State of Environmental Science in Svalbard: Synthesizing the recommendations of the first 4 years

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Revision history

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State of Environmental Science in Svalbard: Synthesizing the recommendations of the first 4 years

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Abstract

One of the main outputs from the Svalbard Integrated Arctic Earth Observing System (SIOS) is the annual State of Environmental Science in Svalbard (SESS) reports, which has been produced since 2018. The SESS reports comprise peer-reviewed science texts and associated outreach summaries for stakeholders about field observations in Svalbard. The report series is an important development towards the SIOS ambition to build the best regional Earth Observing System in the Arctic.

This report provides an overview of outcome of the 40 chapters and 169 recommendations from the first four SESS reports (2018-2021). We have condensed these into disciplinary recommendations and identified the major cross-cutting interdisciplinary steps forward for SIOS. Recommendations mainly concern developing the observation system and the data management system. Naturally, this first review also allows for a thorough discussion of how far SIOS has come in developing a full-scale interdisciplinary Earth System Science (ESS) observation system and identifies potential ways forward.

1. Purpose of the SESS reporting

The State of Environmental Science in Svalbard (SESS) reports are an annual series documenting the state of the Arctic environment in and around Svalbard. The SESS report:

- is established to be an authoritative source of information about the state of the environment in and around Svalbard;
- is an important tool for conveying knowledge to stakeholders and the public, as well as addressing the scientific community. This format ensures that there is synergy between the scientific investigations and the knowledge needed by society to sustainably develop and safeguard the Arctic environment;

- is the main driving force for the science-based development of the observing system and contributing to the report is an opportunity for research groups to actively influence the prioritisation within SIOS.
- is an arena for open sharing of ideas and discussions on which measures should be taken to enable scientists to provide observations needed to gain a holistic view of the Earth System of Svalbard and the Arctic in general.

Contributions to SESS report are written by international and, preferably, multidisciplinary teams under the lead of researchers from SIOS member institutions. All chapters are peer-reviewed and subject to final approval by an editorial board. The editorial board for the SESS report consists of five members, including at least 1 staff of SIOS Knowledge Centre.

The reports summarise the state of current knowledge of key ESS parameters, and analyse how these parameters influence one another. It combines the long-term monitoring data that form the core of the observing system with new, innovative monitoring and research. In addition to evaluating the state of current knowledge, the SESS report highlights questions that remain unanswered and recommends solutions in terms of research infrastructure improvements and research priorities.

The reports highlight the research conducted within SIOS and are a central and integral part of SIOS primarily through contributing to the plan for optimisation of the observing system itself.

The Norwegian Research Council has stated that they are proud of the output in the SESS report from SIOS. Also, in Norwegian polar science priorities SIOS is highlighted as important when it comes to infrastructure, data and cooperation. Therefore, it should be an ambition to make sure that the Norwegian Research Council, and hopefully also other national research councils, funding research in Svalbard, clearly prioritize research that is directly useful for the SIOS ambition and do so by especially highlighting the condensed SESS recommendations presented in this document with respect to key research areas and infrastructure needed.

2. Reporting overview and synthesising the recommendations

Most of the SESS report contributions so far have been reviews, while also data summaries and updates to earlier SESS contributions have been published. A review article is defined as a description of the state of knowledge in a field of ESS or connections between different fields (typically not included in previous SESS reports), including a review of existing work, gaps in knowledge for Svalbard and concrete and practical recommendations on how SIOS can contribute to fill these gaps. A data summary is defined as an analysis of existing long-term data series or of new data on a specific topic in ESS in Svalbard, including sections on unanswered questions and concrete and practical recommendations on how SIOS can contribute to fill these gaps. Finally, an update is defined as a brief update of a data summary published in a previous

SESS report, adding data collected since then and/or new interpretations of the data. For all data mentioned, information about data availability has to be given.

The SESS contributions have been produced by authors from different disciplines within ESS. The recommendations on how to best improve the observation system are written from the perspective of the authors of the respective report chapters and thus are typically focused on their scientific discipline. The recommendations are used to identify research needs, gaps in observations, and new techniques and methods that can improve and optimise the research infrastructure. However, the large number of different recommendations currently spread within the SESS report chapters result in a risk that some important information will not be used for guidance for future studies and research infrastructure development. This synthesis therefore identifies, condenses, and prioritises the recommendations into a single report that can be used by stakeholders and scientists as a comprehensive resource in guiding decision making and use of resources.

The condensation and prioritization are done by categorizing of recommendations and identify stepwise feasibilities of what can be done depending on technical and financial conditions. It seems obvious to start with the easiest ones to achieve. Part of the conditions for the condensation is also the need for acknowledging the human capacity needs for meeting the recommendations, which must be addressed. The contribution of SIOS-KC is seen as important when integrating some tasks and activities, as a lack of manpower can prevent further exchange and inclusion of observations into SIOS.

