Mesospheric Summer Echoes

PMWE – Polar Mesospheric Winter Echoes

RI – Research Infrastructure

SAON – the Sustained Arctic Observing Networks

SAR – Synthetic Aperture Radar

SDMS – SIOS Data Management System

SFI CIRFA – Research-based Innovation (SFI[16]) Centre for Integrated Remote Sensing and Forecasting for Arctic Operations (CIRFA[17])

SOFT – Spitsbergen Ocean Front Transect

SIOS InfraNOR[18] – Svalbard Integrated Arctic Earth Observing System - Infrastructure development of the Norwegian node

SOUSY – SOUnding SYstem (MST Doppler Radar)

SWIR – Short Wavelength InfraRed

UWB – Ultra Wide Band

THREDDS – THematic Real-time Environmental Distributed Data Services

UiT – the University of Tromsø – the Arctic University of Norwa

VTOL – Vertical Take-Off and Landing

WMO – the World Meteorological Organization

16 https://www.forskningsradet.no/finansiering/hva/sfi/
17 https://cirfa.uit.no/
18 https://prosjektbanken.forskningsradet.no/project/FORISS/269927

Appendix 2: Data availability

Dataset	Parameter	Period	Location	Metadata access (URL)	Dataset provider
Etonbreen AWS	Meteorological parameters, snow height.	2004–2021	Etonbreen/ Austfonna glacier	https://doi.org/10.21343/9hez-nz67	Thomas V. Schuler (UiO), John Hult (UiO), Simon Filhol (UiO)
Remote sensing DOAS measurements	NO2	2020–2021	Ny-Ålesund	https://sios-svalbard.org/metsis/elements/no-met-adc-1e3b2283-bc95-5264-9ea1-d51101dc8bfa/search	Ann Mari Fjaeraa (NILU)
APS observations	Aerosol number size distribution	2021–2023	Ny-Ålesund Zeppelin mountain	https://doi.nilu.no/doi/3CZW-UGSH	Markus Fiebig (NILU), Chris Lunder (NILU)
moon tracking PFR	Aerosol optical depth (AOD)	2002–2023	Ny-Ålesund	https://sios-svalbard.org/metsis/search?search_api_fulltext_op=and&fulltext=PFR+NO0057R	Georg H. Hansen (NILU), Natalia Kouremeti (PMOD-WRC), Kerstin Stebel (NILU)
m-NLP on VISIONS-2	electron density (sounding rocket)	2022	Ny-Ålesund	https://sios-svalbard.org/metsis/elements/no-met-adc-28c940f3-bd99-50c2-aecc-f706652ac63e/search	David Michael Bang (UiO), Espen Trondsen (UiO), Andres Spicher (UiT)
Kongsvegen AWS	Meteorological parameters, snow height.	2021–2022	Kongsvegen	https://doi.org/10.21343/5ht4-bj50 (sw110) … https://doi.org/10.21343/1r1z-ae07 (sw250)	Simon Filhol (UiO), Pierre Marie Lefeuvre (NPI), Jean-Charles Gallet (NPI)
Midtre Lovenbreen AWS	Meteorological parameters, snow height.	2021–2022	Midtre Lovenbreen AWS	https://doi.org/10.21343/5ht4-bj50 (sw110) … https://doi.org/10.21343/5ht4-bj50 (sw140)	Simon Filhol (UiO), Pierre Marie Lefeuvre (NPI), Jean-Charles Gallet (NPI)
Hyperspectral measurements	Phenological parameters; SIF (Sun Induced Fluorescence)	2019–2023	Adventdalen	https://doi.org/10.21343/ZDM7-JD72	Hans Tømmervik (NINA), Lennart Nilsen (UiT)
Drone and Sentinel-2 NDVI in COAT	NDVI, biomass, disturbance, temperature	2018–2022	Adventdalen, Brøggerhalvøya, Sassendalen	https://doi.org/10.21334/npolar.2024.c048fa4c	Virve Ravolainen (NPI), Ingrid Paulsen (UiT)
Vegetation phenology	Phenological parameters;	2015–2023	Adventdalen	https://doi.org/10.21343/kbpq-xb91 (2021)	Lennart Nilsen (UiT), Hans Tømmervik (NINA).
COAT	State variables according to the Science Plan (Ims et al. 2013)	See Science Plan	Nordenskiöld Land Brøggerhalvøya, Kongsfjorden and surroundings	https://sios-svalbard.org/metsis/search?search_api_fulltext_op=and&fulltext=COAT https://data.coat.no/	COAT consortium

