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Review

Developing the Svalbard Integrated Arctic Earth Observing System (SIOS)

Hanne H. Christiansen[1], **Ilkka S. O. Matero**[2], **Lisa Baddeley**[1,3], **Kim Holmén**[4], **Clara J. M. Hoppe**[5], **Maarten J. J. E. Loonen**[6], **Rune Storvold**[7], **Vito Vitale**[8], **Agata Zaborska**[9], and **Heikki Lihavainen**[2]

[1]Arctic Geophysics Department, The University Centre in Svalbard, UNIS, 9170 Longyearbyen, Norway
[2]Svalbard Integrated Arctic Earth Observing System (SIOS), SIOS Knowledge Centre, 9170 Longyearbyen, Norway
[3]Birkeland Centre for Space Science, University of Bergen, 5020 Bergen, Norway
[4]Norwegian Polar Institute, Framsenteret, 9296 Tromsø, Norway
[5]Department of Marine Biogeosciences, Alfred Wegener Institute – Helmholtz Center for Polar and Marine Research, 27570 Bremerhaven, Germany
[6]Department of Arctic and Antarctic Studies, University of Groningen, Arctic Centre, 9 Aweg 30, 9718 CW Groningen, the Netherlands
[7]Observing Systems, Norwegian Research Centre, 9019 Tromsø, Norway
[8]Institute of Polar Sciences, Italian National Research Council, 40129 Bologna, Italy
[9]Marine Chemistry department, Institute of Oceanology, Polish Academy of Sciences, 81-712 Sopot, Poland

Correspondence: Hanne H. Christiansen (hannec@unis.no)

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Abstract. Based on the ongoing large climatic and environmental changes and the history of science coordination in Svalbard leading to the development of Svalbard Integrated Arctic Earth Observing System (SIOS), we present an overview of the current gaps in knowledge and infrastructure based on a synthesis of the recommendations presented in the annual State of Environmental Science in Svalbard (SESS) reporting of SIOS. Recommendations from the first 4 years of SESS reporting represent the point of view of the wide scientific community operating the large observing system implemented in Svalbard (SIOS) since 2018 and aim to identify the scientific potential to further develop the observing system. The recommendations are bottom-up inputs for a continuous process that aims to accomplish the vision and mission of SIOS: optimizing, integrating and further developing the observing system in an Earth system science (ESS) perspective. The primary outcome of the synthesis work is the evidence that ESS in SIOS has, during the first 4 years of operation, naturally developed from individual scientists or smaller groups of scientists to larger disciplinary international groups of scientists working together within the different environments (the atmosphere, the cryosphere, and marine and terrestrial environments). It is clear that strategic efforts towards interdisciplinarity are necessary for operating fully at ESS scale in Svalbard. As Svalbard is experiencing the largest ongoing warming in the Arctic and worldwide, SIOS is in a unique position to perform a full-scale study of all processes impacting ESS dynamics and controlling the water cycle using all parts of the SIOS observation network, with a large potential for increasing the understanding of key mechanisms in the Earth system. We also identify the potential to upscale Svalbard-based observations collected in SIOS to pan-Arctic and global scales, contributing to full-scale ESS.

1 Introduction to ongoing climatic and environmental changes in Svalbard

The Arctic Earth system is experiencing rapid transformations driven by climate change. The archipelago of Svalbard (74–81° N), located halfway between Norway and the North Pole, is experiencing some of the largest climatic changes during the last decades, making it an Arctic hotspot. Svalbard has the longest high Arctic meteorological record from the Longyearbyen area extending back to 1898. It clearly shows how surface warming has been ongoing during the last half century (Fig. 1). Isaksen et al. (2022) identify a statistically significant and exceptional to the Arctic and globally record-high annual surface air temperature warming of up to 2.7 °C per decade, with a maximum in autumn of up to 4.0 °C per decade for northeasternmost Svalbard on Karl XII-øya (1991–2020). In central Svalbard the surface air temperature at Longyearbyen airport has had a linear increase of 3.8 °C in the 1899–2018 period. This is about 3.5 times more than for the global mean temperature during the same period (Nordli et al., 2020). In addition, the annual warming rates have accelerated since the 1980s up to the last decade (Isaksen et al., 2022). This warming is closely linked to substantial reduction in sea ice and an increase in sea surface temperatures in the northern Barents Sea. For this region, summers (JJA) have had the lowest decadal surface air temperature warming, ranging from 0 to 0.7 °C, but Karl XII-øya experiences a decadal warming rate of 1.3 °C, while winters (DJF) have seen up to 3.8 °C per decade and springs (MAM) 2.1 °C per decade, with all numbers based on the 2001–2020 period (Isaksen et al., 2022). The sea surface temperature has increased by 0.8 °C per decade for the last 2 decades along western and southern Svalbard and in the southeastern Barents Sea, representing some of the largest sea surface warming rates observed in the Northern Hemisphere and reflecting the larger and warmer inflow of Atlantic Water by the West Spitsbergen Current to this region (Isaksen et al., 2022). This inflow may also influence the late freeze-up of the northern Barents Sea and Franz Josef Land areas. Clearly, the ongoing environmental changes show how different parts of the Earth system are affected and interacting in their responses to the ongoing surface warming both on land and in the sea.

In the mesosphere from 76–90 km, the hydroxyl (OH∗) airglow temperature series from Longyearbyen is one of the longest continuous measurement records of winter temperatures in the world, extending from 1983 to the present (Wüst et al., 2023). The overall daily average mesospheric temperature for the 2005–2012 seasons was −67.15 °C, 3 °C colder than studies from earlier time periods (Holmen et al., 2014). Temperatures at 90 km altitude above Svalbard have also been determined using a meteor wind radar and subsequently calibrated by satellite measurements for the period autumn 2002 to 2019. The cooling rate during summer months is 9.9 ± 2.9 °C per decade between 2002 and 2012, and 4.3 ± 1.2 °C per decade between 2002 and 2019 (Hall and Tsutsumi, 2020). Carbon dioxide is a major driver of long-term trends in the upper atmosphere. This, along with other greenhouse gas emissions, causes a general cooling effect of about −1 to −3 °C yr^{-1} at 250 km altitude (Zhang et al., 2016). Radar observations have also shown that the situation is different between the low- and high-latitude regions, with the high latitudes showing less cooling and even some warming above 300 km altitude (Lastovicka et al., 2017). Similarities between the observations of atmospheric vertical temperature trends and climate model projections are pointed out by the IPCC (IPCC, 2021), who show that new techniques permit more robust quantification of temperature values and trends, allowing for improved confidence in the vertical structure of temperature changes.