The Science Optimisation Advisory Group (SOAG) in SIOS established a task force to develop this synthesis report based on all the SESS recommendations put forward in the four published SESS reports. As the first step in condensing and identifying the most important recommendations for SIOS, the task force decided to review the recommendations within the four environments in the Svalbard Earth System; The atmosphere, the cryosphere, the marine and terrestrial. Further tasks were to assess to which degree these first four reports address the SESS objectives and identify if other objectives should be added.

The detailed work within each of the four environments to synthesise the SESS recommendations was led by the task force, which initiated this as a bottom-up process by inviting at least one author from each SESS contribution within the four environments for a half-day workshop to review and synthesise the key recommendations. Due to COVID19, these workshops had to be online. The workshops provided perspectives for combining the individual and detailed recommendations into more general ones, identifying opportunities for developing both research efforts and infrastructure, as well as enhancing dialogue within and between the different environments of SIOS. Both the amount of SESS contributions up to date and the number of people participating in these workshops varied between the environments.

Certain topics such as microplastics, contaminants and solid earth were suggested as either missing or covered insufficiently in the SESS recommendations, due to the recommendations representing disciplines and interests of the authors of the published SESS chapters. This underlines that this synthesis mainly represents the views based on prior and ongoing research but is not meant to be an exhaustive list of research topics and developments within Earth System Science in Svalbard.

3. Key recommendations from the four environments

3.1 The atmosphere

The four SESS reports that have been published in 2018-2021 contained 10 chapters (26 recommendations) focusing on the atmosphere. There were a further 8 cross-cutting recommendations identified as relevant in chapters focusing on marine, cryosphere or terrestrial topics. The atmosphere of the Earth has four primary layers, the troposphere, stratosphere, mesosphere and thermosphere (which includes the ionised component of the atmosphere – the ionosphere). In the mesosphere / lower thermosphere -ionosphere (M/LTI) system (40 - 400km) the research is focused towards understanding the interaction and coupling between the neutral and ionised atmospheric components, energetic particle fluxes, ionospheric instabilities, and the cusp auroral region. These topics formed 8 recommendations across 3 chapters. In the troposphere, stratosphere (T/S) system (0 - 40km) the research is focused on such topics as aerosol-cloud interactions, atmospheric chemistry in the Arctic boundary layer, stratospheric ozone and surface spectral UV fluxes. These topics formed 18 of the recommendations across 8 chapters.

The Mesosphere / Lower Thermosphere - Ionosphere (M/LTI) system

There is a necessity for long time series datasets of the mesosphere / lower thermosphere – ionosphere (M/LTI) region above Svalbard, in the polar cap and cusp region. The processes in the M/LTI system occur on a very wide spectrum of spatial and temporal scales. For a complete understanding, a multiscale approach using both remote sensing and in-situ measurements of the ionised and neutral components of the upper atmosphere are needed. Established ground-based instruments (such as radars, All Sky Cameras (ASCs) and spectrometers) from the main Svalbard settlements provide mesoscale, remote sensing, observations, whilst sounding rockets (launched from two sites; one in Andøya and one in Ny-Ålesund (Svalrak) provide the only way of obtaining, macroscale, in-situ measurements. The nature of the ground-based instrumentation means that a single instrument can potentially provide data across a large geographical area (such as across the whole of Svalbard). As such, the recommendations are focused on larger instrumentation, which can provide multipurpose datasets, with an established international user base.

Recommendation: Support continued funding of the Svalbard SuperDARN radar

The radar, located near Longyearbyen, is part of one of the most established M/LTI observation systems in the world (over 30 radars with a dataset stretching back over 25 years, http://vt.superdarn.org/tiki-index.php). It has a field of view of 3 million km^2, extending from Longyearbyen across the polar regions to the Northern coast of Alaska providing measurements of the atmosphere every 15km across this field of view every minute. It provides, amongst other things, a vital M/LTI database of parameters as well as real-time global maps of the ionised component of the M/LTI region of the atmosphere. The data are open access, available through an online data portal with a supported analysis and software system and are used in countless global atmospheric models (e.g. AMIE model, WACCM-X model, IPIM model). The Svalbard radar is being rebuilt after storm damage in 2018 and should be operational in 2022. It operates continuously and autonomously. The lifespan of similar systems throughout the world is on the order of 20 years so would represent a significant contribution to a long-term dataset which could be classed as SIOS core data.

Recommendation: Support the continued sounding rocket program

As earlier reported in the SIOS Infrastructure Optimisation Report, there is an observational gap in the altitude range 40-80 km, that can only be filled by rockets. The sounding rocket launches provide the only means for direct measurements to fill this observational gap. Large scale, international, co-ordinated rocket programs (such as the current CGI-MLT (Mesosphere Lower Thermosphere) project, 2022-2026) (https://www.grandchallenge.no/project-mesosphere-lower-thermosphere/) will be an important contribution towards an ESS monitoring program for vertical coupling of atmospheric layers. Therefore, SIOS should continue to support the sounding rocket program by providing a portal for shared data access through the SIOS data management system.