Dataset	Parameter	Period	Location	Metadata access (URL)	Dataset provider
A-TWAIN mooring	CTD, ADCP	2017–2020	Nansen Basin, Barents Sea	https://doi.org/10.21334/npolar.2020.e7041026 https://doi.org/10.21334/npolar.2022.d3a5adc2	Arild Sundfjord (NPI) et al.
InfraNor seaglider	Ocean currents, salinity, temperature	2020–2021	Fram Strait	https://doi.org/10.21335/NMDC-1878084716	Ilker Fer (UiB) et al.
InfraNor seaglider	Ocean currents, salinity, temperature, oxygen	2019–2021	Barents Sea	https://doi.org/10.21335/NMDC-381060465 https://doi.org/10.21335/NMDC-571158912	Eivind Kolås (UiB) et al. Ilker Fer (UiB) et al.
Isfjorden wave observations	Period, height	2020	Isfjorden	https://sios-svalbard.org/metsis/elements/no-met-adc-d9cd7110-3a31-587f-a890-c8833b879de6/search	Frank Nilsen (UNIS)
Ocean Colour Svalbard	Chlorophyll a	2022–2023	Svalbard	https://sios-svalbard.org/metsis/elements/no-nersc-b10c0759-0691-5e29-8a36-07a975dd373d/search	Anton Korosov (NERSC)
SAR avalanche detections	Polygon delineation of avalanche	2021–2022	Svalbard	https://sios-svalbard.org/metsis/elements/no-met-adc-767bf5fb-949d-5990-9fad-5ccd98254abb/search	Jakob Grahn (NORCE)
SAR Wet snow maps	Grid cells classified codes	2004–2024	Svalbard	https://sios-svalbard.org/metsis/elements/no-met-adc-abc1503f-74c6-55a1-b9e5-f0a3838c0492/search	Eirik Malnes (NORCE)
MODIS Daily Snow Cover	Snow Cover Fraction	2000–2021	Svalbard	https://sios-svalbard.org/metsis/elements/no-met-adc-fbb9d256-3387-54db-af38-4e94c2f8ba14/search	Eirik Malnes (NORCE)
UAV GPR Snow depth	Snow depth	2019–2022	Longyearbyen Nordenskjöld Land	https://doi.org/10.21343/zaw8-2g80	Rolf-Ole Rydeng Jenssen (NORCE)

SIOS' contribution to the ICARP IV process (SICAR)

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1. Introduction

This chapter outlines the contribution of the Svalbard Integrated Arctic Earth Observing System (SIOS) to the IV International Conference on Arctic Research Priorities (ICARP IV) process (Lihavainen et al. 2024).

Spanning from 2022 to 2026, ICARP IV is a community-driven initiative for planning Arctic research over the next decade (Figure 1). It brings together Arctic researchers, Indigenous Peoples, policymakers, residents, and stakeholders from around the globe. It will discuss the state of Arctic science and the place the Arctic occupies in global affairs and systems, to:

- Consider the most urgent knowledge gaps and Arctic research priorities and needs for the next decade, and
- Explore solutions to address these research needs.

In the ICARP IV process, seven topic areas have been identified, with each area represented by a research priority team. These research priority teams work to:

- Define the knowledge gaps and research priorities for the next decade for their topic area based on the input collected
- Identify and suggest opportunities to enhance synergies that might exist across existing research plans, or where there is potential for formalising new alliances and collaborative partnerships

SIOS has submitted the recommendations presented in this chapter to the ICARP IV process. The recommendations will be distributed to the corresponding research priority team. After assessment, the research priority teams will present research priorities and implementation plans based on all the contributions, during the Arctic

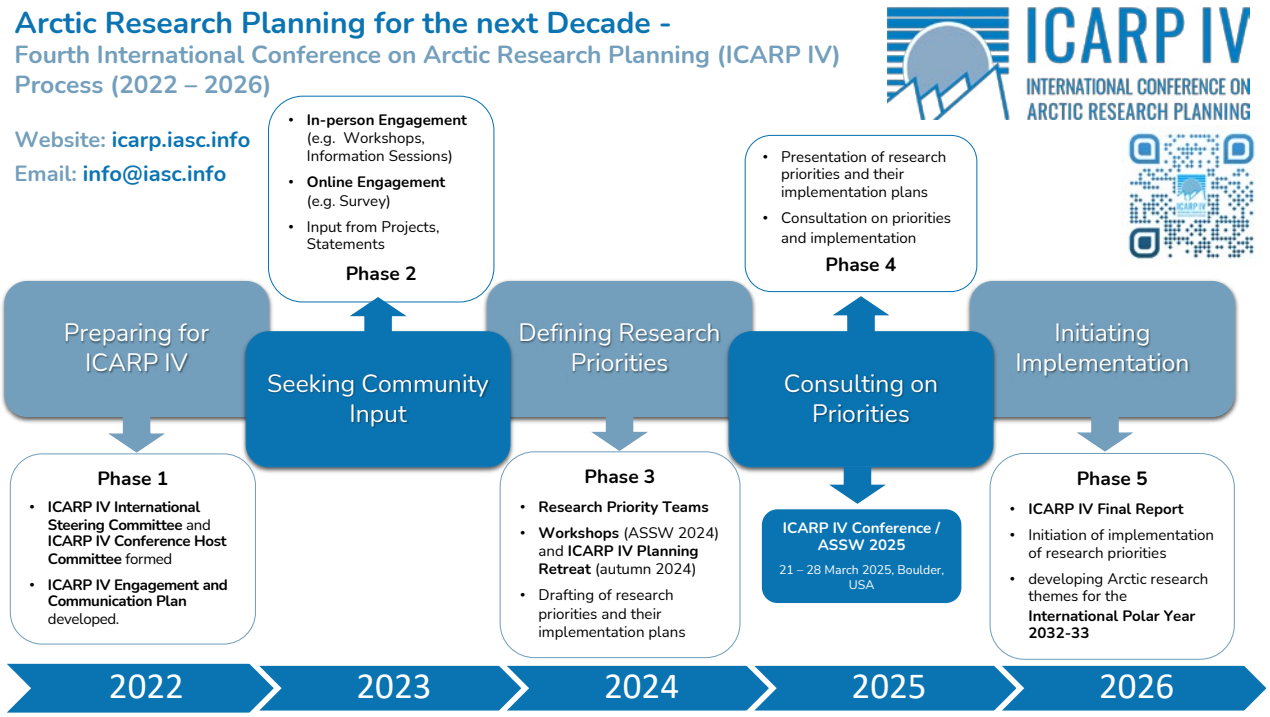

Figure 1: The ICARP process between 2022 and 2026[1]

1 https://icarp.iasc.info/publications/publications-icarp-iv

Science Summit Week. This will be followed by a consultation phase.