The Svalbard region is furthermore experiencing Atlantification of the surrounding seas, as increased ocean heat is transported to the region from the west in the form of Atlantic water masses (Efstathiou et al., 2022). Concurrent changes in oceanographic conditions (e.g. water temperature, nutrient loading, stratification), together with transport of organisms from further south, may significantly alter species composition and productivity of Svalbard's coastal marine ecosystems (Bischof et al., 2019; Assmy et al., 2023). Arctic terrestrial flora and fauna are generally sensitive to warming, but trends over a period of time are heterogeneous and complex (Bjorkman et al., 2020; O'Connell et al., 2006; Pedersen et al., 2020). Most terrestrial Arctic endemic species in Svalbard are experiencing negative consequences induced by the warming environment (Descamps et al., 2017). In the terrestrial ecosystem, increased winter air temperatures are often accompanied by increases in the frequency of "rain-on-snow" events, one of the most important facets of climate change with respect to impacts on flora, fauna and society (Hansen et al., 2014). Also, given that all the cryosphere components are inherently sensitive to temperature change especially around 0 °C, Svalbard has experienced a continued net loss of ice (Meredith et al., 2019). The latter is a natural integrator of climate variability and provides some of the most visible signatures of climate change, with retreating glaciers, shorter snow-covered seasons and thawing permafrost (Constable et al., 2022).

2 Science coordination in Svalbard leading to the Svalbard Integrated Arctic Earth Observing System (SIOS)

Research in Svalbard has a long tradition, going back at least to the "La Recherche" expeditions in 1838 and 1839. Early work was in expedition form, but some permanent observatories emerged from the International Geophysical Year (IGY) in 1957 (Norges Forskningsråd, 1997). A French station ("Corbel") was established outside Ny-Ålesund, and the Polish station in Hornsund was also established in the same period. The first more permanent research establishment came

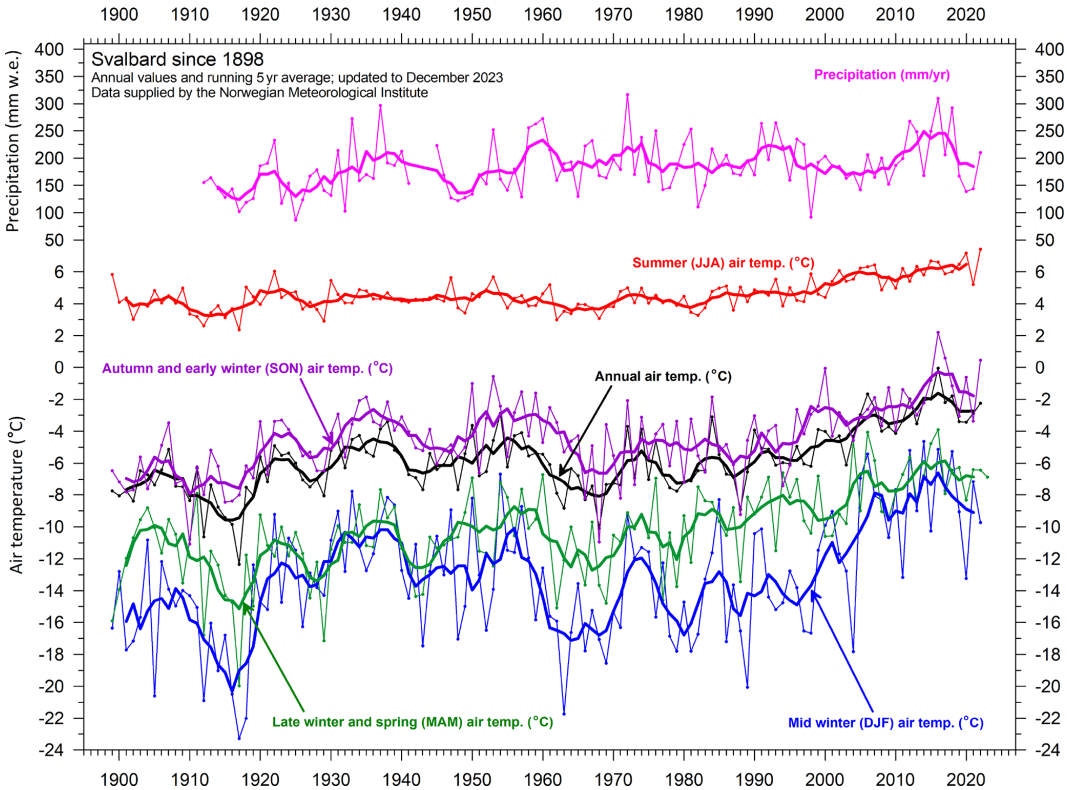

Figure 1. The meteorological record from the Longyearbyen area is composed of the homogenized data series from the Norwegian Meteorological Institute (1898–2022).

in 1967 when the Kongsfjord Telemetry Station was set up in Ny-Ålesund for communication with the European Space Research Organization satellites. This was in close collaboration with The Norwegian Polar Institute, which established a research station in Ny-Ålesund in 1968. The telemetry station was discontinued in 1974. A diversification of research in Ny-Ålesund began with the Norwegian Institute for Air Research and University of Tromsø conducting activities as of the middle of the 1970s. Norwegian universities and other institutions began sending summer expeditions to Ny-Ålesund, followed by expansion of activities after the 1990s with institutions from numerous nations establishing a presence. It soon became apparent that many projects worked on similar topics and were partially duplicating logistical and scientific efforts. This was one of the motivations for establishing the Ny-Ålesund Science Managers Committee (NySMAC) in 1994 as an organization to coordinate research and logistics. As NySMAC matured there was an increased desire to also coordinate the scientific questions addressed. This led to the formulation of the NySMAC flagship programmes, which were essentially established around the four themes that were de facto most studied in Ny-Ålesund (Atmospheric science, Glaciology, Marine Science and Terrestrial Science).