The Troposphere / Stratosphere (T/S) system

Several of the recommendations are specifically devoted to identifying methodological, technological or observational gaps. Suggested improvements include filling gaps in observations of spectral UV, black carbon, local sources of biological aerosol precursors as well as further meteorological and hydrological measurements. Recommended technological improvements include availability of reliable power and communication systems, preferably with sustainable solutions.

Recommendation: Better harmonisation of the geographical and temporal coverage of atmospheric observations and applying standardised observation methods

The observing system in Svalbard Archipelago devoted to the lower atmosphere and coupled processes at its interface with other domains is characterised by large gradients. Ny-Ålesund represents a sort of “supersite” where all parameters are observed, with some redundancy. The west coast observing system is characterised by the presence of four settlement sites (Ny-Ålesund, Longyearbyen, Barentsburg, Hornsund) where it is possible to carry out continuous measurements as well as intensive field campaigns, while the Eastern side of Svalbard Archipelago is observed and monitored almost solely through Automatic weather stations (AWS). Many of the AWS have been implemented to provide supplementary information for mass balance and glaciological studies and are thus limited in parameters and scope compared to comprehensive setups for studying the lower atmosphere.

It is thus recommended to make use of technological progress to increase the number of parameters observed by AWS, in particular in Eastern and Northern Svalbard (Ripfjorden, Pyramiden, Hopen). At least a second point for aerosol chemical characterization in addition to the current setup in Ny-Ålesund should be promoted. Finally, creating a stronger connection and integration with measurements performed in East Greenland (Villum Research Station in particular) is recommended.

Recommendation: Enhance the spatial scale of the atmospheric observational network

Many atmospheric parameters have smaller spatial variability than the coverage provided by the fixed measurement sites, and atmospheric observations are strongly constrained by land distribution. Consequently, there is a large bias in our observation and knowledge about atmospheric processes and parameters. Mobile platforms can reduce this bias without introducing the limitations inherent to satellite observations. Up to now, the main limitations for using mobile platforms were high costs of operating instrumented aircraft and research vessels. However, with recent developments in unmanned aerial vehicles (UAV) and miniaturisation of electronics and instruments, UAVs could be a very powerful tool to be integrated into the Svalbard observing system.

3.2 The cryosphere

The four SESS reports 2018-2021 contained 13 contributions focused on the cryosphere. These distribute themselves with one on hydrology, one on glaciology, one combined on the Kapp Linné environmental monitoring system, one on seismology of the cryosphere, three on permafrost and six on snow. There are also some fully methodological contributions which are not specific to the cryosphere, but very relevant as well, such as UAV use. This distribution of contributions shows that the SIOS work has so far been primarily happening in the different cryosphere subdisciplines, developing good strong international groups working together in Svalbard within their specific scientific fields. This process is very nicely illustrated directly by the condensation that happened in the SESS report from 2020, when three different snow contributions also provided a joint contribution. The continued collaboration of this group has since resulted in a joint scientific paper and a SIOS pilot project. Otherwise, the cryosphere recommendations naturally focus within the subdiscipline fields.

Recommendation: Science based coordination of the cryospheric observations

An overall scientific focus was identified for cryospheric observations in the recommendations put forward: The changing water cycle during climate change. To study this all parts of the cryosphere need to be involved. This includes determination of peak water timing, which demands both small and larger glaciers to be observed. It needs links to meteorology, precipitation measurements need to be combined with detailed snow observations (thickness and water content). Additional glacier observations need to be added of the glacier thermal regime and glacier calving rate. Glacier – permafrost interactions need to be studied in newly exposed glacier forefields, where glaciers are receding and new permafrost might form depending on the hydrological system. Permafrost – observations of ground ice content are necessary for understanding the water fluxes inside the active layer and permafrost, including of permafrost groundwater interactions and even linkages to subpermafrost fluid migration. And finally, of course, discharge recording is then important.

Recommendation: Integrated SIOS observation supersites

It would be great to increase the integration across SIOS and within the cryosphere directly by having as many observations/activities as possible in the same areas, this way building SIOS supersites. Therefore, it would be natural to build a first SIOS observation supersite with all environments involved in the Adventdalen – Longyearbyen area, where many observations already exist, and others can be added relatively easily. A supersite should also be where repetitive central observations using high resolution remote sensing, ground penetrating radar, temperature and more observations can be made. It should also be where society and students have direct needs and can contribute/ collaborate directly with SIOS – so citizen science can be included.

Recommendation: Common cryospheric methodological infrastructure priorities

SIOS should coordinate the use of methods across the cryosphere research field, such as time-lapse cameras, remote sensing (InSAR), fibre-optic cables for high spatial observations, ground penetrating radar (GPR), seismics/cryoseismics, and potentially have networks of these types of measurements available across all of SIOS.