The final report from ICARP IV will be available in 2026, after which the implementation of research priorities will begin. ICARP IV is also a one of the primary tools to determine the Arctic Scientific goals and directions for the upcoming Fifth International Polar Year in 2032–2033[1].

SIOS can serve as an example of how the ICARP IV recommendations can be implemented on the regional scale. It can simultaneously provide a regional platform with well-developed and mature observation facilities where bold questions can be successfully addressed. SIOS is well suited to provide guidance for what can be implemented pan-Arctic during the fifth International Polar Year (2032-2033).

2. Background

SIOS is an international consortium of research institutions with research interests and infrastructure in and around the Norwegian High Arctic archipelago of Svalbard. Within SIOS, researchers collaborate by sharing data and research infrastructure to build an efficient observing system that focuses on long-term monitoring of parameters that are important to understand the Arctic in the context of global environmental change. The vision of SIOS is to be the leading long-term observing system in the Arctic to support societal needs for Earth System Science. SIOS currently has 29 member institutions from 10 different countries active in research in and around Svalbard.

SIOS publishes an annual report entitled "The State of Environmental Science in Svalbard" (SESS), which includes recommendations for future activities to close knowledge gaps in Svalbard-related research. The SESS report is established as an authoritative source of information about the state of the environment in and around Svalbard and it is an important tool to convey knowledge to stakeholders and the public. The SESS report is the main driving force for the science-based development of the observing system and represents an opportunity for research groups to actively influence the prioritisation within SIOS.

The SESS report is a bottom-up process to develop SIOS. Each chapter in the SESS report includes recommendations on how to develop the observing system. Contributions to the SESS report are written by international and, preferably, multidisciplinary groups led by researchers from SIOS member institutions. All chapters are peer-reviewed and subject to final approval by an editorial board. There have been more than 200 recommendations since the first SESS report in 2018. A synthesis of the recommendations presented in the first four SESS reports was published in 2024 (Christiansen et al. 2024). The objective was to condense and prioritise key recommendations for four environments (atmosphere, cryosphere, marine, terrestrial). These were used to identify common and unifying recommendations for SIOS.

An ICARP IV workshop was organised as part of SIOS' main annual event, Polar Night Week (22nd to 26th January 2024[2]). Polar Night Week is an arena for the exchange of ideas, reflection and planning of future activities, and it creates a vibrant atmosphere in the middle of the beautiful polar night. The workshop was organised in according to the seven Research Priority Areas identified by ICARP IV. In the workshop, we discussed six of these. The workshop participants were divided into four groups, each tasked with contributing to a selection of ICARP IV topic areas. The outcomes from different breakout groups were organised, prioritised according to pan-Arctic perspective and similar responses were combined.

A panel discussion with the keynote speakers at Polar Night Week was also organised. This gave an additional perspective from outside SIOS' own environment.

1 https://icarp.iasc.info
2 https://sios-svalbard.org/PNW2024_Programme

The contribution of SIOS to the ICARP IV process is based on group discussion during the workshop, panel discussion, recommendations from the six SESS reports published so far and – especially – the synthesis report (Christiansen et al. 2024). The workshop and panel discussions were important complementary elements and in many cases the outcome overlapped with SESS recommendations. The recommendations ultimately submitted to ICARP IV were prioritised based on their pan-Arctic relevance (Lihavainen et al. 2024).

3. Contributions to interdisciplinarity

SIOS itself is interdisciplinary within Earth System Sciences and thus perfectly suited for the ICARP IV process.

The ICARP IV process is inherently interdisciplinary through its engagement with researchers, Indigenous People, and stakeholders. The scientific focus of ICARP IV will be on important research questions that cut across many disciplines and knowledge systems, and that require new and innovative thinking and collaboration. ICARP IV will develop a vision for implementation and science plans to address these priorities.

4. Recommendations from the SIOS community to ICARP IV topic areas

Seven topic areas have been identified by the ICARP IV process. Recommendations to different identified topic areas resulting from SESS report recommendations and workshop are listed below. It should be kept in mind that the recommendations below are by no means comprehensive and do not include all aspects of global change. SIOS represents research infrastructure in around Svalbard, and this is reflected in the recommendations.

Unless otherwise stated, these recommendations are based on the summaries of the group work and panel discussion.

Topic Area 1: The Role of the Arctic in the Global System

The Arctic encompasses the entire overlying atmosphere from the surface, through the troposphere and stratosphere and out into the mesosphere / lower thermosphere–ionosphere (M/LTI), which extends up to 1000 km altitude. To fully understand the effects of climate change, as well as the dynamics and interactions between these different atmospheric layers (along with the impact of space weather), long time series datasets of the M/LTI region, not only above Svalbard, but in the polar cap, its boundary and cusp regions, are needed. The polar atmosphere is strongly influenced by the solar wind (particles coming from the Sun) along with the solar magnetic field (the IMF or Interplanetary Magnetic Field). The polar cusps are two funnel-shaped regions in the Earth's magnetic field, where solar wind particles can directly enter the Earth's atmosphere. Collisions between these particles and the atmosphere produce the aurora. Cusp aurora is the scientific term for the aurora in daytime. Svalbard's unique location and infrastructure means it is the only place where the cusp and the polar cap boundary can be studied using ground-based instrumentation. Research questions in this topic area are related to the physics of the coupling of the solar wind to Earth's magnetic field in the polar regions and the effects it has:

- how are auroral particles accelerated along magnetic field lines in the cusp and into the

polar cap boundary region;
- how do these energy inputs lead to heating, upwelling and outgassing of Earth's atmospheric gases into space;
- how are atmospheric dynamics driven by the IMF; and
- how does energy and momentum propagate down to the lower atmosphere and lower latitude regions, causing ozone depletion and affecting the polar vortex (a strong westerly thermal wind system which surrounds the polar regions).

