Integrated Arctic Observation System

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Roadmap for a sustainable Arctic Observing System

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EXECUTIVE SUMMARY

The INTAROS Roadmap describes the way forward to improve and sustain the observing capacity in the Arctic. The Roadmap addresses the full data delivery chain from observing sensors to data repositories with focus on in situ observations. The document describes key factors determining how well an observing system can function in the Arctic, involving technological advances, infrastructure and data networks. Furthermore, the document emphasize the importance of cross disciplinary collaboration and stakeholder engagement as part of the data delivery chain. The development of in situ observing systems in the Arctic, especially ocean-based observations in the ice-covered regions, depends heavily on mature technology, transport infrastructures and logistical services allowing personnel to access the areas. Deployment and operation of observing platforms require use of icebreakers, aircraft, manned ice stations and automated systems that can operate year-round

Based on the experience and knowledge of the INTAROS consortium, the following recommendations are formulated:

- The importance of in situ observations must be promoted as the backbone for building knowledge about climate and environmental change in the Arctic, at the same level as satellite observations and modelling systems
- The funding mechanisms for in situ observing systems need to be strengthened and coordinated between programmes, projects and institutions involved in Arctic observation, including local communities
- The Joint Statement of Ministers (ASM 2021), signed by 25 countries and six Indigenous Peoples organizations, states that they agree to strengthen cooperation on implementing Arctic observing and data sharing, implying that they need to allocate resources for in situ measurements contributing to the observing systems.
- Technology development for more robust and reliable in situ observing systems is needed. Here, major industry actors can play a role by investing in platforms and sensors that can operate autonomously in the Arctic
- The data delivery chain from in situ observing systems must be operationalised for each of the discipline-oriented systems in order to facilitate data sharing. This requires collaboration between the research communities, data services and other actors involved in the delivery chain. Collaboration can be enhanced by setting up mediators who can communicate between the actors
- Observing systems must be adapted to evolving priorities, requirements, and technological developments. This requires regular dialogue with researchers, stakeholders in private and public sector, researchers, service providers, local communities and Indigenous rightholders in the Arctic.
- Competence building need to be strengthened in observing methods, technologies, and procedures across gender and generations.

The INTAROS roadmap builds on the experience and knowledge from the INTAROS consortium comprising more than 300 scientists from 49 institutions in Europe, Asia, and North America. In addition the document builds on discussions with representatives of Indigenous and local communities, private and public stakeholders, scientists and service providers at more than 50 workshops organised by the INTAROS project.

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1. Introduction

The INTAROS Roadmap is based on the work and results from all workpackages in the project and the expertise from the different disciplines in the consortium. INTAROS has contributed to enhance and exploit existing and evolving observing capacity in the atmosphere, ocean, and land through extensive field work over five years. The project has benefited from close collaboration between scientists producing and exploiting observations in different disciplines, data managers from different data systems, and service developers using observations in applications towards stakeholders. Collaboration between 36 European institutions and 13 partners from USA, Canada, Russia, China, Japan and South Korea made it possible to carry out extensive the field work, data collection and data sharing across the Arctic both on land and at sea. These activities have made a significant contribution to a number of different observing systems in the Arctic.

Most of the resources have been allocated to in situ observations based on ocean and sea ice platforms, while some work has been devoted to terrestrial studies including ice sheets, glaciers, snow and other hydrological topics. Observing systems for earthquakes and other geohazards have been demonstrated, and several modelling and data assimilation studies have been conducted. Land-based observing systems are addressed more thoroughly in other H2020 projects (e.g. INTERACT, NUNATARYUK). Satellite remote sensing methods have been applied and developed further for sea ice, sea level and water vapour. Community-based observations have been supported and further developed in several regions. Some important topics are not addressed in the project, such as terrestrial ecosystems, vegetation and geology. Studies of permafrost are not included except for some data collected from sites in Alaska, Canada and Russia.

Development of Arctic observing systems in the coming years will need to include new observing technologies, improve data formatting and standards, provide methods and tools for data processing and analysis including new digital technologies. A major challenge is the implementation of field experiments due to logistical constraints and high costs of operating expensive systems in ice-covered seas. Also data management and data sharing within and between scientific disciplines is a challenge. This is due to the heterogeneity and complexity of observational data collected in various scientific disciplines. With development of new instruments and platforms, the amount of environmental data collected is expected to increase year by year. Citizen science (CS) and community-based monitoring (CBM) are also growing and will contribute to the observing systems. To improve the data delivery chain, it is necessary to strengthen the collaboration between countries, institutes and industry involved in Arctic observing. Furthermore, it is important to continue to support capacity building, teaching, and training in all parts of the data delivery chain.

The Roadmap describes the main elements of the in situ observing systems with data delivery chains and how they should be developed further. The Roadmap is organised in the following chapters: Chapter 2 presents the data value chain and data delivery chain, which are central elements of the observing systems. Then the process of defining and updating requirements is described. Chapter 3 describescommunity-based observations and citizen science as part of the Arctic observing systems. Chapter 4 describes existing observing capacity and how it can be expanded. Chapter 5 presents examples of how new technologies can be used to improve the in situ observing systems. Chapter 6 describes different aspects of the data systems that can be further developed as part of the data value chain. Chapter 7 gives a number of examples of applications and development of services towards stakeholders. Chapter 8 gives some perspectives on further development of the observing systems, collaboration with stakeholders and competence building. Finally, chapter 9 gives a conclusion.

2. Arctic observing and stakeholders

The needs and requirements for in situ observations in the Arctic are defined in collaboration between scientists, service providers and other stakeholders and rightholders, including Indigenous and local communities. The requirements are updated through an iterative process taking into account developments in technology, essential variables, and new societal needs. The in situ observing systems are therefore developed, scaled and adapted to a wide variety of stakeholders needs. An integrated observing system will therefore consist of several sub-systems which produce specific data that are needed for a given application and stored in dedicated data repositories. Examples of sub-systems for ocean observations are shown in Fig. 1.

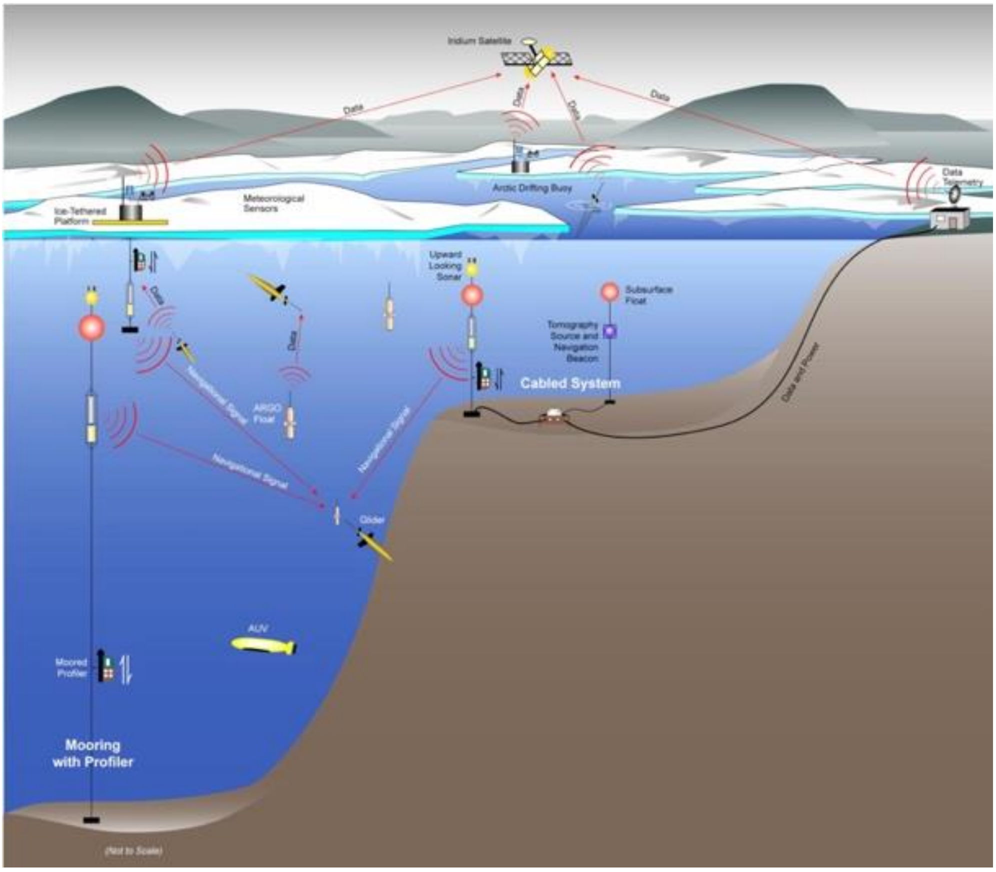

Figure 1. *Components of in situ observing systems in the Arctic Ocean envisioned for the Ocean Decade 2021-2030*