Recommendation: Establish a SIOS action force for extreme events

SIOS should be equipped to address sudden cryospheric events such as e.g. GLOFs (glacial lake outburst flood) or various meteorological (extreme) events affecting the cryosphere such as autumn or winter rainstorms causing landslides and increased runoff due to extensive snow melting. This is important for interdisciplinary studies and studying physical processes driving change in detail.

3.3 The marine environment

The four SESS reports contained 10 chapters focusing on the marine environment. Most chapters showed monitoring datasets that concerned different subdisciplines. Contributions covered the topics of oceanic circulation, ocean-atmosphere interactions, plankton monitoring, sea ice thickness, microplastic pollution and the status of Svalbard coastal waters. SESS reports raised recommendations that indicated open scientific questions relevant to these topics. The recommendations were provided with different levels of detail. Data harmonisation was identified as an important need. Development of the marine environmental observing infrastructure was commonly recognized as a key requirement to provide in situ data that are critical to address the main research gaps. The provision of new datasets should be achieved by (i) establishing autonomous observational sites for long-term monitoring to collect time series on ocean physics, biogeochemistry and ecology, (ii) enhancing measurements/sampling capabilities during the winter/spring season, (iii) increasing data collection by a wider involvement of ships of opportunity e.g. tourist vessels, and (iv) conducting additional multibeam surveys to investigate the shelf-slope dynamics and sampling of marine sediments needed to deepen the knowledge on geological history. Other recommendations indicated the need for high-resolution numerical models to better interpret the relationships between different environment compartments e.g. ocean and atmosphere. Recommendations also pointed to a need for harmonised methodologies for in situ observations and to strengthen multidisciplinary research. A dedicated programme for harmonisation of marine measurements around Svalbard would help to ensure homogeneous data collection in different areas and by different teams. This could be fulfilled by preparation of a handbook of best practices for ocean observing and data management.

Four recommendations are identified, all of which are efficiently covered by a broader use of autonomous measurements and autonomous integrated platforms such as multisensor moorings.

Recommendation: Extend the geographical and temporal coverage of research activities around Svalbard and include more biogeochemical measurements

It is a goal to extend the geographical and temporal coverage of measurements and to provide long-term time series with autonomous observatories measuring ocean physical and biogeochemical parameters simultaneously (salinity, temperature, alkalinity, DOC, Chl-a, Turbidity/SPM etc) around Svalbard. This recommendation could be put into practice with the deployment of at least three moorings in key sites representing different oceanographic conditions. Since several oceanographic moorings are already regularly deployed in the western (Kongsfjorden and Isfjorden) and northern (Rijpfjorden) Svalbard fjords, and along the west and north offshore margin, the deployment of a new mooring at the East coast should be prioritised as this is a particularly understudied area. Since most of the current moorings measure mostly physical ocean variables, we would advise to add more biogeochemical sensors. This goal has a high priority, and the implementation should be initiated as soon as possible.

Recommendation: Enhance year-round observations to resolve seasonal variability in the ocean around Svalbard

There are large data gaps in the autumn-winter-spring seasons when the access to study sites is logistically difficult. We recommend exploring possibilities for enhancing data collection in these seasons. Ships of opportunity, including commercial and tourist vessels operating in Svalbard fjords and shelf areas could be equipped with FerryBoxes to collect surface measurements. Another solution is to deploy more autonomous platforms and cabled observatories (with the near-real time data transmission) particularly in coastal areas where it is technically feasible. This is an important goal due to the lack of data currently.

Recommendation: Support research activities exploring linkages between fjord, shelf and open ocean systems.

Ocean measurements in Svalbard fjords should be better aligned with long-term observations collected in shelf areas and open ocean around Svalbard (e.g. by implementing dedicated moorings to monitor fjord-shelf exchanges). This is critically needed to understand the interactions between exchange and local processes. An extended and coordinated field campaign, including concurrent ship-borne measurements of key physical and biogeochemical ocean variables in different Svalbard fjords should be periodically repeated (e.g. every 5 years) to link data from year-round moorings (at least three sites) and data from other locations. Also, a better exploitation of *in situ* measurements in combination with data obtained from other sources (e.g. remote sensing or high-resolution numerical modelling) should be encouraged to fill these knowledge gaps.

Recommendation: Establish long-term year-round monitoring of marine biota

The efforts to monitor marine environments around Svalbard are scientifically and geographically very fragmented. Only selected parameters are measured and there are gaps in time series. There are very limited research activities within SIOS focusing on marine ecology, particularly regarding the benthic environment as well as the links to marine biogeochemistry. There is a need for sustained long-term year-round monitoring of marine biota. Climate-forced changes manifest themselves primarily as changes in physical ocean properties and processes (as temperature, heat content, stratification, freshening, circulation patterns) and are reflected in biogeochemical and biological seawater characteristics. Moreover, intensified human activity impacts chemical seawater characteristics (e.g. acidification, pollution) and in consequence affect ecosystem functioning. Studies that specifically focus on these topics by means of long-term monitoring should be encouraged. Long-term monitoring efforts, that are of key importance but currently missing, concern also ocean warming in Svalbard fjords, ocean freshening in fjords due to the increased melting of tidal glaciers and glacial runoff and its impact on ecosystems, as well as systematic sea ice monitoring in Svalbard fjords.