Space weather also has serious effects for man-made technologies such as GPS systems and satellite operability. For example, the solar storms in May 2024 caused NASA's ICESat-2 satellite to be knocked ~ 100 km off its nominal ground track and placed the satellite into safe mode. This resulted in the loss of five weeks of data and significant usage of fuel to get it back to its correct orbit.

Ground based instruments located at the Breinosa super observing site such as site at the Kjell Henriksen Observatory[3], the SuperDARN radar network[4] and the EISCAT Svalbard Radar are able to give long term, continuous observations of the M/LTI region both over Svalbard (in the case of the KHO and ESR[5]) and the entire polar region (in the case of the SuperDARN network). Sounding rockets[6] are currently the only way to gain in-situ measurements of the processes within the M/LTI region of the cusp and polar cap boundary region. This dynamic combination of in-situ and remote observing techniques for the cusp and polar cap region is unique worldwide.

Topic Area 2: Observing, Reconstructing, and Predicting Future Climate Dynamics and Ecosystem Responses

To understand the changing water cycle in the Arctic, it is essential to monitor all parts of the cryosphere (Christiansen et al. 2024).

- Both small and large glaciers must be observed to determine peak riverine discharge, which necessitates linking meteorological data with detailed snow measurements, such as thickness and snow water equivalent. Additionally, more observations are needed on glacier thermal regimes and calving rates. In the European Arctic, it is also essential to study the impact of Atlantic waters entering fjords on glacier dynamics and nutrient cycles
- As glaciers recede, permafrost may emerge or form in freshly exposed glacier forefields. It is crucial to study landscape evolution in response to glacier change to understand the influence of the changing hydrological system on permafrost development.
- Understanding water fluxes within the active layer and permafrost, including permafrost–groundwater interactions and sub-permafrost fluid migration, requires comprehensive observations of ground ice content, hydrological flows and aqueous geochemistry.
- The physical, chemical, and biological interactions of snow with the atmosphere, soil, and sea ice are major observation gaps. Increased rain-on-snow events impact the entire system, highlighting the need for interdisciplinary studies.

As Svalbard is warming faster than the rest of the Arctic, it is an ideal location for detailed climate studies. The strong temperature gradients across Svalbard can be used to simulate the broader Arctic environment and thus findings can be scaled to the broader Arctic and global contexts. In addition, the climatic gradient between warmer Svalbard and cooler Northern Greenland offers valuable insights for pan-Arctic studies.

While temperature and precipitation are vital parameters, studying events like temperature inversions provides deeper insights to atmospheric conditions. There is an urgent need for continuous observations of the vertical structure of the atmosphere. This calls for more sounding stations

3 https://kho.unis.no/
4 https://www.unis.no/project/superdarn-radar//
5 https://eiscat.se/about/sites/eiscat-svalbard-radar/?highlight=Svalbard
6 e.g., https://www.nasa.gov/soundingrockets/

and sustained operation of existing stations.

Research into the discharge of microorganisms from thawing permafrost is necessary to understand the impact on downstream environments, such as fjord ecosystems. This requires prioritisation of monitoring microbial communities in permafrost vulnerable to thaw, as well as measuring parameters such as hydrological flow and sediment or substrate composition.

Topic Area 3: Understanding the Vulnerability and Resilience of Arctic Environments and Societies and Supporting Sustainable Development

In the SIOS community, there is a recognition of the importance of coastal studies, particularly in the interdisciplinary exploration of coastal erosion. Understanding the stability of coastal areas is crucial for both human societies and the environment, demanding collaborative efforts across disciplines. Coastal regions are dynamic interfaces where the atmosphere, marine, terrestrial, and cryosphere environments converge and interact. An interdisciplinary approach is essential for comprehensively addressing the complexities of coastal dynamics and developing sustainable management strategies.

It is crucial to prioritise the monitoring of pollutants. For instance, benthic animals have high concentrations of antibiotic residues, which also affect humans. Moreover, surveillance of the airborne bacterial population is an important area requiring further investigation.

Topic Area 4: Scientific cooperation and diplomacy

It is vital that research in the Arctic becomes more interdisciplinary. Interdisciplinarity requires a common language and vocabulary, not only between scientists from various fields, but also between scientists, policymakers, and funding organisations. There is a gap between data and knowledge creation and the communication of this knowledge to the public, thus it is important to integrate rather than confine discussions within our scientific bubbles.

Collaborating with experts from other professions can be a more effective way to promote interdisciplinary research than solely focusing on economic and administrative aspects. Environmental pollution and climate change acknowledge no boundaries. These challenges require global answers, and it is our duty as scientists to take a stand and promote global cooperation. Stronger cooperation and coordination amongst national funding agencies are necessary for achieving this goal.

Topic Area 6: Preparing present and future generations through Education, Outreach, Communication, Capacity Building, and Networking

The significance of a common language was discussed in Topic Area 4. Communication and exchange should be encouraged at many different levels, including scientists in various fields, policymakers, local and indigenous people, and other stakeholders. There need to be more exchanges and communication with society on all fronts. In the modern age, social media is evolving rapidly. Social media and related algorithms have a tendency to produce “echo chambers”. To effectively convey our message, we must be innovative.