2.1 Data Value Chain

It is important to show the data value chain resulting in provision of services adressing specific Societal Benefit Areas (SBAs). Fig. 2 illustrates the data value chain for the case of snow avalanche warning. The steps in this data value chain is illustrated by the five sections in Fig. 2 starting with the observing system to the left and ending with a service that is useful in several SBAs. . At the bottom of the figure examples of research activities are marked in red. The role of research projects is critical, not only in the development and validation phases of the services, but also in the data collection where different observing systems contribute to delivering the required variables. In the Arctic the first step is often the bottleneck because there is lack of relevant observations. In many cases Community Based Monitoring (CBM) programs can contribute to data collection as well as the whole data value chain. At present CBM programs are often stand-alone systems which are not integrated with the scientific observing systems. For snow avalanche warning it is expected that CBM systems will play a more important role and become integrated with other date modelling systems.

2.2 Defining the needs and requirements

A two-step process is needed to involve different stakeholders in the formulation of requirements for Arctic observing:

1. The stakeholders formulate their needs and requirements for Arctic information, products, and services within their domain. The formulations should be done in dialogue with the service providers and data producers
2. Service providers and data producers should then translate these requirements into a service production line that consists of observations, analysis, modelling/forecasting and product/service generation. Each component has a set of specific requirements regarding accuracy, timeliness and resolution in time and space.

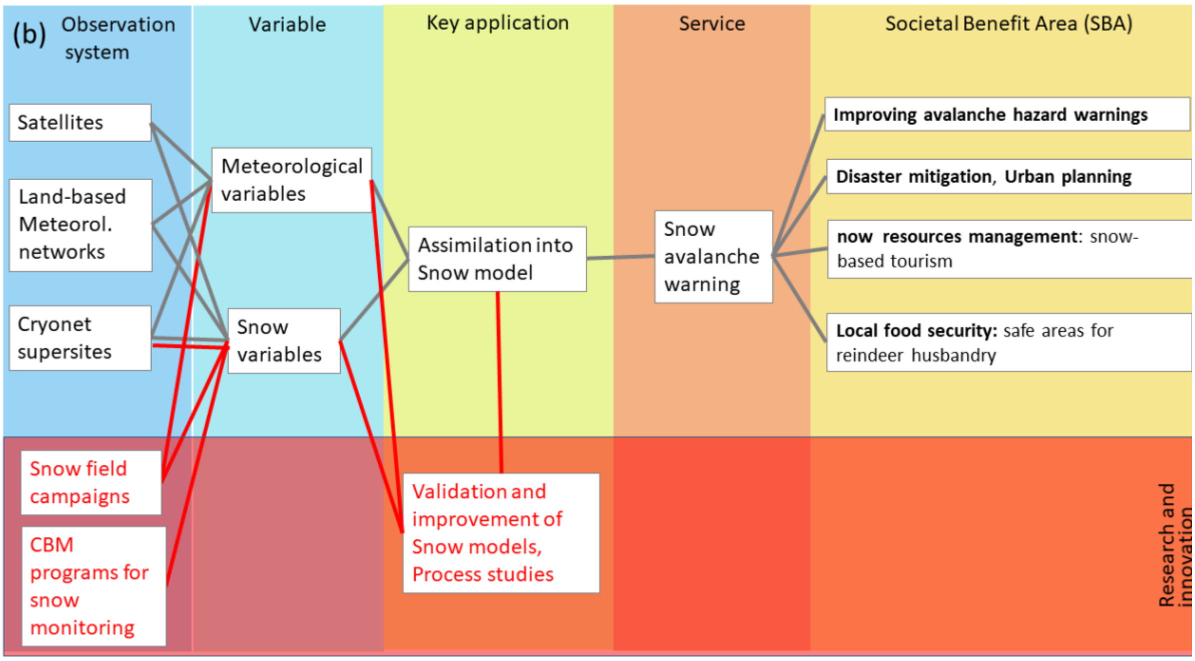

***Figure* 2** *Examples of a data value chain for snow avalanche warning. Each column of the diagram corresponds to a step in the chain, from data collection in the observing systems (on the left) up to the services for the benefit of society (on the right). The development of the data value chain depends on research projects and operational systems for monitoring and forecasting, that can deliver a service*

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Stakeholders within fisheries, aquaculture, marine transport, tourism, renewable energies, conservation, as well as climate, weather and ocean forecasting services need relevant, up-to-date, and integrated information to make knowledge-based decisions. The required products and services can range from high-level information to support policymaking, and management decisions to provision of information of sea ice, currents, and waves to ships. Obtaining a clear picture of user requirements is not straightforward because of changing political priorities, new concerns among the stakeholders and new technologies which can advance the observing capabilities. It is therefore very important to establish mechanisms to regularly capture new user requirements and provide feedback to the observing systems. This can be illustrated as a circular process as illustrated in Fig. 3

It is important to build collaboration and trust between actors in the data value chain through education and knowledge transfer. Those providing observations and synthesizing data should learn about stakeholder requirements. While the stakeholders should learn to understand what observations can be provided to meet their requirements, along with technological limitations and cost. The stakeholder involvement will lead to enhanced relevance of Arctic observing in support to the societal benefit areas for the Arctic (IDA 2017, SAON 2018)

Figure 3. *The steps required for successful user engagement (Source: U.S. IOOS Summit report) published in 2013 by Interagency Ocean Observation Committee for development of an Integrated Ocean Observing System (www.iooc.us). Each of the steps present challenges, many of them related to communication and coordination.*

Key questions to be addressed in dialogue with the stakeholders will be

- Which environmental and/or climate phenomena should be observed?
- Which variables should be measured?
- Which observing platforms and sensors should be used?
- If relevant, how should in situ observations be combined with remote sensing, and/or modelling systems?

In-situ observations are mandatory components of the observing system, providing basis for:

- Information of the present state of the Arctic,
- Analysis of environmental processes, trends in seasonal, annual and decadal changes,
- Validation of satellite observations and model outputs,
- Assimilation into models

Arctic in situ observing systems should fulfil requirements related to spatio-temporal coverage and resolution, quality of data products, timeliness in data delivery, which are defined by the different applications. Which variables to be observed have been defined by international programs such as Global Ocean Observing System (for Essential Ocean Variables) and by Global Climate Observing System (for Essential Climate Variables). SAON is in the process of defining Shared Arctic Variables as part of their ROADS process (Starkweather et al., 2021). Taking note of discussion and recommendations from these organizations and other relevant communities (e.g., Copernicus Program, WMO, IOC) INTAROS has tried to synthesize the recommendations and to formulated more concrete and achievable requirements for in situ observations in the Arctic, addressed in subsequent chapters.

Generally, there is a good consensus on the requirements for time resolution, quality, and timeliness, while spatial resolution is constrained by logistical and infrastructure conditions which make it difficult to collect in situ data in a regular grid with a predefined resolution. Therefore, it is a necessary to find a balance between what would be “nice to have” and what is feasible to achieve from a technical, logistical, and especially economical point of view. A gridded format with fixed horizontal and vertical distances between data points is feasible for satellite data and models but is not practice for in situ data. Instead in situ data should be collected in key locations which are important for processes or can be representative for a larger region. Furthermore, it is important to distinguish between the requirements for an observing system optimised for the whole Arctic serving the global monitoring systems and the requirements for regional systems which has more national and specific needs. Use of Observing System Simulation Experiments can be helpful in deciding the location of the observing systems. In practice, the locations are often selected based on what is practical to implement and what is important scientifically.