3.4 The terrestrial environment

In total 82 recommendations in 16 chapters of the SESS reports were categorised. These include 7 studies on snow, as this is an important factor for understanding ecological variation. Most chapters showed interesting datasets and brought together a group of scientists (average 10 per chapter), but this did not always result in a combination of different types of datasets. The best example of combining different datasets was a comparison of satellite data, on-site measurements, and modelling results. It is advised to work on such combined datasets more often.

The recommendations most often relate to studies of snow. Several recommend specific infrastructure, wider data collection and remote sensing. As scientific focus, measurements on different spatial scales, model development and a need for an interdisciplinary approach are regularly mentioned. Unfortunately, interdisciplinary use of data is sometimes mentioned but rarely further developed. Remote sensing might help to solve the data collection on different scales. Surprisingly, there is no contribution on lake systems and only one time a recommendation proposes an experimental design.

The SIOS terrestrial environment offers opportunities for long-term ecosystem-based monitoring crucial to establish how various anthropogenic pressures affect the Arctic environment, and to assess the effectiveness of management actions. Such knowledge is instrumental for environmental conservation, management, and policy decisions. Addressing complex issues requires a holistic ecosystem-based adaptive approach that combines clearly defined monitoring goals with relevant biotic and abiotic measurements and scientific hypotheses.

Recommendation: Focus on co-location with basic cryospheric observations and subsequent long-term studies at similar spatial and temporal scales for interdisciplinary biosphere-cryosphere use

Integration of a broader range of cryospheric observations related to snow properties, permafrost conditions and energy balance into terrestrial sampling programs, as this allows for development of joint products relevant for monitoring both the biosphere and the cryosphere, as well as analyses that that elucidate interactions between the two environments. This will allow focus on the ecosystem implications of a rapidly warming climate, which is a generally important arena for interdisciplinary research between ecologists and geoscientists. In this regard, particularly, a wider exploration and further development of the various sources of data related to snow properties and vegetation is recommended.

Recommendation: Focus on new methods and technologies

In ecosystem monitoring, a new era has come with novel technologies allowing for automatic measurements of biotic observations that are spatially and temporally more extensive and have higher resolution than traditional manual measurements. Such ground (automatic sensors) and remotely sensed (drones, satellites) technologies should be optimised to improve the scope of field measurements. There is substantial effort involved in consolidating sensor-based data to ecosystem processes occurring on the ground. New methodological developments should include analytical tools (algorithms) that aid assimilation and processing of large amounts of raw sensor and optical data and produce operative ecological observations, as well as refined statistical models that can be used for more robust causal inferences and short-term predictions based on such state variables.

Recommendation: Improved ecosystem process understanding: Developing model-based quantitative analyses using SIOS datasets

Focus on SIOS data to be used for developing model-based quantitative analyses, based on the datasets collected, on the causal links between ecosystem observations and drivers to improve the understanding of the implications of changes in the variables for ecosystem condition. This should be done especially in cases when the same structures and/or functions are simultaneously impacted by multiple stressors. Such efforts should be guided by the best available empirical knowledge.

Recommendation: Interphase with end-users and cooperation

One of the ambitions of SIOS is to be highly relevant to policy makers and managers. Given the prospects of climate change, Arctic ecosystems are likely to be transformed beyond scientists' current abilities to make predictions and managers' capacity to implement mitigation and adaptation strategies. This grand challenge requires more sincere efforts to develop structured interphases between monitoring-based ecosystem science and end-users than are presently implemented.

4. Joint recommendations across the SIOS environments

To respond to societal needs and provide necessary information for policy makers, mechanistic understanding of the ongoing environmental changes as well as realistic future projections are needed. While this is recognized by the scientific community, it is difficult to be implemented in practice. The multidisciplinary character of SIOS can help to overcome some of the challenges. In this section we present the interdisciplinary or overall recommendations that the experts in the four environments have identified based on the SESS recommendations, and further synthesize them for improving the interdisciplinarity of SIOS.

4.1 Recommendation: Develop the water cycle as the most important Earth System Science that SIOS should address interdisciplinarily

Very naturally, SIOS should focus on the ongoing large climatic changes, which are larger in Svalbard compared to the rest of the Arctic and other areas on Earth. Operating what is already by now probably the largest regional coordinated Earth observation system in the high Arctic, and being located in its warmest part, clearly comes with demands for making the very best scientific use of its potential. This is clearly reflected in the presented SESS recommendations from all four environments, recommending the need for cross-cutting observations.