The SIOS community strongly believes that early career scientists should be encouraged to participate in the ICARP IV process. Those early career scientists who participate are an asset to the process and must be treated as equals. Today’s early career researchers will comprise most of the participants in the Fifth International Polar Year (2032-2033).

Topic Area 7: Technology, Infrastructure, Logistics, and Services

Scientists need to consider sustainability and the environmental impact of their work. There are multiple ways to address these considerations.

Uncrewed observation platforms (for instance, drones and floats) have a lower environmental impact than icebreakers. Sampling and observations should be automated whenever possible. It is desirable to develop interdisciplinary supersites for observations, sharing research infrastructures[7] and coordinating fieldwork activities to avoid duplicate efforts onshore and offshore.

Remote access to research infrastructures is also recommended, such that sampling and observations can be conducted by scientists or other qualified personnel already on location, significantly reducing the environmental footprint.

Interdisciplinary supersites are also natural meeting places of different disciplines and a fertile ground for new inter- and multidisciplinary scientific initiatives.

Improving the reuse of existing data, including the continuation of existing data series, relies on timely data publication following the FAIR guiding principles and the use of open tools that support this publication and reuse. It is crucial to actively develop and implement data management standards throughout the entire value chain of science, not just in the final stages before publication. Harmonising observation protocols allows for easy comparison of different datasets.

The development and utilisation of new and emerging technologies, along with AI and the digital twin concept—numerical simulation models linked with harmonised data in both observation protocols and documentation—can help identify interconnections between processes and knowledge gaps. Making observations available in real time where possible will further support sustainable scientific practices and support operational services.

5. Recommendations for the future

The general recommendations from SIOS for the ICARP IV process are:

- Ask bold questions. What do we need to do to make sure the world remains liveable for future generations? Finding answers to such questions requires broad collaborative networks like SIOS.
- Improve multidomain integration of science, ideally based on long-term, continuous time series supplemented by implementation of new technology.
- Encourage co-location of observations to focal sites for researchers from multiple disciplines. This will also encourage cross-disciplinary cooperation and new joint scientific initiatives.
- Minimise duplication of observations and datasets through cooperation and coordinated use of infrastructure and logistics, thus also minimising the environmental impact of research.
- Leverage interest in the Arctic by bringing together researchers from around the world to share data and infrastructure (e.g., within SIOS), build common understanding, and ultimately shape environmental policy in a geopolitically strategic and resource-rich region.

7 EU strategy recommends sharing infrastructure, resources and services even more broadly, e.g. for education and outreach. Collections, archives, data computing systems, communication networks—in some cases even advanced scientific equipment and instruments—could be made more readily available. https://research-and-innovation.ec.europa.eu/strategy/strategy-2020-2024/our-digital-future/european-research-infrastructures_en

6. Acknowledgements

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7. References

Christiansen HH, Matero ISO, Baddeley L, Holmén K, Hoppe CJM, Loonen MJJE, Storvold R, Vitale V, Zaborska A, Lihavainen H (2024) Developing the Svalbard Integrated Arctic Earth Observing System (SIOS). Earth Syst Dynam 15:933–946. https://doi.org/10.5194/esd-15-933-2024

EU Strategy. European Research Infrastructures. https://research-and-innovation.ec.europa.eu/strategy/strategy-2020-2024/our-digital-future/european-research-infrastructures_en. Accessed 4 December 2024

ICARP III Final Report 2015: Integrating Arctic Research - a Roadmap for the Future, https://icarp.iasc.info/images/pdf/ICARP3/Downloads/ICARPIII_Final_Report.pdf

Lihavainen H, Singh A, Godøy Ø, Luks B, Steen H, Baddeley L, Partamies N, Mohaupt V, Matero I, Jones EL, Hübner C, Denkmann R, Morris A (2024) SIOS contribution to ICARP IV process. https://icarp.iasc.info/images/Engagement_Activities_Final_Reports/SIOS_ICARPIV_event_report.pdf

Frequently asked Questions

Secular shift of the magnetic dip pole and its consequences for auroral boundaries (PoleMotion)

Why is motion of the magnetic pole of relevance for Svalbard?

The motion of the magnetic pole affects navigation and infrastructure in Svalbard. Changes in the magnetic field require regular updates to maps and runway designations, as seen at Longyearbyen airport. Additionally, Svalbard's increasing proximity to the dip pole results in stronger local magnetic fields.

Why does the auroral oval shift in response to changes in the magnetic field?

The auroral oval's position is governed by Earth's magnetic field, as electrons traveling along magnetic lines generate auroras when interacting with the atmosphere. Changes in the geomagnetic field, including shifts in the magnetic pole, alter the configuration of these lines, leading to a poleward or equatorward movement of the auroral oval.

What are the potential long-term consequences of a shifting pole position and a weakening magnetic field?

A shifting pole and weakening magnetic field affect space weather which, in turn, can cause disruption in navigation and communication systems. Additionally, changes in the magnetic field orientation require more frequent updates for navigation maps and aviation charts.

Geology of Svalbard: Deep-time and Deep-Earth (SVALGEOL)

Why should society care about Svalbard's geology?

Geology has historically controlled the location of Svalbard's permanent settlements and is an integral element of the future sustainable development of Svalbard.

Why and where do earthquakes occur in Svalbard?

Many smaller earthquakes occur at plate tectonic boundaries west and north of Svalbard; these are too small or too far from the settlements to be felt by people. However, moderate earthquakes (up to M6) have been felt in Longyearbyen that originate in the Storfjorden area, making Svalbard Norway's most seismically active region.