2.3 Bridges in the data delivery chain

The data delivery chain shown in Fig. 4 describes how data from different observing systems flows through several steps in the data delivery chain. It is important to develop this chain into an efficient data delivery stream, enabling users to get easy access to the data.

Standards for geospatial metadata and data formats are complex and therefore time consuming to gain a working knowledge of. While data managers and curators are well versed in documenting and formatting data, they often do not participate in data collection and processing. Scientists and engineers working in the field are experts in their discipline and the technologies used. They have detailed knowledge of the data collected and how processing is carried out, but often have limited expertise in metadata and data standards. Communication between data management and data observation disciplines is hampered by lack of common understanding of each others' expertise and clear distinction of roles and responsibilities. Therefore, we recommend establishing a mediator mechanism where data managers, scientists and new sensor/platform developers can work together to adopt and adapt standards for metadata and data to ensure datasets are produced in accordance with FAIR (Findable Accessible Interoperable Reusable) (https://www.go-fair.org/fair-principles/).

As an example, INTAROS formed a working group of ocean scientists and data managers to define and document a joint metadata structure for ocean mooring data. This will make it easier to reuse the mooring data in different applications and user communities. We recommend a continuation of the ocean mooring data working group, to harmonize formats for new sensors and ensure that the specification is kept updated with evolving standards in the ocean data community.

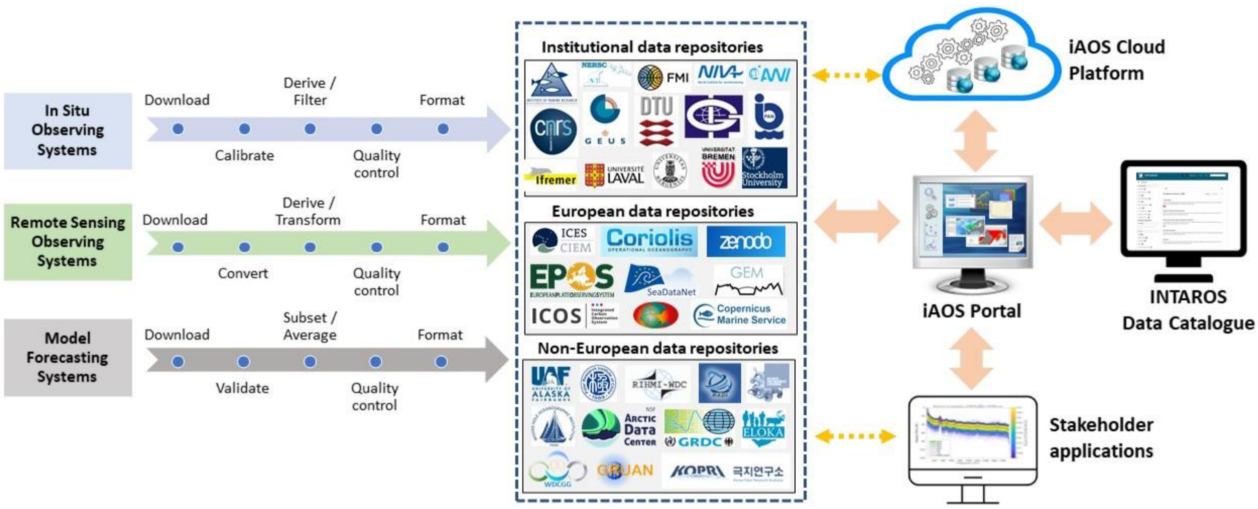


Figure 4. *Data delivery chains focused for integrating INTAROS data into the various iAOS subsystems (portal, data catalogue, cloud platform, stakeholder applications).*

3. Communities and Arctic observing

Community-based monitoring (CBM) and citizen science (CS) programs are developing rapidly on global scale and can provide significant contributions to environmental data collection. These programs are also developed for the Arctic and can help to raise awareness and provide more facts about the environmental and climate changes in the region. The programs engage a wider group of citizens in data collection supplementing the data collected by scientists. The data can contribute to decision-making in resource management, risk management, safety, and food and water security. Moreover, engagement of community members in observing can enhance local actions to engage with the environment, may provide a mechanism for community empowerment in natural resource management, and helps advance sustainable common resource use practices (Danielsen et al. 2022).

3.1 Local community participation and priorities

Many observing and research programs fail to address local community priorities or address them only marginally (Eicken et al. 2021). This can arise when the programs are informed more by the goals of scientific researchers or management agencies than by community members. As a result, the programs do not support local priorities such as health and wellness, economic opportunities, and transmission of local or Indigenous knowledge and place-based skills. In the coming years it is expected that scientists and government agencies further involve representatives of community members including women and youth, in observation and research programs, thereby contributing to develop platforms and networks for trust-building and long-term collaboration. This implies that top-down and bottom-up approaches are connected in environmental observing (Fig. 5).