With the ongoing warming in Svalbard, SIOS offers excellent possibilities to answer the urgent need to quantify the rate of this change and to understand in detail the physical processes that ultimately turn ice into water and the consequences on the entire Earth System. This change is controlled by the atmosphere and affects all parts of the cryosphere as well as of the terrestrial and marine environments. Scientifically, this means focussing on studying the water cycle changes and its consequences using all parts of the ESS observation network SIOS possess.

Many cross-cutting individual SESS recommendations in contributions not dedicated directly to the atmosphere, clearly indicate the relevance and need of atmospheric parameters and observations for studying the other environments in SIOS. Cross-cutting actions between the atmosphere, hydrology and cryosphere communities have been indicated as areas of clear interest. The atmosphere largely affects the cryospheric processes, providing precipitation and wind action for long and short-range transport of dust and aerosols, as well as causing accumulation of black carbon on snow and glaciers. The atmosphere also largely directly controls the Arctic terrestrial ecosystems in particular vegetation and microbial communities, which are largely dependent on the air temperature providing energy, wind and precipitation. An example of special direct links are the spectral characteristics of downwelling flux that is very important with respect to vegetation and microbial community. Melting glaciers, snow and thawing permafrost from thicker active layers supply water, sediment and biogeochemically relevant elements via the hydrological system through the terrestrial environment into the marine environment, thereby linking all the environments in SIOS.

4.2 Recommendation: SIOS workshops – to increase interdisciplinarity

To be able to increase the interdisciplinarity within SIOS and thus be able to address the overall scientific potential outlined in the above, efforts need to be made by all SIOS communities to better understand and voice their information needs from other communities. Having this information available will allow for taking the needs of the other SIOS environments into account when developing observational programmes. To get this to function across the traditional disciplinary divisions, a stronger dialogue needs to be developed between the different environments that in SIOS together built the Earth System observation system. This could be done through dedicated interdisciplinary workshops organized around certain topics such as radiative forcing between two or more SIOS environments. These workshops should address the future needs for the optimal observations with the aim to provide optimal datasets for crosscutting activities. Work for development of SIOS core data and the Shared Arctic Variables (SAVs) currently under development could also offer a good way to define narrow areas in which to develop a strong collaboration between observation and modelling communities. Such workshops could potentially also be related to initiatives such as the Ny-Ålesund flagship programmes, allowing for cost-effective collaboration this way.

4.3 Recommendation: Increase and promote the use and usefulness of the SIOS data platform

It would be beneficial if the research community can make increasingly more direct use of the SIOS platform for data integration, cooperation and new developments contributing towards better detection, documentation, understanding and prediction of climate change in all part of the Earth System. To achieve this, resources should be invested in carrying out the planned development of the functionality of the SIOS data management system including the data catalogue and data portal.

5. Condensation of recommendations and conclusion

5.1 Characterisation of the four environments overall recommendations

Overall, four recommendations are presented for each of the four environments in this synthesis. The following overarching recommendations have been condensed based on individual recommendations that were present in multiple chapters in the four SESS reports. They are mostly cross-disciplinary in nature, with some topics having already been introduced in the environment -specific sections.

The spatial/geographical and temporal coverage of observations

An overarching recommendation among all environments is the need for better primarily spatial/geographical and temporal coverage of observations in Svalbard. For the majority of the environments this is focused around increased, co-ordinated, instrument deployment with better coverage of different subregions of the Svalbard archipelago away from the major science hubs in Longyearbyen, Hornsund and Ny-Ålesund. In the case of the M/LTI environment, the already established extensive geographical coverage offered by a single instrument (as mentioned in section 3.1, the SuperDARN radar has a geographical field of view of 3 million km^2, within which an atmospheric measurement is obtained every 15km at a 1-minute cadence) means that the recommendations focus on continued support of those instruments and research programs.

Higher temporal resolution is also needed for many environments, with a special focus on the fall to spring period. A higher resolved characterisation and monitoring of different landscape/seascape/icescape types, as well as boundaries between them, e.g. the coastal zone connecting the cryosphere, terrestrial and marine environments, is also suggested with recommendations proposing linkages from fjord over shelf to the open ocean.

Co-location – develop supersites

Likewise, there are general recommendations of the need for co-location or development of so-called supersites where different types of observations are done in geographically the same area or site. Most of these recommendations suggest having observations from different SIOS environments and disciplines in one place. Co-location of measurements and complementing existing infrastructure with smaller instruments that can use the existing power and data connections, would also result in less sites to maintain. A nested structure with co-located instrumentation within but importantly also across different environments as well as their boundaries is desirable, which requires a high level of coordination, as well as long term planning and funding. Furthermore, shorter deployments and single sampling events should be linked to such sites, when possible, to enhance cross-linkages and system-based understanding.