The research landscape in Svalbard then further developed. In Barentsburg there have been scientific activities under the auspices of the Russian Arctic Antarctic Research Institute for decades. In Longyearbyen there were several research projects present from around the time of the opening of the airport in 1975. The University Centre in Svalbard was established in Longyearbyen in 1993 and has since grown to its present scale of ~ 50 scientific personnel and an annual throughflow of about 750 students (200 student year equivalents per year). In addition to research activities in these permanent sites, a large number of studies and projects have been carried out in the surrounding parts of the archipelago, with the scope to study the glaciers, permafrost, vegetation and ecosystems in a changing climate.

With the diversity of research spreading across Svalbard, a need for better sharing of information about ongoing research was seen and Svalbard Science Forum (SSF) was established in May 1998 under the auspices of the Norwegian Research Council (St.meld.nr.22, 2009). SSF expanded its activities with a new mandate in 2005 and rapidly evolved to its present organization with a permanent office in the Svalbard Science Centre in Longyearbyen. The initial task of SSF was to establish the Research in Svalbard (RiS) database, which then was a paper-based annual report. Today RiS is a fully digital direct information platform with past, ongoing and planned research projects in Svalbard. Everyone doing research in Svalbard is expected to contribute to the RiS database. SSF has two meetings per year for Svalbard-wide research, providing information exchange between the major research nodes in Svalbard (Barentsburg not participating since February 2022). SSF does not make scientific priorities or recommendations per se but facilitates the flow of information. SSF also provides some funding opportunities to further scientific cooperation in Svalbard and enable the recruitment of young scientists to Arctic research, as well as organizing a conference focusing on Svalbard Science every other year.

The next challenge for the scientific community was to dare to formulate and tackle larger Svalbard-wide endeavours with questions larger than any one of the research entities would be able to pursue on their own, e.g. an Earth system science (ESS) perspective. Another challenge was harmonizing data and making it openly available using machine-readable formats, meaning that results from different contributors can be utilized together with minimal data revision. These were visions and roles that none of the existing structures were designed to undertake. The creation of Svalbard Integrated Arctic Earth Observing System (SIOS), an ESS-guided independent international consortium was therefore a next step (St.meld.nr.22, 2009) to bring together the full scientific benefits of the previously established practical research cooperation bodies. Against this backdrop the potential to develop a full ESS regional distributed research infrastructure (RI) to study Arctic environmental change in Svalbard was already identified in 2007. To achieve this, the concept of SIOS was developed through an EU-funded preparatory-phase project in 2010–2013, and the operation continued with an interim phase in 2014–2017. Thanks to great efforts undertaken during the previous 10 years, SIOS entered its operational phase in 2018.

The mission of SIOS is to study the environment and climate in and around Svalbard to develop an efficient observing system, share technology, experience and data, close knowledge gaps, and decrease the environmental footprint of science. The aim of SIOS is to perform an integrated assessment of how Arctic Earth system changes are developing and interacting with a clear aim to connect the different scientific subdisciplines for improved ESS understanding. SIOS presents opportunities for research and the acquisition of key knowledge on global environmental change, with a focus on processes and their interactions between different environments, i.e. biosphere, geosphere, atmosphere, cryosphere and hydrosphere. The vision of SIOS is to be the leading long-term observing system in the Arctic to serve Earth system science for society (https://sios-svalbard.org, last access: 25 July 2024).

SIOS is currently a consortium of 28 international research institutions from 10 different countries (https://sios-svalbard.org, last access: 25 July 2024) that own or operate research facilities in the Svalbard region or that provide research data relevant for the consortium. Together the consortium develops and maintains a regional observational system (Fig. 2) for long-term measurements in and around Svalbard, addressing Earth system science questions related to global change. The members own and give access to their research infrastructure. The SIOS data policy states that new data contributions from the consortium are to be made available through the SIOS data management system (SDMS, https://sios-svalbard.org/Data, last access: 25 July 2024) and that they need to follow the FAIR (findable, accessible, interoperable, reusable) guiding principles for scientific data management and stewardship (Wilkinson et al., 2016). SDMS includes a federated database system, in which the individual datasets are hosted at contributing data centres across the globe, and metadata records about these data are stored is kept in a SIOS metadata catalogue. The datasets can be accessed through a portal hosted on the SIOS website (https://sios-svalbard.org/metsis/search, last access: 25 July 2024). At the time of writing the database provides access to over 550 000 datasets, with the longest time series spanning over 70 years back to 1945. The currently available datasets follow the FAIR guiding principles to a varying degree, and a large fraction of them are from the Norwegian National Ground Segment for satellite data (https://www.satellittdata.no/en/metsis/search, last access: 25 July 2024). SIOS also hosts a separate portal (https://www.sios-svalbard.org/sios-ri-catalogue, last access: 25 July 2024), in which the current, historic and planned observation facilities collecting SIOS data are documented.

The operations of the SIOS consortium are coordinated by the SIOS Knowledge Centre, the central hub of SIOS. SIOS has five active working groups with different tasks: the Science Optimisation Advisory Group, the Research Infrastructure Coordination Committee, the Data Management System Working Group, the Remote Sensing Working Group and the Information Advisory Group. The mandate of the Science Optimisation Advisory Group (SOAG) is to prioritize ideas and initiatives for observing system development, considering scientific and societal relevance, feasibility and realism.

The previously mentioned flagship programmes of Ny-Ålesund are developing and taking an increasing role in formulating upcoming research projects and programmes that have direct similarities to the priority processes in SIOS. An intimate relationship between SIOS and the NySMAC flagship programmes is a logical and emerging development. The organizations differ in their respective approaches to supporting science projects. SSF provides support in a neutral manner, whereas SIOS seeks to promote cooperative scientific endeavours in which institutions merge their activities specifically to enhance the environmental observations in Svalbard.