How can geology contribute to the energy transition in Longyearbyen?

Geologists have a strong understanding of the rocks beneath Longyearbyen and can provide critical input for potential geothermal energy production, exploiting the local natural gas or CO_2 storage possibilities.

Can Svalbard's rocks tell us something about how the climate changed in the past?

Absolutely! Svalbard's rocks record over 500 million years of near continuous climate history and have been studied by many international research groups. The rocks are currently also being targeted by a comprehensive scientific drilling project, and have been the focus of numerous outcrop and drill core studies.

What is the ancient beast swimming in Longyearbyen's "downtown"?

The popular playground installation is based on a plesiosaur, a marine reptile fossil that lived around 150 million years ago, one of many discovered in central Spitsbergen.

Surging glaciers in Svalbard: Current knowledge and perspectives for monitoring (SvalSurge)

Why do glaciers surge?

A "normal" glacier accumulates mass at higher elevation and loses mass at lower elevations. This introduces a surface slope which governs the flow, or discharge, of ice. Surge-type glaciers are different and instead build up mass over time before releasing all of that ice during an "active" surge. This period is short-lived and eventually the glacier slows down and begins to build up mass again. This cycle of fast and slow flow are driven by changes in subglacial water pressure (and enthalpy) and processes at the glacier bed which impact on glacier sliding.

Does ongoing climate change influence glacier surges?

Surging glaciers are located in geographical clusters which are determined by temperature and precipitation patterns. Therefore, climate change could shift the optimal conditions needed for surging away from Svalbard. Furthermore, climate warming leads to more melt and liquid precipitation which may be temporarily triggering more surges as more melt reaches the glacier bed causing an increase in glacier flow. Increased snow precipitation can also lead to larger mass accumulation and precondition glaciers to surge. Ultimately, the impact of climate change is not known.

Why is Svalbard an important location to study surges?

Svalbard has one of the highest concentrations of surge-type glaciers on Earth. Many of these are relatively easily accessible on foot, boat or helicopter. Svalbard also has an extensive collection of historical records which can be used to detect surges in the past, increasing the long-term record. Finally, Svalbard is one of the fastest warming locations in the Arctic, making it a prime location to study the influence of climate warming on surge-type glaciers. This all makes Svalbard an extraordinarily well-suited natural laboratory to study glacier surging.

Methane in Svalbard (SvalGaSess)

Are natural methane emissions from Svalbard significant in a pan-Arctic context?

Unlikely, due to the relatively small land area compared to known hotspots such as Siberian wetlands and efficient removal processes (methanotrophy) in the sea and the summer thaw layer. Data from Zeppelin Observatory (Ny-Ålesund) show that the main driver of present day variability in atmospheric methane above Svalbard is long-range transport of emissions from Northern Europe/Russia. Svalbard's emissions could be up to 0.2 Tg CH_4 per year, whilst global emissions according to models are probably about 580 Tg CH_4 per year.

What is Svalbard's place in the Arctic methane story – interesting anomaly, hotspot or broadly representative type-site?

Svalbard is a small hotspot whose data-rich, accessible and international research environment make it an ideal analogue for the expansive yet poorly studied Arctic regions with similar methane dynamics (e.g., the glacierised Russian and Canadian Arctic islands and parts of Western, Northern and Eastern Greenland). Working on methane in Svalbard also provides an important contribution to the global network of atmospheric methane observation.

What changes can we expect in methane emissions from Svalbard due to rising temperatures?

At least in the short-term, an increase seems likely. On land, this requires an expansion of wetlands, the ongoing retreat of Svalbard glaciers, and the pressurisation of deeper groundwater flowpaths by more rain, snowmelt and glacier ablation. At sea, this requires less sea ice to enhance ventilation

and reduce the time spent by gas within the water column during winter. Major, sudden increases are possible (and have occurred during warming periods on the past) if driven by geogenic methane escape from beneath permafrost and glaciers.

Are current observing capabilities sufficient to quantify regional emissions and understand the impact of a changing Arctic?

No. Networked global/regional background atmospheric methane measurements at sites such as Zeppelin (Ny-Ålesund) are typically used in tandem with more localised measurements at hotspots to help constrain their emissions. In this context there are too few background sites in the wider Arctic region to sufficiently constrain emissions from Svalbard, while a full accounting of local methane hotspots alongside a parametrisation of their response to climate change is also lacking.

Can natural gas be utilised as a potential energy source in Longyearbyen?

Possibly. The potential for energy utilisation of the methane beneath the permafrost in Adventdalen has been assessed in the literature described in this report. At the time of writing, there is little enthusiasm to harness the gas, in spite of its lower CO_2 emissions than imported diesel and ongoing natural leakage into the atmosphere. For now, this leakage appears to be small compared to the total volume of gas thought to be trapped beneath permafrost and glaciers.

The Atlantification process in Svalbard: a broad view from the SIOS Marine Infrastructure network (ARiS)

Why do we need marine observatories around Svalbard?

The marine observatories around Svalbard are essential for collecting long-term and spatially distributed data to capture climate signals and understand their impact on weather patterns, sea ice, ecosystems and ocean circulation. Svalbard is a rapidly changing region with easily accessible infrastructure, which makes it an ideal location for studying the ongoing climate changes in the Arctic environment.

What are the full ecosystem impacts of Atlantification?

Rising temperatures and salinity in the Arctic may trigger significant changes in ecosystems, from loss of sea ice and disruption of the food web to altered nutrient dynamics and fish migration. All these processes could have downstream effects also on biodiversity and the global climate system.