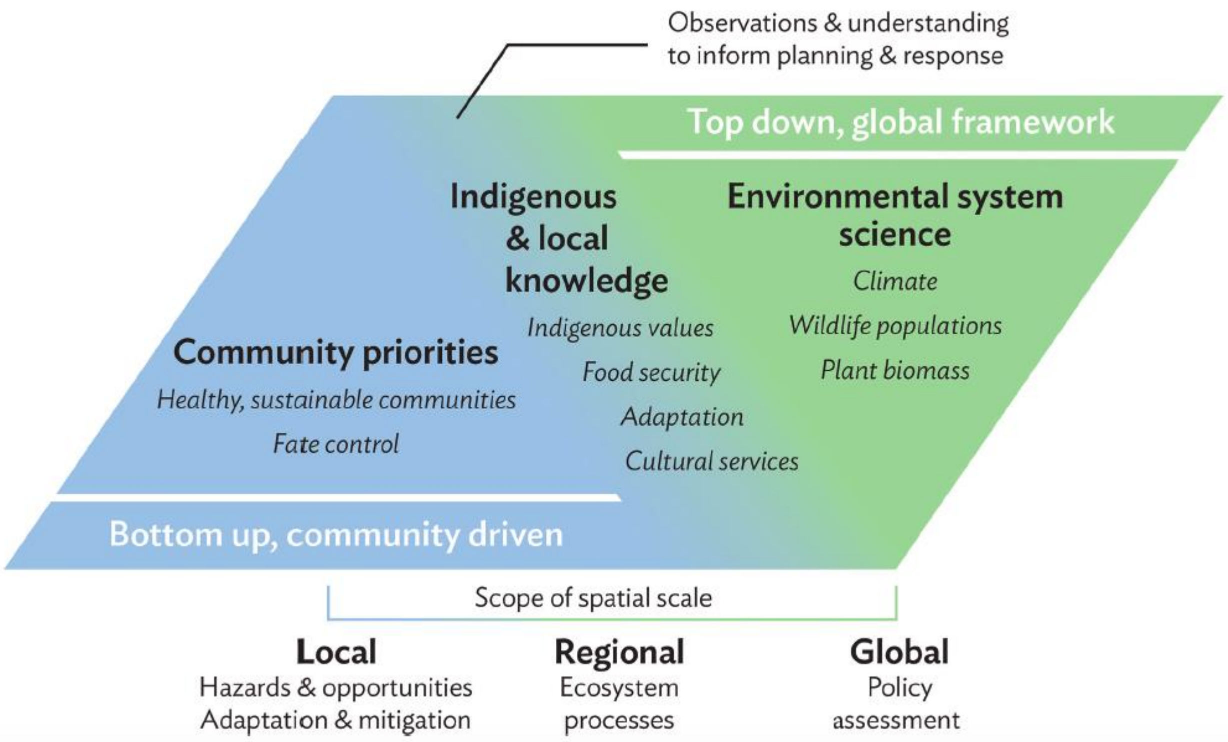


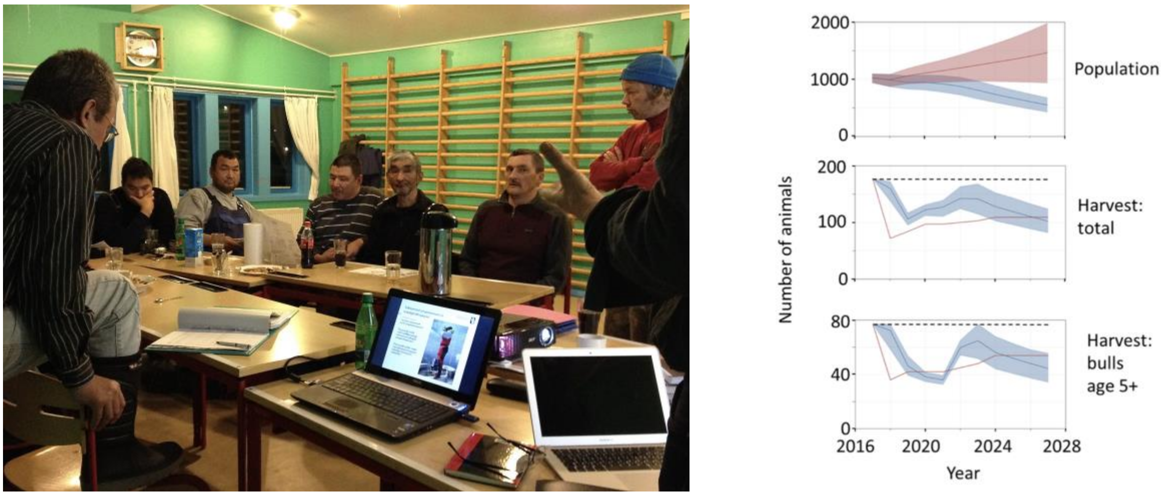
Figure 5. *Observing scales and priorities for global and pan-Arctic monitoring approaches embedded in international frameworks and focused on indicators and assessments or projections of system state, versus bottom-up, community-driven monitoring approaches initiated and steered within the local community and focused on outcomes desired by community members. Indigenous and local knowledge inform community-driven approaches but also may serve as a bridge between approaches and scales (from Eicken et al. 2021, Fig. 1; CC BY).*

One challenge lies in a lack of broad awareness and understanding within the scientific community of intellectual property rights, the need for respect and reciprocity when working with Arctic communities, and free, prior, and informed consent (Johnson et al. 2021). This challenge has both historic and contemporary dimensions, and it affects the interest, capacity, and long-term commitment of Arctic community members, scientists, and management agencies to participate in long-term collaborations.

One barrier to maximizing the potential of CBM and CS programs for decision-making in the Arctic has been that management authorities are sometimes slow to act upon, community observations in their decision-making. Community members expect that their hard work will lead to action from authorities. These limitations appear to be rooted in misconceptions about the value of CBM and CS, logistical and bureaucratic barriers and, sometimes, reluctance to relinquish authority to lower levels (Danielsen et al. 2021).

3.2 Community-based observation and citizen science approaches

There are critical gaps in Arctic data systems which are caused by the limited engagement of community members in observing efforts (Starkweather et al. 2021). Involving local people, including women and youth, in the collection and interpretation of environmental data can have many positive benefits (example in Fig.6).



a b

Figure 6. *(a) Meeting where local community members discuss observations and status of natural resources in Disko Bay Greenland (Photo by M. K. Poulsen); (b) Expected population grown in the upper graph is used to plan harvesting to ensure supply of meat for subsistence and of old bulls for trophy hunting (from Cuyler et al. 2000; Fig. 2; CC BY 4.0).*

The local communities store their data in different ways with different terminology and structure. This sometimes makes it difficult to share data and knowledge in mutually beneficial ways. Moreover, there is a lack of shared protocols enabling cross-weaving, and insufficient dialogue on how to ensure knowledge synthesis and coordinated action (Danielsen et al. 2021). It is recommended that international scientific organizations and managers of scientific data repositories (1) increase their understanding of CBM and CS data and support initiatives to establish and sustain CBM and CS projects; (2) include available CBM and CS data in climate and environmental research projects; (3) adapt repositories so that they are better able to receive data from CBM and CS projects; (4) training in use of CBM and CS so as to enhance "good" practice and develop protocols and procedures to enable government agencies and international scientific organizations to incorporate local and CBM-derived knowledge in their planning and decision-making.

3.3 Further development of community-based observation and citizen science.

A major effort of INTAROS was to strengthen CBM projects among Indigenous and civil society organizations, government agencies and scientists in several Arctic regions (e.g. Enghoff et al. 2019). This work need to be continued through other projects where CBM activities are connected to science-driven projects. The combination of top-down and bottom-up approaches, as shown in Fig. 5, can stimulate stronger linkages between CBM programs and decision-making processes. Core principles central to such linkages are: (1) collected data must provide information to support decision-making in important matters for the community (e.g. food supply, safety), (2) data management must be responsive to CBM needs and capacities, (3) intellectual property rights of Indigenous people must be respected, which means that some data will not be open, (4) sufficient organizational and financial support to the CBM programs must be available, and (5) community members' commitment to sustain the CBM efforts needs to be addressed. The challenges and potential interventions are illustrated in Fig. 7.

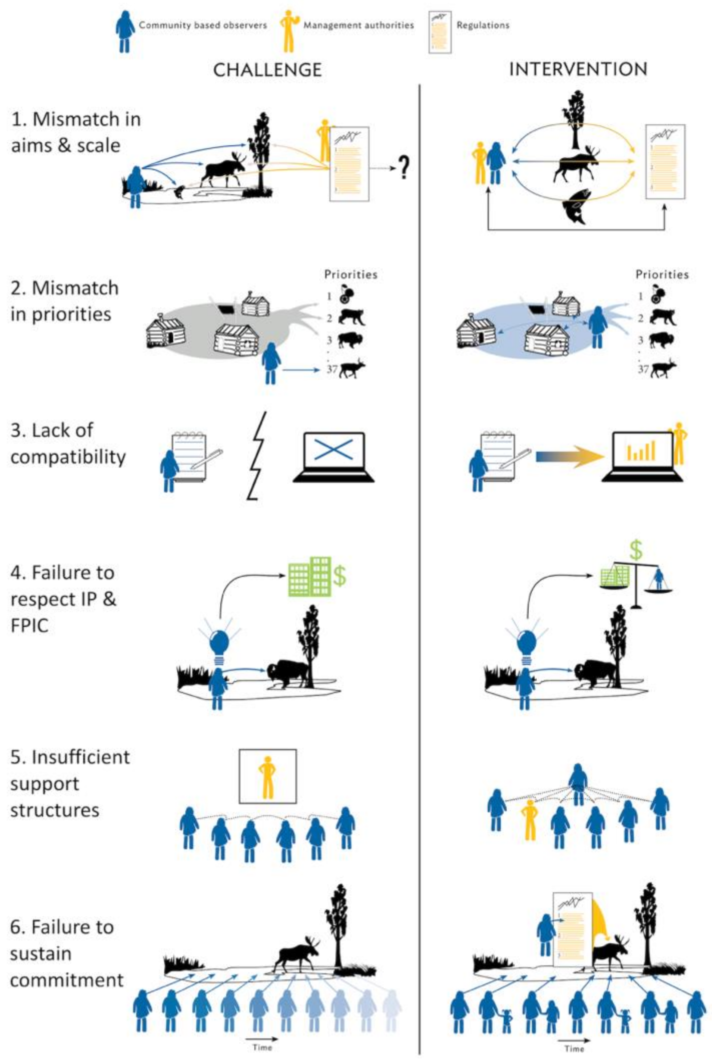


Figure 7. *Summary of challenges and interventions in linking bottom-up and top-down observing. Each panel corresponds to issues and interventions discussed in the text. Input through community observations into resource management regulations is shown in yellow, while transfer of intellectual property (symbolized by light bulb in panel 4) into applications and associated generation of revenue ($) are shown in green. The most promising interventions include a focus on knowledge co-production principles covering the appropriate scales and priorities. (from Eicken et al. 2021, Fig. 4 CC BY).*

Citizen science encompasses a diverse range of interdisciplinary methods to tap into the collective intelligence (Kragh et al. 2022) of the general public from collecting data to involving the public more broadly in research design, resource management, and decision-making. These processes often require a diverse set of skills by project managers whose backgrounds are principally scientific. EU provides a useful platform for sharing CS projects, resources, tools, and training activities (https://eu-citizen.science/). The platform will serve as a knowledge Hub and become the European reference point for CS.