2.1 State of environmental science in Svalbard

As SIOS entered operation in 2018, an important overview tool for the observing system was initiated, the annual report

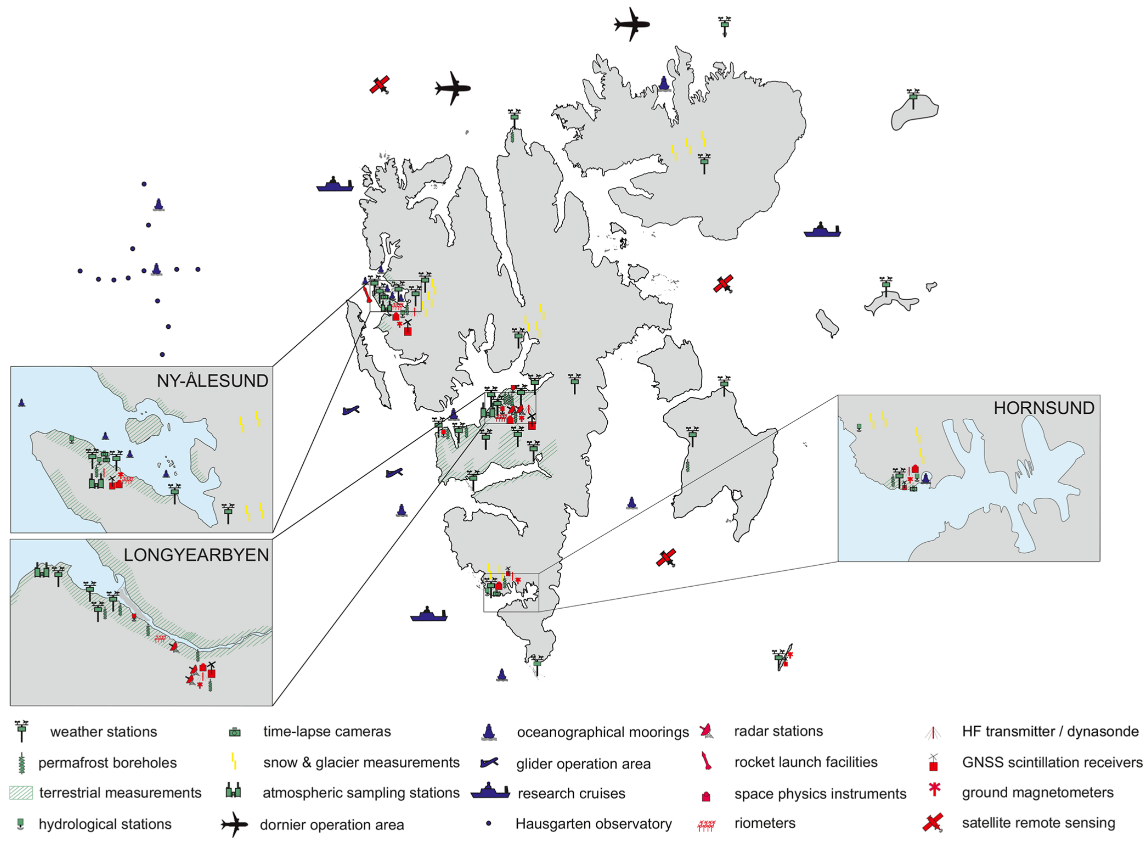

Figure 2. SIOS observation infrastructure in Svalbard, with the three main science hubs Longyearbyen, Hornsund and Ny-Ålesund inset to present all the various types of observations in more detail.

series: State of Environmental Science in Svalbard (SESS). The overall aim of the reports is to summarize the state of current knowledge of key ESS parameters and analyse how these interact. The SESS reports contain peer-reviewed scientific chapters and associated outreach summaries. During the first 4 years of operation (2018–2021), a total of 40 individual chapters presented 169 recommendations (Orr et al., 2019; Van den Heuvel et al., 2020; Moreno-Ibáñez et al., 2021; Feldner et al., 2022). Most SESS contributions have been reviews, but data summaries and updates to earlier SESS contributions have also been included. The SESS contributions have been authored by international and sometimes multidisciplinary groups.

SESS reports are an integral part of the SIOS work programme aimed at developing a coherent Svalbard observing system for many uses and users (Fig. 3). SIOS, i.e. the SIOS member institutions, the SIOS working groups, and the SIOS Knowledge Centre, includes the internal forces that try to move the Svalbard scientific community forward to provide better Earth system science data in Svalbard and thus serve societal needs related to climate change, pollution and biodiversity loss. The different aspects of the Earth system and the means to improve the observing system are the preoccupation of the many SIOS working units, including task forces that are formed from different SIOS working groups, individuals from SIOS member institutions working in secondments on a specific topic within SIOS and expert residents such as the SIOS chair targeting the utilization of SIOS data in scientific research. With the principles of cooperation, innovation and data harmonization this work ensures that the SIOS community produces relevant long-term data series, the SIOS core data (https://sios-svalbard.org/CoreData, last access: 25 July 2024) and improved research infrastructure (https://www.sios-svalbard.org/sios-ri-catalogue, last access: 25 July 2024) as a basis for new research projects and capacity building. The SESS report allows research groups from member institutions to identify observational gaps and provide recommendations on how to close those in a bottom-up process. The SESS reports are released annually in the last week of January during an annual SIOS conference called the Polar Night Week. This event is also the main venue for stakeholders, researchers and SIOS working groups to meet for discussing and finalizing consortium activity plans for the following years. The plans are then further aligned with strategic aspects by the General

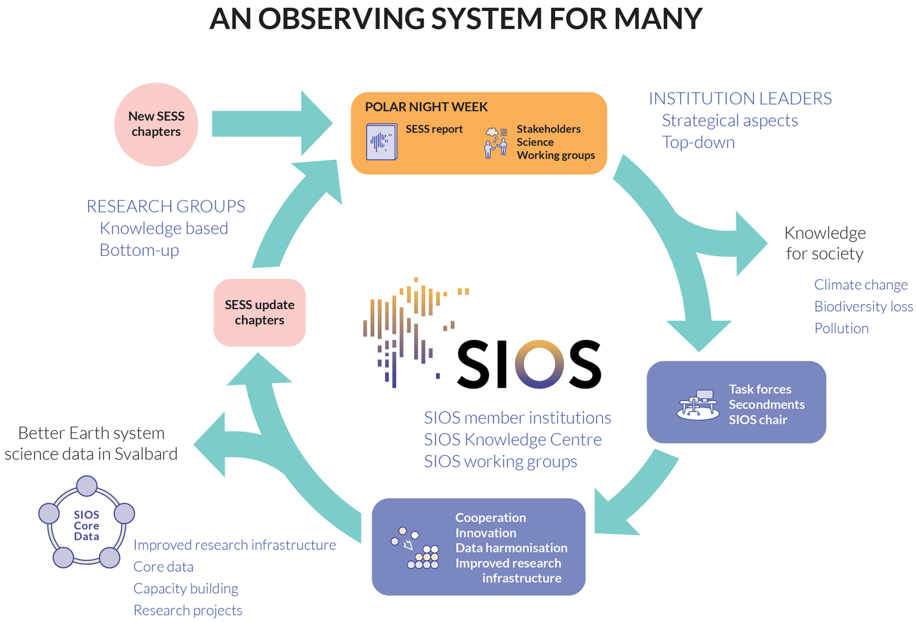

Figure 3. SIOS science wheel that provides an overview of developing the observing system for many uses and users.