What is the main driving mechanism of Atlantification?

The most important mechanism driving Atlantification in the Arctic is the increasing inflow of warm and saline Atlantic Water into the Arctic Ocean via the Barents Sea and the Fram Strait. This process is mainly driven by changes in oceanic and atmospheric circulation patterns and influenced by climate change.

Microbial communities as sentinels of environmental changes in Svalbard (MicroSIOS)

Do we have enough information on microbiological variables?

No. The currently available data come from widely scattered sites and are scarcely related to other disciplines. Long-term microbiological monitoring systems coupled with existing infrastructure for physical-chemical monitoring should be encouraged.

Are microbiological variables good candidates as environmental proxies?

Yes. Starting from a baseline description of current microbial diversity and functions, the detection of changes in microbiological variables could furnish information that is crucial to understanding the

effect of environmental dynamics and predicting possible future scenarios.

Is bacterial antibiotic resistance spreading, and could it represent a serious threat for humans?

Yes, antimicrobial resistance (AMR) is spreading rapidly and some antibiotic resistance genes have been detected in Svalbard just a short time after they were first observed in other parts of the globe. However, it is currently hard to assess the extent of dispersion of antibiotic resistant and pathogenic bacteria in the Arctic and the associated risks for humans. Much more research will be necessary to develop appropriate management strategies.

How can researchers describe all the different types of microbes within a community?

Combined use of traditional methods (e.g., culture followed by isolation and screening) and molecular biological methods (e.g., DNA extraction and sequencing) helps researchers gain complete information on microbial taxa and their distribution in the different environmental compartments. We can figure out if a compartment hosts many or few taxa and how much the community structure differs from sample to sample from the same location. We can also learn much from studying metabolic pathways and physiology.

What methods could be applied to microbial research to aid SIOS' mission of reducing the carbon footprint of research in Svalbard?

Protocols and methods adopted in Svalbard environmental monitoring must be inspired by the principle of reducing carbon footprints. To this end, remote monitoring systems for microbial variables should be encouraged, as well as the application of automatic sampling (i.e., sensors or devices allowing sampling to be automated), thus limiting anthropic pressure on vulnerable environments.

Terrestrial and freshwater invertebrate science in Svalbard in a changing world: from regional to pan-Arctic scales (STAFIEN - Svalbard Terrestrial and Freshwater Invertebrate Ecology Network)

Are there really insects and spiders living in Svalbard?

This is a question that terrestrial ecologists often receive. But yes, there are – and not only mosquitoes. To date, the invertebrate community is known to be composed of over 1 000 species of which 200+ are insects and 18 are spiders. What is more, the total mass of terrestrial invertebrates in Svalbard is measured in the thousands of tonnes with often immense abundances.

https://www.learningarcticbiology.info/

What do they do?

They play a variety of roles, for example in nutrient cycling and the creation of organic soils. They pollinate flowers and enable seed production. They may eat the plants or be food for predators such as snow buntings. They form a key element in the ecosystem we see around us. Without them Svalbard would appear very different from what we observe today. As an example, plants including the cream or yellowish mountain avens (reinrosa) or purple saxifrage (fjellsmelle) would not be present since organic soils would be non-existent or too thin.

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Where did they come from?

Much of the community is thought to have colonised Svalbard since the retreat of the ice after the Last Glacial Maximum, although some may possibly have survived here in refuges, including some species that are currently only known from the archipelago (endemic). Most of the species probably arrived here by accident, for example being blown here by the wind or carried on driftwood or ice-rafted debris by ocean currents. In some years the migratory diamondback moth can be observed around Longyearbyen, having been blown here by southerly winds.

https://www.learningarcticbiology.info/learning-arctic-biology/species-and-adaptations/invertebrates/colonisation-of-svalbard/

Are they here in the winter then?

None of the resident invertebrates in Svalbard migrate. While we occasionally see vagrants, species blown here accidentally by the wind, the remaining species are here the whole time. In the winter the terrestrial species shelter in the soil, or within vegetation, and often in a specific physiological state that enables survival of being surrounded by, or encased in, ice. There are three basic cold tolerance strategies, those that desiccate and remove almost all body water, those that trigger freezing of body water in particular regions of their bodies, and those that produce antifreeze.

https://www.learningarcticbiology.info/learning-arctic-biology/species-and-adaptations/invertebrates/invertebrate-adaptations/

Do they face any threats due to climate change?

Terrestrial invertebrates face a range of threats, the principal of which is indeed ongoing current climate, or environmental, changes. For example, changes in the timing of snowmelt, and the release of the ground from winter, alter the length of the summer period as well as, potentially, soil moisture. Warmer winters with increased occurrence of rain-on-snow events and the creation of thick surface ice layers is an additional stress that is increasing in frequency, the effect of which is unknown. Other potential threats include new invasive species (often introduced by humans), pollution, and land-use changes.

Operationalisation of COAT in SIOS – an example of adaptive ecosystem-based monitoring in practice (COAT)

What is the High-Arctic tundra?

The High-Arctic Tundra is the most northerly community of plants and animals inhabiting a very dry and cold climate with short cool summers and long cold snow-covered winters. Permafrost (ground remaining frozen for two or more years) is a characteristic of the High-Arctic tundra, and areas are mostly treeless and covered with low-lying vegetation. The ecosystems of the High-Arctic tundra contain a diverse range of plants and animals, many of which are endemic. Currently, the Arctic tundra is exposed to rapid, dramatic changes from climate change.

What is the Climate ecological Observatory for Arctic Tundra in Svalbard (COAT Svalbard)?