There are several well-established natural science CS projects which include data form the Arctic, such as *Happywhale* (https://happywhale.com/home), *iNaturalist* (https://www.inaturalist.org/) and *eBird* (https://ebird.org/home) which have been built up over decades. To establish and operate new CS projects require sufficient time and resources for coordination, manage volunteers, promote public engagement, and manage the data with analysis and presentations. Instead of building a new CS project it is recommended to check if already existing CS projects can be used. This will reduce costs and help to collect quality data using established protocols. provided that the CS program organizers have access to the CS project data for local and regional use. New ideas for CS projects must be interesting and appealing for the participants. *Happywhale* and *eBird* are examples of successful projects because many tourists find it exciting to watch whales and birds and to document and share their observations.

In a sustainable Arctic observing system scientists, local communities and governmental agencies should collaborate to develop CBM and CS programs addressing community data needs as well as national and international research priorities. Data ownership and use rights must be clarified taking into account ethical aspects, promote the development of a holistic data 'ecosystem' for the Arctic, bridging conceptual, political, and geographical distances, and strengthen the coordination of decision-making at the various levels of the public sector.

4. Expanding observing capacity in the Arctic

4.1 Assessment of existing observing capacity

There is no extensive assessment of the maturity and capacity of previous and ongoing in situ observing systems in the Arctic . Such assessment will be useful for research and monitoring programs as well as for funding agencies in planning new research projects and observing systems.

INTAROS developed a methodology for assessment of the maturity of observing systems, which was implemented as a web application called ARCMAP (http://arcmap.nersc.no). Examples of information form ARCMAP are shown in Fig. 8. The application allows for registering and provide dynamic update of statistics. The application is maintained by NERSC after the INTAROS project ends. It is the recommended that other projects use it to ingest information and extract updated statistics on observing systems as new capacities are implemented There are other inventories of observing systems, but they do not provide for assessing the data value chain. It is recommended to develop interoperability between other inventories and ARCMAP, which will give a more complete overview of the observing systems.

The assessment in INTAROS have shown the large temporal and spatial gaps in Arctic *in situ* observing systems, in particular for the ice-covered ocean. This is due to several challenges such as deficiencies in observing technology and data management, or lack of sustained funding mechanisms (Tjernstrøm et al. 2019, arcmap.nersc.no). In INTAROS the characteristics of the systems (e.g. documentation, data management, uncertainty handling, sustainability) was assessed using a maturity score from 1 to 6. It was found that the systems with highest maturity were those with sustainable funding for the whole data production and data management chain. Sustained funding are provided from national sources to monitoring programs for resource management, climate monitoring, seismological stations, and weather services. Longterm funding of research infrastructures are also provided through the ESFRI program, e.g., EuroArgo ERIC, EPOS ERIC, ICOS ERIC. However, the European infrastructures have a poor coverage in the Arctic, and often there is a lack of adequate platforms and sensors for use in the Arctic.

However, there exists several scientific multidisciplinary in situ observing system on land and in the ocean, including cryosphere and atmosphere. Most of these observing systems are funded through time-limited research projects funded by national or international research agencies. Disrupted and insufficient funding of the research project often results in low scores on management, uncertainty characterization, metadata, and documentation, although the data may be of excellent quality. This leads to mismatch between the funding agencies expecting data and metadata to be inline with FAIR, and availability of resources to make this happen. Correspondingly, these observing systems have low maturity and sustainability compared to RI, but they provide important observations.

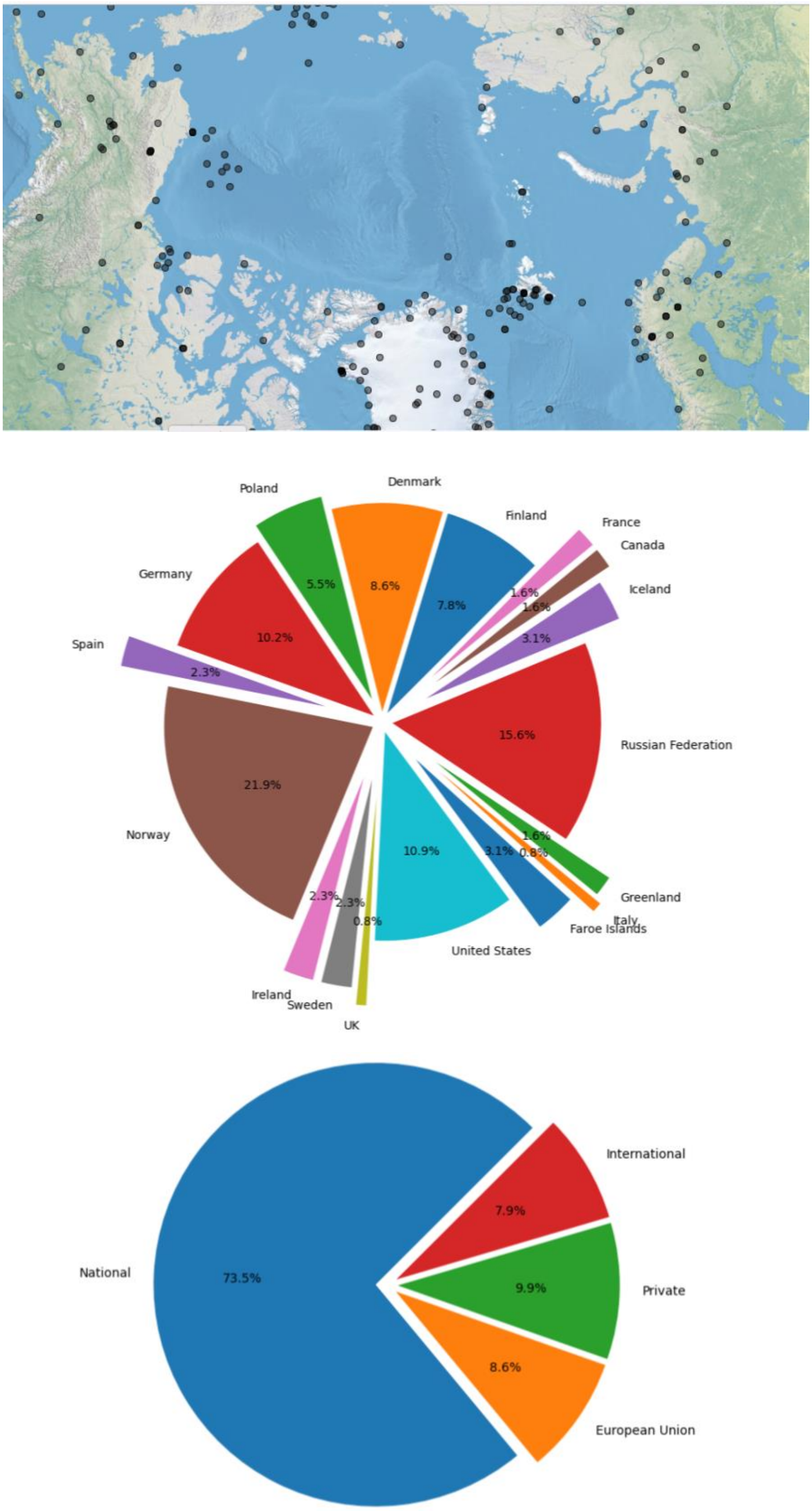


***Figure 8**. (a) ARCMAP map of selected assessed observing systems (b) percentage of assessed systems sorted by countries, c) distribution of funding sources for the observing systems.*

It is important that research funded observing systems are transformed into infrastructures to provide sustained measurements serving both scientific and operational needs. The funding must cover the whole data delivery chain in line with the FAIR principles.