Assembly of SIOS in a top-down process, allowing the work programme to develop with input from all levels of SIOS.

The SESS reports help develop the SIOS research infrastructure, as topics are proposed by international research groups and selected through a review process. The calls for input to the SESS reports have been open to all interested researchers from the SIOS member institutions and from other institutions with research activity in Svalbard. Each SESS contribution has been urged to connect interdisciplinarily with the different ESS spheres to allow for improved ESS understanding. SESS recommendations within the reports form an integral part of the contributions and help identify the scientific knowledge gaps and recommend improvements in terms of RI and rising societal needs in Svalbard. The topics of SESS chapters have ranged across the many subdisciplines of ESS from the atmosphere and cryosphere to marine and terrestrial environments. The objective of this paper is to (1) present the synthesis of the SESS recommendations and (2) discuss how to further develop SIOS to serve the pan-Arctic ESS community.

2.2 The state of interdisciplinary Earth system science in Svalbard

Understanding the state of the interdisciplinary scientific background is obviously essential to assess the value of the work performed in SIOS and published in the SESS reports. There are numerous publications on the state of science within the separate ESS disciplines in Svalbard. Only a few of these address interdisciplinary research questions cutting across disciplines. However, a few exist, such as Peeters et al. (2019), who identified a climate–cryosphere regime shift stressing the linkages between the ongoing meteorological changes towards more winter rain precipitation and thicker ground ice cover affecting the cryosphere and the biological environment with animal foraging being moved to ice-free grounds. This changing form of precipitation is thus identified as important for changes in the high Arctic terrestrial environment (Peeters et al., 2019). It has also been identified at Arctic scale (Bintanja and Selten, 2014) that increased winter precipitation is primarily due to intensified local evaporation typically from open sea, thus clearly linking the ongoing increases in Arctic winter precipitation to the marine environment as well. The most recent review of snow research in Svalbard (Zdanowicz et al., 2023), largely based on SIOS work and collaboration, identifies knowledge gaps and research needs in snow science. In doing so, the review relates these gaps and needs to other cryospheric fields such as glacier mass balance and active layer thickness above permafrost, atmospheric conditions in relation to snowpack pollution, and terrestrial ecology and hydrology. Clearly some scientific fields do recognize their interdisciplinary scientific connections. With respect to extreme precipitation events over Svalbard, it is well known that these are caused by moisture transport extending thousands of kilometres south into the subtropical Atlantic and often characterized as "atmospheric rivers" (Serreze et al., 2015; Müller et al., 2022). The increase in extreme precipitation events over the last 4 decades in Svalbard have been directly linked to the sea ice extent east of Greenland, as this sea ice shields the west coast of Svalbard from incoming southerly moist air (Müller et al., 2022). Thus, results show clear linking of meteorological changes with changes in the marine environment and with well-known consequences for ecosystems, cryosphere and society at Arctic scale.

3 Methods

SOAG performed the first synthesis of the output of the SESS reporting to identify how to improve and develop SIOS. A task force was established from SOAG and SIOS Knowledge Centre which included experts from all ESS environments. This approach was considered most natural and sustainable when reviewing and condensing the recommendations, focusing on the atmosphere, the cryosphere, and the marine and terrestrial environments. The main aim of the synthesis was to identify, condense and prioritize the recommendations into key recommendations for the four environments and use these to identify joint interdisciplinary or overall recommendations that expand across the entire Svalbard earth system.

An open process took place with as much participation from all SESS authors as possible, inviting lead authors from all SESS chapters within the four environments to thematic workshops, with the focus on condensing the range of recommendations within each of their environments. The task force has worked fully online, and due to COVID-19 the four thematic environment workshops unfortunately had to be held online in early winter 2022. The cryosphere workshop brought together six SESS authors covering widely different parts of the cryosphere SESS contributions. For the atmosphere, five authors and experts largely discussed the list of recommendations extracted for this domain.

In each environment workshop, the recommendations were grouped and condensed to obtain an overview of the main recommendations within each environment. Based on this thematic condensation of the key recommendations from the four environments, the task force then discussed and further condensed the recommendations for the entire ESS focusing on interdisciplinarity. Finally, the entire SOAG provided feedback and the board of directors of SIOS approved the report as a guiding document for developing SIOS RI.

4 Results

4.1 Key recommendations from the atmosphere, cryosphere, and marine and terrestrial environments

Here we briefly present the main recommendations from the four different environments of the SIOS ESS.

4.1.1 Atmosphere

In the mesosphere–lower thermosphere–ionosphere (M/LTI) system (40–400 km), research focuses on understanding the interaction and coupling between the neutral and ionized atmospheric components, energetic particle fluxes, ionospheric instabilities, and the cusp auroral region. In the troposphere–stratosphere (T/S) system (0–40 km) research focuses on topics such as aerosol–cloud interactions, atmospheric chemistry in the Arctic boundary layer, stratospheric ozone and surface spectral UV fluxes. Several recommendations focus particularly on identifying methodological, technological or observational gaps, along with the need to continue existing long time series measurements (Table 1). For the M/LTI region this is centred around maintaining well-established, larger facilities, such as radars, which can provide multiple parameters such as temperature, density, atmospheric motion and energy dissipation rates across multiple scales with an established and extensive international use base. The facilities have built up extensive long-term databases and provide the opportunity for additional instrumentation to be deployed in their vicinity.