The Climate Ecological Observatory for Arctic Tundra (COAT) is a response to the urgent international calls for establishment of scientifically robust observation systems that will enable long-term, real-time detection, documentation, understanding and predictions of climate impacts on Arctic tundra ecosystems.

Is a milder climate good for herbivores in the Svalbard tundra?

A milder climate influences the herbivore species in the Svalbard tundra in ways both good and bad. It advances spring and extends the summer grazing season. This can be positive because breeding grounds for migratory geese are accessible earlier and herbivore forage for non-migrating species will be available for a longer time-period during autumn. However, this can also cause phenological mismatches between reproduction and important food plants.

Understanding and analysing recurrent warm events in Svalbard: a comprehensive review on land cryosphere (AWARE)

What is the difference between heatwaves and warm spells?

A heatwave can be described as a brief period of unusually hot weather compared to the average temperature of the location, and lasting for at least two consecutive days. In contrast, a warm spell

refers to a persistent period of unseasonably warm weather (at least 5 days), typically occurring during a cooler time of year such as autumn, winter, or early spring.

What is a rain-on-snow event?

Rain-on-Snow (RoS) events occur when rain falls onto an existing snowpack with 100% coverage (i.e., no snow-free areas). These events are associated with winter extreme events like heatwaves and warm spells.

How can RoS events be identified separately from solid precipitation?

Precipitation is considered rain when the air temperature is at or above 1°C. However, rain can also occur with a lower probability when atmospheric temperatures range between 0.5°C and 1°C.

What happens when rain falls over a snowpack?

The most direct effect of a RoS event is the significant modification of the snowpack structure. This can lead to the formation of ice layers within the snowpack and at the bottom, potentially covering the ground with ice. Intense events may partially melt the snowpack and activate the area's hydrological system, forming streams and ponds, even beneath the snow surface, with potential consequences for human activities (snowmobiling, skiing, dog sledding) and wildlife.

Assessing anthropogenic and natural aerosol sources in the Arctic: A baseline to detect changes due to climate change (AAA-Source)

Why is it important to know the chemical composition of the atmospheric aerosol in the Arctic?

The chemical composition of atmospheric aerosol allows us to identify and possibly quantify its source. The more "tracer" compounds we measure the easier it is to identify the sources. Chemical analysis also allows us to determine the concentration of toxic elements or compounds. Finally, physical properties, such as the capability to affect cloud properties, depend on the aerosol chemical composition.

What are the sources of Arctic aerosol?

The main natural aerosol sources in the Arctic are sea salt, the biosphere, Earth's crust, and wildfires. The main anthropogenic source is continental regions located at mid-latitudes. Local anthropogenic sources (such as aerosol from ship emission) contribute very low concentrations and are seen only in specific situations.

Is the contribution of aerosol sources the same across the Arctic?

Although more sites are needed to assess aerosol spatial variability, the data collected in this chapter reveal that both anthropogenic and natural sources are not spatially constant. For instance, the impact of long-range transported anthropogenic aerosols is higher in the European Arctic than in the American Arctic. Among the natural sources, biogenic aerosol is more abundant at Svalbard, which receives aerosol from the most biogenically active oceanic areas (Greenland and Barents Sea).

How do Arctic sources vary over time?

The impact of different aerosol sources varies with the season. In general, winter and spring seasons are dominated by anthropogenic long-range transported sources, whereas in summer and fall, natural local sources dominate. In addition, there have been and will continue to be long-term trends that depend on both sustainable development policies in mid-latitude countries and especially global change. This is the main purpose of this chapter: to study the present to be prepared for future change.

At present, what is the air quality in the Arctic?

This data set collected from ten Arctic and pan-Arctic sites show that the quality can be considered very good at present. However, the Arctic is

connected to mid-latitudes, particularly via the atmosphere, and shows episodes of air pollution. Arctic air quality is expected to worsen in the future. Therefore, monitoring in several sites is very important to assess the effects of environmental sustainability policies.

Towards an integrated data-driven infrastructure (InfraNor)

What is the InfraNor Project?

Based on new and upgraded research infrastructure, SIOS-InfraNor is improving our understanding of key Earth system mechanisms. This research is crucial in the context of the pronounced warming observed in the Arctic, particularly in Svalbard and its surrounding seas.

What is COAT in InfraNor?

COAT – Climate-Ecological Observatory for Arctic Tundra, is an integrated ecosystem-based monitoring programme at the core of the biosphere components of InfraNor's terrestrial research capabilities. COAT combines ecology and physical sciences to enable real time detection, documentation, and understanding of climate impacts on arctic tundra ecosystems. The infrastructure used within COAT's Svalbard branch is supported and integrated in InfraNor.

SIOS' contribution to the ICARP IV process (SICAR)

What is the ICARP IV process?

The Fourth International Conference on Arctic Research Planning (ICARP IV) is a multi-year planning process that will take place from 2022 to 2026. It brings together Arctic researchers, Indigenous Peoples, policymakers, residents, and stakeholders from around the globe to collaboratively discuss the state of Arctic science and the region's role in global affairs and systems. After the final report is published in 2026, the implementation of research priorities will be initiated.

What is the 5th IPY?

The International Polar Year (IPY) 2032–2033 will carry on the long-standing tradition of organising regular IPYs in response to the current, unparalleled demand for extensive, coordinated, large-scale research on polar and global changes. It will expand upon four groundbreaking IPYs from 1883 to 2008, which when combined provide a 150-year history of reliable scientific data about environmental changes in polar areas. ICARP IV is one of the large-scale processes feeding into IPY priorities.

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