Global or regional transnational organizations should engage more with Arctic issues to support the transition of research based observing systems and data system into an long-term research infrastructures. Collaboration between transnational and national organizations and Arctic research projects is needed to advance operationalization of research-driven critical observations that require long-term sustainability. The most influential organisations are WMO (World Meteorological Organization), GOOS (Global Ocean Observing System), GCOS (Global Climate Observing System) who focus on coordination and collaboration activities. These organizations should collectively mobilize their members to work together for long term national funding commitments for Arctic observation systems similar to space programs. The funding commitments should provide resources to the whole data delivery chain.

4.2 Terrestrial Arctic in situ observing systems

There is a pan-Arctic network of land based meteorological and atmospheric stations providing operational data to the weather forecasting centres. Those systems will continue to operate under the WMO. Furthermore, several pan-European RIs have been established to produce high-quality data and information on air quality. ACTRIS is one such RI producing high-quality data and information on air quality. The observing network of terrestrial hydrosphere, including glaciers and snow have large gaps in the Russian Arctic and along the peripheral Greenland and Canadian Arctic. River discharge data is monitored by national hydrological services in all major Arctic rivers, but still the un-gauged area of the drainage basin of the Arctic Ocean is about 40%. In addition, open near-real time access to the monitoring data is in practice limited to areas outside Russia. In future, there should be a dedicated effort to coordinate different sustained EU terrestrial RIs when developing sites in the Arctic, especially to enhance the observational capacity of existing stations that miss key variables. Moreover, sustained EU RIs and Global Cryosphere Watch should establish collaboration channels with pan-Eurasian networks such as PEEX and Russian institutions to coordinate the implementation of actions to fill the major gaps in atmospheric, cryospheric, and hydrological observations.

4.3 Geohazard observations in the Arctic

The observing systems for geohazards need to include terrestrial as well as marine-based systems. It is expected that geohazards will increase in the Arctic as result of climate change. Recommendation for observing systems for some geohazard risks are described below.

Earthquake, landslide and tsunami: Earthquakes and landslides can occur in the Arctic with potential severe impact on local communities. For example, a Mw6.1 earthquake occurred in Storfjorden in 2008, and in 2017 a landslide in Karratfjord in Greenland was followed by a tsunami. Seismograph networks, designed for monitoring earthquake activity are recommended to measure the movement of the ground at micrometer to nanometer scale. The seismometers can also detect other geohazard events such as landslides, tsunamis, submarine slides and volcanic activities. In the Arctic Ocean, earthquakes occur mainly along the ultra-slowly spreading Gakkel Ridge (Fig. 9). Improved observation of this activity will allow a much better understanding of the ongoing processes in the spreading ridge, and thus the potential for other hazards such as volcanic activity, submarine slides and tsunamis. The land-based network of seismic stations in Greenland and islands in the European Arctic provide operational monitoring, but there is a large gap in the network in the Arctic Ocean. It is recommended to deploy a network of Ocean Bottom Seismometers and explore new methods to observe seismicity in the ocean areas. Continuous and high resolution timeseries of seismic events are required to assess the hazard and risk of earthquakes as needed by local authorities. Seismometers can register not only earthquakes but also landslides, snow avalanches and to some extent tsunamis. Studies focused on landslides in West Greenland show how combining seismological data with satellite observations improves the detection and understanding of such events.

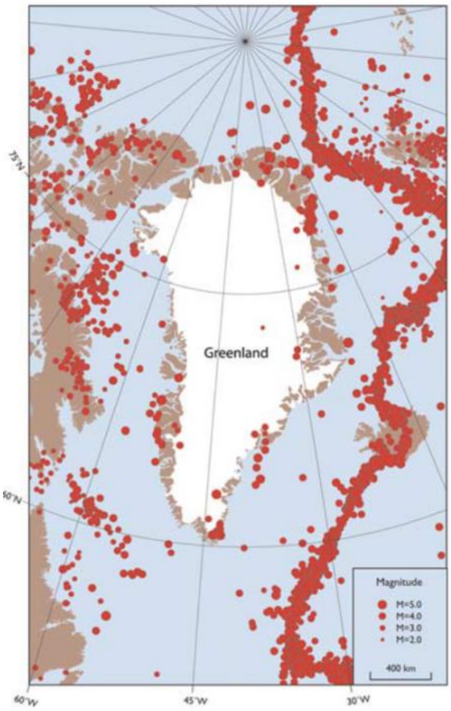


Figure 9*. Earthquake map of Greenland for the years from January 1970 to June 2004. (Gregersen and Voss, 2009)*

Snow avalanches: There is an increase in risk for snow avalanches due to increased precipitation in several regions of the Arctic. For example, several serious events have occurred in Svalbard, where systematic observations of snow avalanches have been established (Fig. 10a). It is important that better monitoring and forecasting systems are established and validated. Forecasting models depend on input from local observations of snow depth and meteorological variables, obtained over long time as well as real-time data. Use of automated snow observation stations (Fig. 10b) should be extended to provide more realtime data on snow depth.

a b

Figure 10 *(a) Manually observed snow avalanches in Longyearbyen area in Svalbard. The numbers are observed incidents registered in www.regobs.no; (b) An automatic snow observation station in a release area near Longyearbyen (Photo: Martin Indreiten). (Engeset et al., 2020)*

Mass loss from ice sheets and glaciers, and sea level rise Mass loss from glaciers and ice sheets from either melt or calving eventually ends up as a freshwater input to the oceans (Fig. 11). It therefore constitutes both possible local and global hazards making it important to both local and global stakeholders. The rise in the global mean sea level represents a natural hazard to coastal communities worldwide. Increased global sea level due to melting glaciers and ice caps will in the future have a significant effect on sea level, with an irregular geographic distribution associated with change in the gravitational field by e.g. the Greenland ice mass loss. For monitoring of sea level rise in the Arctic Ocean it is essential to build up long time series from tide gauges combined with modelling of vertical land motion to estimate sea level rise relative to land. Unfortunately, the number of active tide gauge stations around the Arctic Ocean has declined in recent years in particular, in the Russian areas. It is necessary to strengthen the network of these stations because the data are crucial for monitoring sea level in combination with satellite altimeter and GRACE data.

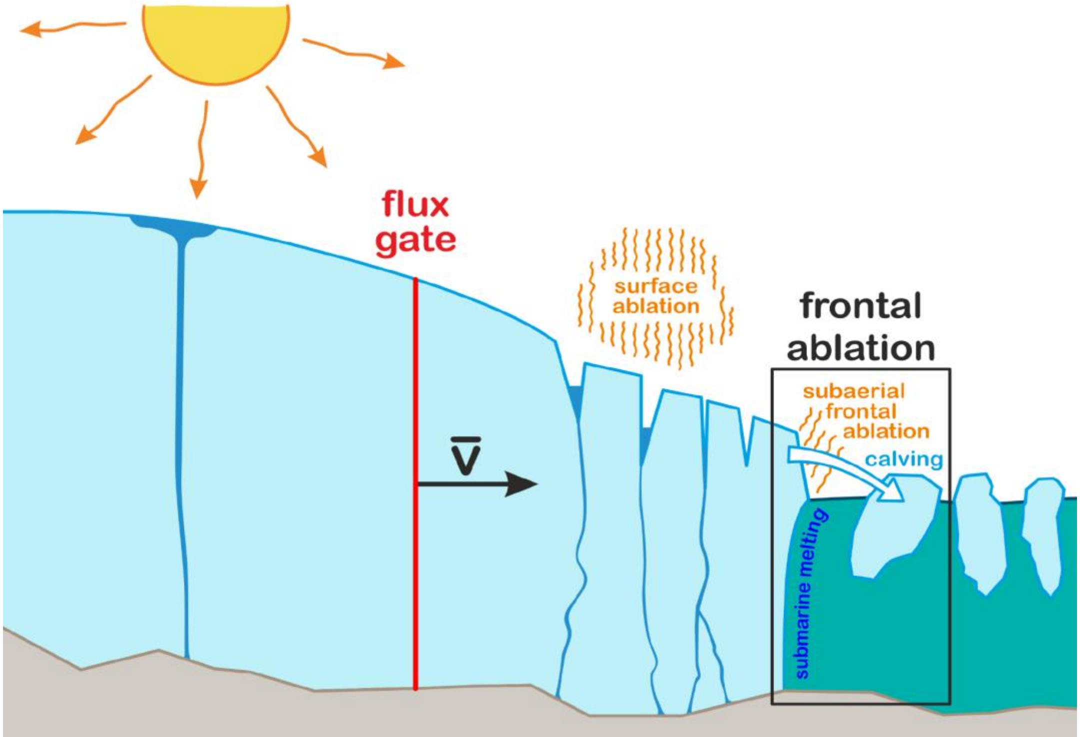


Figure 11. *Illustration of mass loss from a glacier resulting icebergs drifting in the ocean.*