New technology collaboration

Another widely listed recommendation related to technology. The joint use, cross-calibration and deployment, coordination of widely used technologies should be enhanced. Importantly, coordination efforts should focus on new methods/technology across SIOS. Here, experiences from other users in terms of deployment and recovery strategies, best instruments to be used in the special Arctic environment (e.g. regarding battery power, temperature resistance, environmental pollution aspects) etc should be efficiently shared among the SIOS community, and investments made feasible through data and instrument sharing. This leads to realistically aiming for SIOS to also be able to respond to extreme events such as GLOFs (glacial lake outburst flood) or various meteorological extremes such as rainstorms, for example by setting up method-based action force groups.

Observations in real time

Online real-time observations are also a widely mentioned recommendation, which is related to future ambitions of extended use of SIOS observations. Real-time observations are needed to respond to and subsequently be able to capture extreme events by dedicated data collection efforts (e.g. by the above mentioned task force groups). They also allow a better assessment of fast developments and short-term phenomena, as well as increase the return of data from desirable but high-risk deployments (such as moorings near or instruments on surging glaciers). An example of the possibilities offered comes from the M/LTI environment, in which online real-time observations are used to evaluate atmospheric conditions for a 'go / no go' rocket launch decision, ensuring the science aims of 'high risk, high reward' experiments are achieved.

Improved process understanding based on ESS modelling using SIOS observations

Finally, several recommendations relate to increasing scientific ESS understanding by making use of modelling based on SIOS observations/data, in particular related to improved process understanding in all environments. Observational data can identify correlations and proposed potential causal relationships, which should directly feed into the generation of hypotheses to be tested in modelling (and laboratory) experiments. Achieving this goal will require to broaden the SIOS community and engage with modellers from different scientific fields. Enhanced collaboration between modellers and observational groups needs to be established early to collect data on relevant scales and resolution, as well as with respect to missing parameters. Assembling and collecting temporal trends of physical climate variables in all environments into the SIOS data catalogue would be valuable, along with those of biogeochemical tracers of system changes (methane, aerosols, carbon isotopes, and water isotopes).

5.2 The state of synergy and development of interdisciplinarity for improved ESS

With the SESS report aiming to be the main driving force for the science-based development of the Svalbard observing system, the presented review and condensation of the provided 169 recommendation shows good outcome. It is clear that SIOS' ambition to have synergy between the different observations is not yet fully met, but clear ways forward are identified based on the first years of operation. This is fulfilling one of the stated objectives for the SESS reporting: to analyse how the observed parameters influence one another.

Clearly there is room for more dialogue between the environments, as the initial phase of SIOS has been automatically focussed within disciplines and even subdisciplines mainly. This kind of development is a natural step when developing an overall observing system with the comprehensive full scale ESS ambition that SIOS has, with current partner institutions having carried out research programs in Svalbard also prior to the initiation of SIOS. However, efforts such as the SIOS logistics sharing notice board, the Research in Svalbard (RiS) catalogue and the SIOS Observation Facility Catalogue are important tools providing overview, allowing researchers and infrastructure developers to share resources and research between them. The SESS report adds to this by creating incentive to form a consortium of scientists in a specific field and talk about future ambitions.

The level of the development of the joint recommendations across SIOS clearly shows that there is focus on increasing the synergy in both developing the science, but also in the use of technology, particularly new and developing technologies. The identified joint scientific focus on studying the water cycle changes and its consequences using all parts of the ESS observation network that contribute to SIOS is natural and will function well as a condensation point for cross-disciplinary work.

The overlapping topics for the SIOS community that were mentioned most during this synthesis process are related to (i) snow and (ii) precipitation and hydrology. These topics are connected to all environments, and are observed and treated in different ways in each environment: Snow, for example, for atmospheric research is mainly considered in connection with albedo, surface budgets (radiation, energy), and its role on temperature and Atmospheric Boundary Layer vertical exchanges; for the cryosphere is mainly related to glacier dynamics and mass balance; for marine research snow has an important influence on sea ice properties (e.g. light transmission into the ocean) and evolution during late spring and summer season (e.g. affecting the uncertainty in determining sea ice depth from satellite measurements); for the terrestrial environment it is considered in terms of barrier, with both positive effects in insulate vegetation from wind and very cold air, and negative effects on food chain mainly when present as ice layers. The research community should utilise the opportunities SIOS offers for multidisciplinary studies, and to develop data products and modelling approaches that are based on a variety of data sources, ultimately aiming at an Earth system level understanding of current and future dynamics.

There is room for improvements and areas where standardisation of observing methods and data analysis is far from a satisfactory status. Weakness and challenge arise from the peculiar conditions of the harsh Arctic environment that can prevent the applicability of procedures developed for middle and lower latitude observations. The atmospheric community is quite well organised in terms of standardisation of observation and data processing, largely due to efficient regional and global networking, and as a consequence of the efforts promoted by WMO. There is, however, room for improvement for all environments.