Suggested improvements for the lower atmosphere include filling gaps in observations of spectral UV, black carbon, local sources of biological aerosol precursors, and further meteorological and hydrological measurements. Recent developments in uncrewed aerial vehicles (UAVs) and miniaturization of electronics and instruments should be exploited to develop more mobile observational platforms. There should also be a push to increase the number of parameters observed by AWSs (automatic weather stations), especially in eastern and northern Svalbard. There should also be a stronger connection and integration with measurements performed in eastern Greenland.

4.1.2 Cryosphere

The cryosphere synthesis is based on contributions within hydrology, glaciology, seismology, permafrost and snow, as well as the use of UAV studies of the cryosphere. SIOS has fostered international groups collaborating in Svalbard within the different cryospheric subdisciplines. The group on snow research has been leading the way with collaborating extensively and is now running a SIOS pilot snow project. The group has also submitted a joint manuscript for peer review based on this collaboration. The four main recommendations from the cryosphere group are listed in Table 1. The changing water cycle during climate change was identified as an overall scientific knowledge gap that needs all parts of the cryosphere to be involved and in addition needs extended links to the atmosphere. Integration across SIOS was found to be increased by establishing supersites building on existing SIOS observations. The Longyearbyen–Adventdalen area was identified as an obvious candidate where repetitive central observations in combination with remote sensing can serve society and students, and it even presents possibilities for citizen science to be developed. There is also a wish for methodological coordination across the cryospheric research fields with, for instance, time-lapse cameras, remote sensing (InSAR), fibre-optic cables for high spatial observations, ground-penetrating radar, passive and active seismic and cryoseismic measurements, and potentially networks of these types of measurements across different SIOS super-

Table 1. Key synthesized recommendations identified with the four environments of SIOS.

Atmosphere	Cryosphere	Marine	Terrestrial
Support continued funding of large-scale, multi-disciplinary infrastructure, such as the Svalbard SuperDARN radar	Science-based coordination of the cryospheric observations	Development of the marine environmental observation infrastructure – autonomous observational sites	Focus on co-location of basic cryospheric observations and subsequent long-term studies on biota at similar spatial and temporal scales
Provision of data management and online open-access portal to facilitate easier sharing of datasets	Integrated SIOS observation supersites	Provision of new datasets by, e.g. enhancing measurement capabilities	Focus on new methods and technologies using automated sensors, animal trackers and cameras
Better harmonization of the geographical and temporal coverage of atmospheric observations and applying standardized observation methods	Common cryospheric methodological infrastructure priorities	Harmonized methodologies for in situ observations and data harmonization	Develop model-based quantitative analyses of ecosystem processes using SIOS datasets
Enhance the spatial scale of the atmospheric observational network	Establish SIOS action force for extreme events	Support for research exploring linkages between fjord, shelf and open-ocean systems	Develop interphases between monitoring-based ecosystem science and end users

sites. Supersites are also instrumental for developing and harmonizing methods to ensure that all collected data are comparable and immediately usable.

Finally, it would be optimal to equip SIOS for observing sudden cryospheric events affecting the cryosphere such as glacial lake drainage (GLOFs) or meteorological extreme events such as autumn or winter rainstorms causing landslides and increased runoff due to extensive snow melting. These topics are also important for interdisciplinary studies.

4.1.3 Marine

The marine synthesis is based on contributions covering the following topics: oceanic circulation, ocean–atmosphere interactions, plankton monitoring, sea ice thickness, microplastics pollution and the status of Svalbard coastal waters. Major recommendations identified a need for a marine-observing infrastructure development that provides data needed to fill critical gaps in the observing system. Specifically, these included autonomous observational sites for co-located long-term monitoring of ocean physics, biogeochemistry, and ecology (with the latter two currently being under sampled with continuous methods); enhanced sampling capabilities during the winter and early spring season; and spatially increased data collection by a wider involvement of ships of opportunity. This recommendation could be addressed by specific funding via SIOS access and optimization calls that provide access to existing infrastructure and aid the development of new infrastructure. Homogeneous data collection in disparate areas and by various teams could be ensured by a dedicated programme for harmonization of marine measurements around Svalbard. To fulfil this need, marine infrastructure network workshops have been organized by SIOS, encouraging further cooperation on joint scientific programmes. This network would be well suited to develop a handbook of best practices for ocean observing approaches and data management. The four most essential recommendations for marine ESS Observing System development were identified as follows: (i) to extend the geographical and temporal coverage of research activities; (ii) to enhance year-round observations to resolve seasonal variability in the ocean; (iii) to support research activities exploring linkages between fjord, shelf, and open-ocean systems; and (iv) to establish long-term year-round monitoring of marine biota.

4.1.4 Terrestrial

Several recommendations relate to infrastructure, wider data collection and remote sensing. Measurements on varied spatial scales and development of models are mentioned frequently but still need further implementation. Notably, there is no contribution on lake systems and just one recommendation for experimental design. Overall, there is a need for co-location of measurements to integrate various disciplines, temporal and spatial scales, and experimental manipulations and to facilitate model-based quantitative analysis. Current examples include the terrestrial flagship in Ny-Ålesund (Pedersen et al., 2022), the COAT programme led by the Norwegian Polar Institute (Ims et al., 2013) and the Bjørndalen Integrated Gradients study initiated by the University Centre in Svalbard. COAT is a national ecosystem-based monitoring system of low and high Arctic terrestrial environments, developed as a joint effort by institutions of the Fram Centre in 2013 before SIOS was initiated. COAT is now fully integrated into SIOS, and the two projects have received joint Norwegian infrastructure funding. These studies should further develop, with new methods and technologies facilitating more spatially and temporally extensive and high-resolution automated measurements of biological parameters. There needs to be a focus on long-term ecosystem-based monitoring to establish how various anthropogenic pressures affect the Arctic environment. Climate change is likely to transform Arctic terrestrial ecosystems beyond scientists' current abilities to make predictions. Therefore, it is important to have scientifically robust, ecosystem-based, and integrated systems to detect the fast changes due to climate change, which is the overall overriding threat, in terrestrial ecosystems.

4.2 Knowledge gaps and associated improvement potential in Svalbard Earth system science

In addition to these environment-specific recommendations, interdisciplinary and overall recommendations that all four SESS environments have brought up have been identified and further synthesized for increasing and improving the interdisciplinarity of SIOS.