Understanding the underlying process requires detailed models at the local scale, which must be fed by a variety of data which are seldom available. For instance, for analysing the processes involved in the glacier-ocean interaction, which are crucial to understand the partitioning of mass losses from marine-terminating glaciers into iceberg calving and frontal submarine melting, plenty of data from both glacier, ocean and atmosphere are needed. These include 1) weather and precipitation 2) glacier measurements e.g. high accuracy surface velocity measurements, 3) ice thickness data, 3) detailed fjord bathymetry and oceanographic data. While some of these data can be obtained from remote sensing observations (e.g. satellite-derived ice surface velocities, front position changes) and from modelling (e.g. regional climate modelling), field data are still needed for coupled glacier-fjord model parameter calibration and validation of model results. Having available such an amount and variety of data is, of course, not feasible at a wide scale. But, thinking of process understanding, it is crucial to collect such data for a set of benchmark glacier/fjord systems or “supersites”.

4.4 Atmospheric in situ observations in the Arctic Ocean

There are very few vertical atmospheric in-situ observations over the Arctic Ocean. During summer and autumn there are scattered shipborne observations, but they do not include routine observations of the vertical structure of the atmosphere or of clouds. The ship observations are not necessarily assimilated into operational weather forecast services, and hence not used in climate reanalysis.

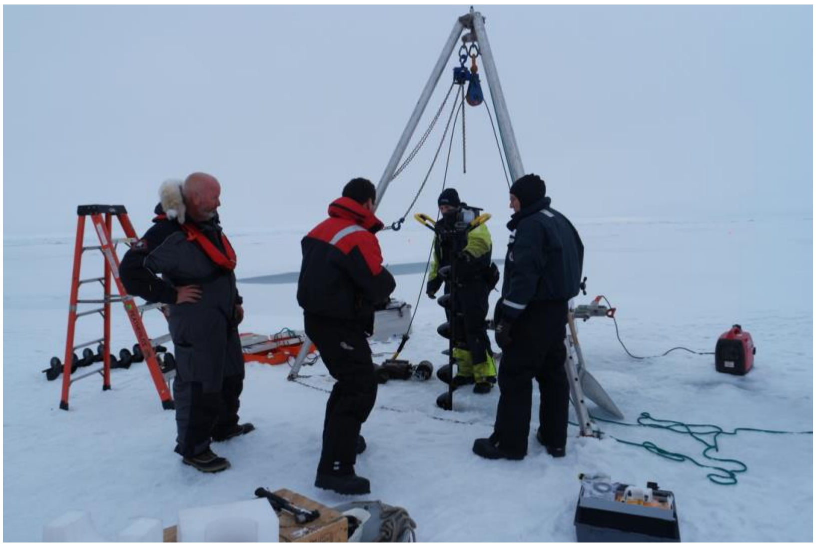
In coming years, the quality and timeliness of atmospheric observations from ships should be improved to make the data useful both in research and operational forecasting services. To achieve this, an international WMO program should be developed where all shipping actors in the Arctic can integrate multi-domain observations as contribution to Voluntary Observing Ships (VOS), an operation observing system under OCEANOPS (http://sot.jcommops.org/vos/index.html). It is recommended to increase coordination among Arctic VOS participants to guarantee a common set of measured variables, and to engage all Arctic vessels to contribute to the VOS network. This program and VOS should be coordinated with the International Arctic Buoy Program with respect to deploy/recover autonomous ocean-ice-atmosphere platforms from ships.

4.5 Ice-ocean in situ observing systems

The global Argo program (https://argo.ucsd.edu) has a large gap in the Arctic because the Argo floats can not send data or receive positions if they are under the ice. Sea-ice buoys, including ice-tethered profilers and ice mass balance buoys (e.g., SIMBA buoys) are the counterpart of the Argo program capable to delivers ice-ocean data in near real time. Most of these buoys are reporting data into the International Arctic Buoy program. However, some buoy programs operates and reports to their own research program or institution. Data from Argo and IABP buoys are available at operational level, and used in assimilation activities as well as in model validation, process studies, and climate monitoring. Buoys, drifters, and buoys platforms are relatively short lived and must be regularly supplemented by new ones. The deployment needs to be done by icebreakers that can operate in the ice-covered ocean. To extend the Argo program and glider activities into ice covered regions, the Argo program and glider operators should collaborate with experts in underwater acoustic and networks to develop under ice capabilities.

The most robust observing system for ice-covered oceans are sea floor installations and bottom-anchored moorings standing vertically in the water column protected from the harsh environment. They provide long timeseries of observations of multiple parameters at selected depths at the fixed location. These installations are deployed and recovered by research vessels or icebreakers in ice covered regions. Data are generally only available in delayed mode from subsea installations after recovery. Several systems of moorings are operated by institutions through research programs or with institutional funding. This makes the sustainability highly variable and unsecured. An important consequence of this is that these heterogenous data sets does not always go into interoperable data systems. All this leads to a relatively low maturity score for advanced subsea observing systems.

To fill the significant gaps in ocean observations in the deep Arctic basin and the surrounding shelves it is important for ocean observing communities to continue and enhance international and pan Arctic collaboration. A European mechanism to develop and operate a sustained Arctic Ocean Observing System (AOOS) would be to establish a Research Infrastructure under ESFRI (https://www.esfri.eu/about). This process starts with preparing the AOOS for the ESFRI roadmap which requires commitment from several European countries at national and international governmental level (e.g., Arctic Council). To achieve this, institutions, and organizations active in Arctic ocean research and monitoring programs must collaborate and coordinate the promotion of the AOOS. In this process it will be important to engage users of ocean in situ observation within private and public sector such as Copernicus Marine Services. A Norwegian initiative has been taken to start the work towards a sustained Arctic Ocean Observing System (AOOS) based on previous and ongoing research projects (Fig. 12). This initiative proposes aim to prepare an ESFRI proposal by 2025. The Norwegian AOOS initiative, involving major institution in research, technology development, and management, will engage with major international actors in Arctic Ocean observing such as existing research infrastructures (e.g., IABP, Distributed Biological Observatory, FRAM), data infrastructures (e.g., Canadian Consortium for Arctic Data Interoperability, PANGAEA), and umbrella organizations (e.g., SAON, ICES).



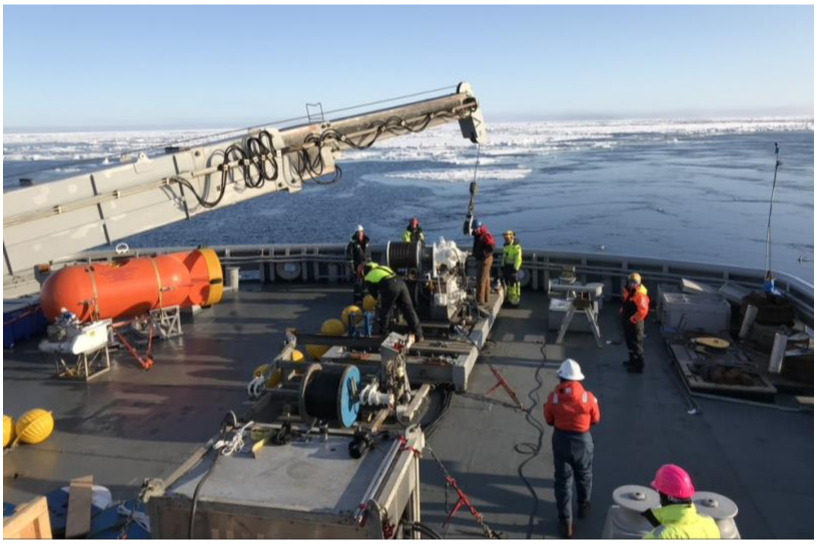


Figure 12. Upper photo shows deployment of an ice tethered platform at the North Pole in 2019. The lower photo shows deployment of a multipurpose mooring as part of the CAATEX 2019 cruise with KV Svalbard.. The photos give examples about the mobilization needed to install observing platforms in the Arctic. The deployment of the ice tethered platforms takes 2-3 people for 3-5 hours depending on the ice conditions. Deployment of deep water moorings in the ice takes 1-2 days including surveys, monitoring of ice drift, and the actual deployment of the mooring. Many people are involved in such an operation.