Better exploitation of observations collected in the marine environment around Svalbard for cross-cutting research activities, in particular those addressing regional scales, requires harmonisation of observing infrastructure and data processing chains, including data publishing (e.g. standardised sensor calibration and data processing, unified standard procedures for data quality control, metadata formats, or jointly agreed science-based indices for phenomena such as atlantification). This could be achieved by preparing documentation of best practices that could be followed to ensure interoperability between different observing systems and data which they deliver. Research methodologies should also be harmonised regarding data interpretation (e.g. microplastic studies). We also recommend taking on efforts to improve data availability and interoperability, which will result in more straightforward and likely data usage for multidisciplinary research.

All the different environment working groups recommend thematic workshops as a good place to facilitate better communication and knowledge sharing through bringing together experts and involved researchers. These are seen as a potential forum for exchanging experiences and best practices, as well as allowing for discourse leading to the adoption of optimal procedures, methodologies and standards for observing specific parameters in Svalbard. This cooperation is also recommended to be extended to specific regional networks, of which the research stations in Greenland are highlighted by the participants of the lower atmosphere workshop.

5.3 Data ambitions

Lack of coordination has on multiple occasions led to the adoption of different standards, protocols and methodologies, and the lack of adoption of common practices limits the interoperability of SIOS datasets. This issue should receive attention when developing the SIOS core data variables, with the overall aim to better harmonise procedures and analysis methodologies. Promoting communication and collaboration both within the SIOS environments and between all research communities is recommended as a way towards more efficient use of resources and enhancing scientific impact.

SIOS should demand online access to all SIOS observations and datasets and encourage the adoption of FAIR guiding principles for data management and stewardship for all SIOS data. This represents the next important overall, but not small step in increasing accessibility to and usage of all SIOS observations and products. SIOS should also encourage data producers and managers to avoid embargoing data unless deemed necessary, as this will increase the timeliness of data and their usefulness for validating operational models. Enhancing interoperability of the datasets will facilitate access to a better overview of what data is stored in the SIOS data catalogue. In turn, increasing the data coverage across environments and making its use easier will allow for putting SIOS in the international front on Arctic observations.

An important goal should be to integrate currently missing datasets into the SIOS Data Management System / Data Access Portal / SIOS Core Data, which was mentioned in several chapters. To achieve this, metadata formatting needs to follow common standards and the data needs to be published in harvestable data centres.

Furthermore, Baddeley et al. (SESS report 2020) suggest developing a Svalbard space physics data portal where SIOS data management can provide a coherent data platform, as well as online visualisation tools needed for datasets currently scattered across multiple online databases. Thematic platforms like these could potentially best serve the SIOS community through integration into, and expansion of the Data Access Portal as a one-stop shop for all SIOS data.

5.4 Panarctic upscaling of SIOS research

SIOS mainly focuses on the existing research infrastructure primarily located in western Svalbard, however, the large difference between East and West Svalbard also needs to be considered if we want to achieve a regional perspective of the variability within Svalbard.

Panarctic upscaling of SIOS observations is highly relevant and requested particularly by the Norwegian polar strategy, the EU Arctic strategy and other national funding bodies. This demands modelling, and recommendation of building better connections between the observing and modelling communities is identified in several recommendations. Clearly, for many processes SIOS needs to consider scales broader than just Svalbard. This means considering the connections with the rest of the Arctic in particular, and of course first other observation networks close to Svalbard, and to make better use of developing observations and studies with aircraft and unmanned mobile platforms.

An important step on the way to panarctic upscaling would be to make direct use of the largest climatic gradient in the Arctic between warm Svalbard and cold Northern Greenland, which seems a very natural way to proceed for SIOS. Greenland hosts several types of observation networks like SIOS, many of which are operating in the GIOS (Greenland Integrated Observation System) collaboration. A cross disciplinary workshop for both funding agencies and scientists on how to potentially proceed with this potential is planned for September 2022.

However, for all such listed regional research collaborations to occur and make real use of SIOS and its ambition to contribute significant to panarctic ESS, there is a very clear need for increased regional collaboration between national funding agencies and for specific international funding such as e.g. from the EU. This seems reasonable specifically now that the observation system is well established in Svalbard.

6. Perspectives

Preparing this recommendation synthesis has led to a clearer identification of interdisciplinary possibilities and needs in SIOS than what was provided by the individual SESS recommendations alone. Clearly, the synthesis will now provide SIOS direct guidance in further developing the ESS approach. The task force also recommends that the synthesis report process should be repeated in regular intervals to review and incorporate the upcoming recommendations in future SESS reports.

Hopefully, SIOS can make use of the identified synthesised recommendations and further develop these when applying for future expansion of the observation network, but also when participating in panarctic research ambitions. To be able to do so it would mean running the suggested interdisciplinary workshops, potentially as an important basis before developing further the overall scientific ambition of e.g. addressing the water cycle changes and its consequences across all environments in SIOS.

One of the ideas that SIOS has earlier worked with is the establishment of a SIOS Chair. It might be a possibility for such a position to be tasked with focussing on taking SIOS further within the identified overall recommendations from this synthesis, just as SOAG of course will work with the output of this synthesis.