With Svalbard experiencing the largest ongoing warming in the Arctic and worldwide and with the closely associated further environmental changes, this puts SIOS in a unique position to provide coordinated datasets to investigate ongoing processes in the Earth system in a coupled manner. SIOS can quantify and understand in detail all physical processes that ultimately warm the atmosphere, turning ice into water with all the resulting consequences this has on the entire Earth system. This warming is controlled by the atmosphere and changes in ocean currents and impacts the cryosphere and terrestrial and marine environments. By using the entire observation network of SIOS to perform a full-scale study of all the processes that impact Earth system dynamics controlling the water cycle, a major potential for increasing the understanding of key mechanisms in the Earth system has been identified. Such a study has potential to provide large knowledge gain and thus further the understanding of effects on the Svalbard Earth system.

Many cross-cutting individual SESS recommendations indicate the relevance of and need for atmospheric parameters and observations for studying the other environments in SIOS. Also, cross-cutting actions between the atmosphere, hydrosphere and cryosphere have been indicated as areas of clear interest. Influences on the upper atmosphere from within the Sun–Earth system, unique to the polar regions, have been shown to affect ozone depletion down to stratospheric altitudes (30 km), and this may become more prominent with climate change (Maliniemi et al., 2020). In turn, lower-atmospheric processes, such as waves and tides, can influence the dynamics and behaviours of the upper atmosphere (Stober et al., 2021). The degree of influence is a topic of debate, with global models failing to reproduce some of the observed effects (e.g. Oliver et al., 2013; Cnossen, 2020). Precipitation and wind action in the lower atmosphere result in long- and short-range transport of dust and aerosols and accumulation of black carbon on snow and glaciers. Arctic terrestrial ecosystems, such as vegetation and its components and microbial communities, are impacted by air temperature, wind and precipitation, all of which are directly controlled by the atmosphere. For instance, spectral characteristics of downwelling flux influence vegetation and microbial communities. Melting of snow and glaciers, coupled with thawing of permafrost and an increase in active layer depth, supply water, sediment, microbes and aqueous chemical species through the terrestrial environment into the marine environment via the hydrological system. The pathway from the cryosphere through to the terrestrial to marine environments thus links all spheres in SIOS. Thus, all of these identified cross-cutting topics clearly have large potential if coordinated to fill the identified knowledge gaps regarding the water cycle and its consequences.

With the bottom-up approach of the SESS contributions, the development of a perspective from within the four environments was clearly a very natural starting point for synthesis. To start increasing the interdisciplinarity and cross-cutting nature of SIOS, a next step is to increase the dialogue between the different environments. Potentially, dedicated workshops on specific topics such as radiative forcing between two or more SIOS environments could be a starting point. Such workshops should also be tasked with pointing out optimal observations needed for datasets to fill and address the overall identified cross-cutting knowledge gap.

Additionally, all environments of SIOS depend on obtaining better spatial and temporal coverage of observations in and around Svalbard. This can be achieved through increased and coordinated instrument deployments that better cover the physiographically different regions of Svalbard including various landscape, seascape, and icescape types and the boundaries between them (e.g. the coastal zone). As warming is greatest in the eastern part of the Svalbard area (Isaksen et al., 2022), it is a future goal of SIOS to expand the observation system to also cover the eastern and northern part of Svalbard. Given the lofty ambition of preserving these relatively untouched parts of the archipelago of Svalbard, such expansion might have to be mainly based on remote sensing observations and/or dedicated supersites based mainly on the use of new low-maintenance technology. For example, the findings regarding Arctic vegetation and its climatic control by Bjorkman et al. (2020) highlight the need for more geographically widespread, integrated, and comprehensive monitoring efforts that can better resolve the interacting effects of warming and other local and regional ecological factors. In this case, studies across the entire vegetation zonation of Svalbard are important to fully understand the effects of climatic changes on the entire flora of the different Arctic vegetation zones. The spatially distributed network approach by COAT with large spatial and temporal coverage and co-location of measurements covering the terrestrial above-ground food web is another example. COAT measures vegetation from 57 module stations covering large parts of Nordenskiöld Land, Isfjorden and Brøggerhalvøya in central Svalbard. There is a clear need across all studied environments for special focus on the autumn and spring periods.

While the current focus on the major science hubs represents a disadvantage in terms of covering more different areas and habitat types as detailed above, there is clear potential for co-location of all the different types of observations from all parts of the ESS and thus developing real supersites. This should complement existing infrastructure, with a high level of coordination, long-term planning and funding. It would have the advantage of fewer sites to maintain, allowing for a more sustainable observation system. It would also allow for focusing on much closer collaboration on new methods and technologies across SIOS, with potential for more efficient sharing of knowledge. Knowledge gained from the supersites may be used to guide the selection of a subset of measurement types for observations with higher spatial and temporal coverage.

An ambitious tool identified is dedicated method-based action forces that would make SIOS able to respond quickly to extreme events such as solar storms; sudden stratospheric warmings (SSWs); glacial lake outburst floods (GLOFs); or various meteorological extremes, such as rainstorms and avalanches, the latter of which are also highly relevant to be able to perform a full-scale study of the water cycle changes and its consequences.

Likewise, the need for real-time access to SIOS observations is important, particularly for extreme events, for increasing the return of data from desirable but high-risk deployments (such as moorings or instruments near or on surging glaciers or rocket launches into specific atmospheric phenomena) and for more widespread use of the SIOS data.

5 Discussion and conclusion

This synthesis of knowledge gaps based on the first 4 years of operation of the Svalbard Integrated Arctic Earth Observing System (SIOS) builds on a unique and strong international collaboration. No other observing system exists that is this wide-ranging, covering all parts of the ESS within a specific regional area, while at the same time being supported so widely internationally and so well coordinated. When developing a full-scale Earth science observation system like SIOS, with the comprehensive full-scale ESS ambition that SIOS has, it is very natural for researchers within the individual disciplines and even subdisciplines to first start working more closely together before being able to focus more on the interdisciplinarity necessary for performing full-scale ESS analysing how the observed parameters influence each other. This is clearly the case for SIOS after the first 4 years of operation.

Ways to accommodate this important next step include the implementation of above-mentioned workshops on interdisciplinary topics and the development of supersites. Also, a workshop across all of SIOS working groups is planned to increase the collaboration and interdisciplinarity of SIOS. Hopefully, scientific collaboration between two environments might also start being more developed in SIOS, such as what has already been developed in the fully ecosystem-based observation system of COAT combining climate and ecology that is designed to observe, understand and predict outcomes from climate change (drivers) on tundra ecosystems (Ims and Yoccoz, 2017). In addition, SIOS is operating training activities in the form of small courses on different key SIOS observation techniques, SIOS data availability and SIOS remote sensing opportunities for all interested. Increased interdisciplinarity can also be obtained by further developing the major science hubs in Svalbard into real supersites complementing existing infrastructure allowing even closer collaboration on particular new technologies and methods including real-time access to observations across SIOS. Just as with obtaining better spatial and temporal observation coverage in and around Svalbard, including the physiographically different regions of Svalbard; the various landscapes, seascapes, and icescapes; and the boundaries between them in the coastal zone, would lead to increased potential for interdisciplinarity.

Other ways forward will be to increase the use of the SIOS observations through the SIOS data catalogue for Earth system modelling to obtain improved process understanding that bridges science disciplines. This will demand working to expand the SIOS community with modellers from different scientific fields, just as increased collaboration between modellers and the observational groups in SIOS needs to be established to enable observing at the relevant scales and resolutions and observation of missing parameters. The Earth system modelling community could make little use of high-resolution regional data in the early stages of SIOS, but presently as model resolution approaches sub-regional scales it becomes increasingly relevant to utilize models for observation design and use accrued data to calibrate and verify model output. The SIOS Observation Facility Catalogue and the Research in Svalbard (RiS) database are important tools for developing interdisciplinarity in Svalbard ESS. Just as the SESS reports are an integral part of the strategic development of the observing system. This bottom-up approach, which is complemented by rising societal needs and member priorities, leads to the outcomes from the SIOS science wheel (Fig. 3). In addition, the harmonized SIOS core data and new research infrastructure and research projects are all innovations leading to increased interdisciplinarity, and these are highly encouraged through the SIOS optimization and access calls. Finally, SIOS offers innovation awards to encourage further developing high risk and high reward, technological, and/or other ESS key activities that address knowledge gaps identified by the SIOS community.

Further, as Svalbard is experiencing the largest ongoing warming in the Arctic and worldwide, this puts SIOS in a unique position to perform a full-scale study of all processes impacting ESS dynamics controlling the water cycle using all parts of the SIOS observation network, with large potential for increasing the understanding of key mechanisms in the Earth system. The clear identification of a joint scientific focus, studying the water cycle changes and its consequences using all parts of the SIOS ESS observation network, will also function well as a focal point for cross-disciplinary work. Despite a disciplinary focus, snow, precipitation and hydrology have been identified as overlapping topics in many SESS contributions but are not prominent in the marine environment. These topics are therefore connected to all environments primarily on land but are observed and treated in different ways within the different environments. This is important for the identified scientific focus on the changing water cycle. Hence, SIOS has potential to develop a multidisciplinary study with data products and modelling approaches based on the variety of observations that is being collected and supplement this with additional necessary new observations leading to increased Earth system understanding of current and future dynamics.

There is also a need for increased regional collaboration using SIOS in scales broader than just Svalbard when aiming for full Earth system understanding within the Arctic. This means collaborating primarily with the rest of the Arctic. The international "Sustaining Arctic Observing Networks" (SAON) is the regional facilitator aiming at coordinating, improving, integrating and sustaining pan-Arctic observations during rapid environmental and social change, with a main focus on specifically addressing key gaps in coordination (Starkweather et al., 2021). With SIOS in the warmest part of the Arctic, and the largest climatic gradient in the high Arctic existing between Svalbard and cold northern Greenland, closer collaboration with Greenland could be a first natural step. In Greenland, the main aim of the "Greenland Integrated Observing System" (GIOS, https://gios.org/, last access: 25 July 2024) is to resolve and understand the mechanisms behind climate and environmental change in Greenland and beyond. GIOS is developing a network of sustainable long-term research infrastructure in and around Greenland observing the changing air, ice, land and ocean conditions. GIOS is, as opposed to SIOS, a national research infrastructure linking all institutions and universities currently carrying out Arctic research in the Danish Realm. SIOS and GIOS have started discussing increasing collaboration within research, higher education and logistics. Interhemispheric co-operation is also another obvious step with networks in the Antarctic Region such as SCAR (Scientific Committee on Antarctic Research) as an obvious collaboration partner. Initiatives in specific disciplines, such as GRAPE (Global Navigation Satellite System Research and Application for Polar Environment) are already in place. The research outlined through SIOS would benefit from being part of global observing systems such as the SuperDARN (Super Dual Auroral Radar, Chisham et al., 2007) atmospheric network. Such global networks, with commensurable data products, allow regional effects to be placed in a global context.

SIOS is making use of the Earth Observing System (EOS) programme of NASA with its different satellite missions and scientific instruments comprised of a series of coordinated polar-orbiting satellites designed to monitor and understand key components of the climate system and their interactions through long-term global observations of the land surface, the biosphere, the atmosphere and the ocean (Braun et al., 2022). This also enables direct comparison between Svalbard and the rest of the Arctic in terms of the different ESS components that are being remotely observed. To make the best use of this data, links between existing EOS data need to be established, and the data need to be available in formats that global Earth system modelling can make use of.

Finally, many of the observations collected by regional observation systems like SIOS have large potential to add to improved understanding of how people living in the Arctic are affected by climatic changes in many different ways (e.g. by landslides, avalanches, coastal erosion). COAT has a clear goal of providing management relevance. Clearly, SIOS can also assist humans and societies to develop management of climate change impacts. Such assistance is needed for developing resilience and adaptation to enable Arctic communities to deal with the consequences of the ongoing climatic changes. Presently, with the move towards involving local communities directly in climate change observations and research, this might place SIOS in a new role as also contributing more directly to societal needs.

Data availability. Data for Fig. 1 are available through the Norwegian Meteorological Institute online service. Locations of infrastructure presented in Fig. 2 are available in the SIOS Observation Facility Catalogue.

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