It is similarly demanding to recover the moorings. Since this is resource demanding it is important that moorings and ice buoys are multidisciplinary and multipurpose. (Photos H. Sagen, CAATEX/NERSC)

4.6 Data delivery chain

Arctic data is held by many different data systems, developed, and maintained by various organisations over a long period of time. Despite substantial efforts to standardise protocols for metadata and data search and retrieval, there is no single accepted standard that all data systems follow. This is due to several factors, including, among others, the heterogeneity and complexity of in situ data, lack of community accepted terminology in some disciplines, experimental sensors delivering new parameters not yet covered by existing vocabularies, and incomplete semantic metadata. In addition, elements of organisational and even legal character may hamper interoperability between data systems.

With so many data systems and different interfaces, it is difficult for service developers to find and assess the suitability of datasets for a given use case. Even scientists or technical personnel experienced in a given field may have difficulties in finding relevant data. Current search engine technologies, both general web search and portal search engines, fail to give a clear overview of initiatives, data producers and online repositories that can provide relevant data for a use case. To develop a more streamlined and efficient data delivery chain for all the types of observations should be of high priority in the coming years.

5. Advancing technological observing capabilities

Several technological developments are needed to enhance the observing capabilities in the Arctic both on land and in ocean areas., as illustrated in Fig. 13.

Only very few established observing networks deliver multidisciplinary observations while a majority of in situ observatories are focused on providing data to a limited research field. Operation of observing systems in the Arctic are expensive and it is important that the resources are used efficient. Therefore, it is important to promote implementation of multipurpose and multidisciplinary in situ observing infrastructure on land, on sea ice and in the ocean. Some of these systems can potentially provide additional services for other platforms and systems and one example is multipurpose mooring networks providing ice-ocean observations as well as acoustic signals for geo-positioning of floats under the sea ice.

The backbone of a future ocean observing system, should be based on fixed and mobile (drifting and self-propelled) autonomous platforms, augmented with periodic ship-based reference measurements. These multipurpose systems should be composed of robust and proven technology. For instance, by benefitting form technical developments made by the oil and gas industry for underwater operations and instrumentation. Robustness is critical for establishing and operating a sustained Arctic observing system. Collaboration with relevant developers and suppliers should be stimulated to leverage on-going progress in observing technology.

However, heavily instrumented observing platforms and systems are costly to implement and operate should be operated key position int the Arctic. Therefore, simpler, low-cost and low-power, miniaturized sensors should be developed to be deployed in larger quantities to improve spatial scales and representativeness of observations and mitigate data gaps. This requires further support and attention by both the engineering and research community. A concern is how to minimize the impact on the environment using expendable equipment.

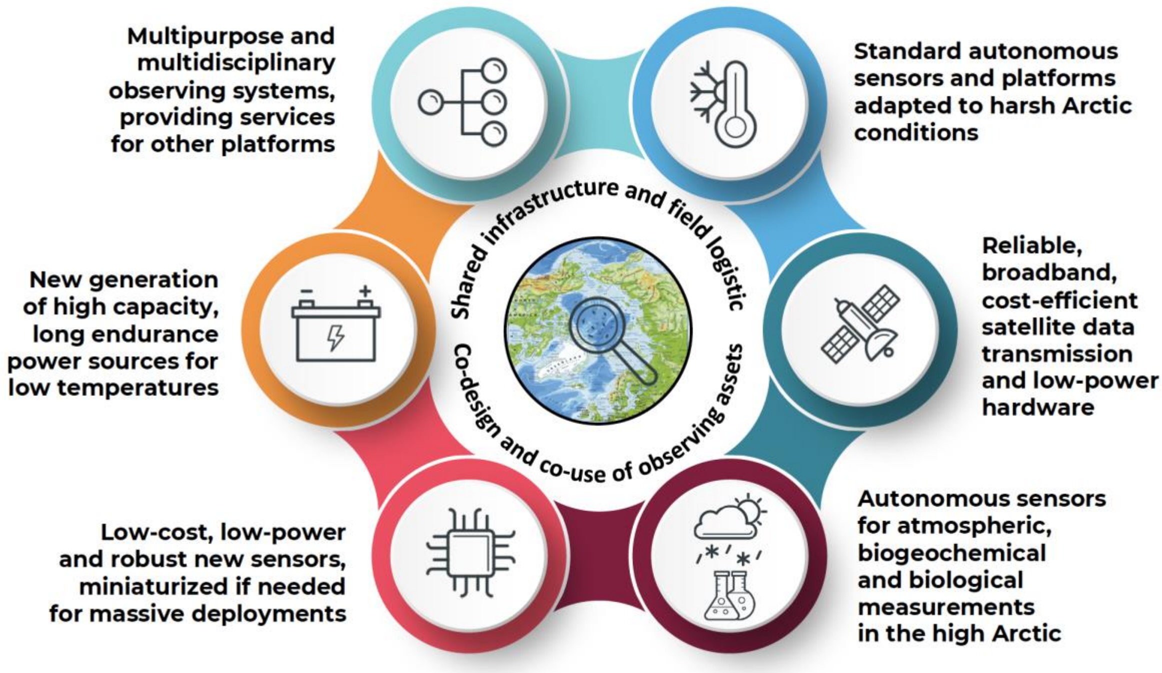


***Figure 13**. Overview of the most important technological developments to improve the observing systems. (Figure by Agnieszka Beszczynska-Möller).*

Fragmentation and heterogeneity of the present-day observing systems in the Arctic is reflected in a large variety of sensors and platforms used to collect in situ observations. This impose need for highly qualified technical personnel to prepare, deploy, and recover a variety of complex observing systems. Difficult environmental conditions demand dedicated procedures for installation and maintenance of observing assets. Low interoperability of observing sensors and platforms hampers possibilities of shared use of infrastructure and optimized logistic efforts.

Best practice documentation for operating different in situ sensors, platforms, and systems in the Arctic should be encouraged and supported. These best practices should be made available through open access channels such Zenodo, and Ocean Best Practices System. Competence building within ocean technology and engineering within different disciplines in Arctic observing should be offered through open technical trainings e.g. Webinars. There is also a need to establish a joint, open, and sustained forum for integrating and exchanging technical expertise as an integral part of a future Arctic observing system including actions to introducing early career engineers to participation in cruises.

5.1 Atmospheric observing capability

Compared to land-based monitoring, atmospheric observations in the Arctic Ocean are extremely limited. Comprehensive measurements are only made during irregular research cruises, while basic meteorological parameters are more frequently measured from ice-based platforms.

It is crucial to develop, validate, and implement a wider network of autonomous systems for atmospheric measurements over land, sea ice and ocean. The measurements should include radiative fluxes, winds, aerosols, and clouds. The foreseen increase in shipping activity in the Arctic provides an opportunity to expand the Ship-of-Opportunity Program (SOOP) for autonomous collection of surface ocean and atmospheric observations in the Arctic Ocean. Statements from the Arctic Ministerial have repeatedly encouraged collaboration on observations with SOOP. A program under SOOP should be established to provide resources so that ships operating in the Arctic can install instruments onboards to measure a minimum of atmospheric parameters or to deploy autonomous ice-based platforms.

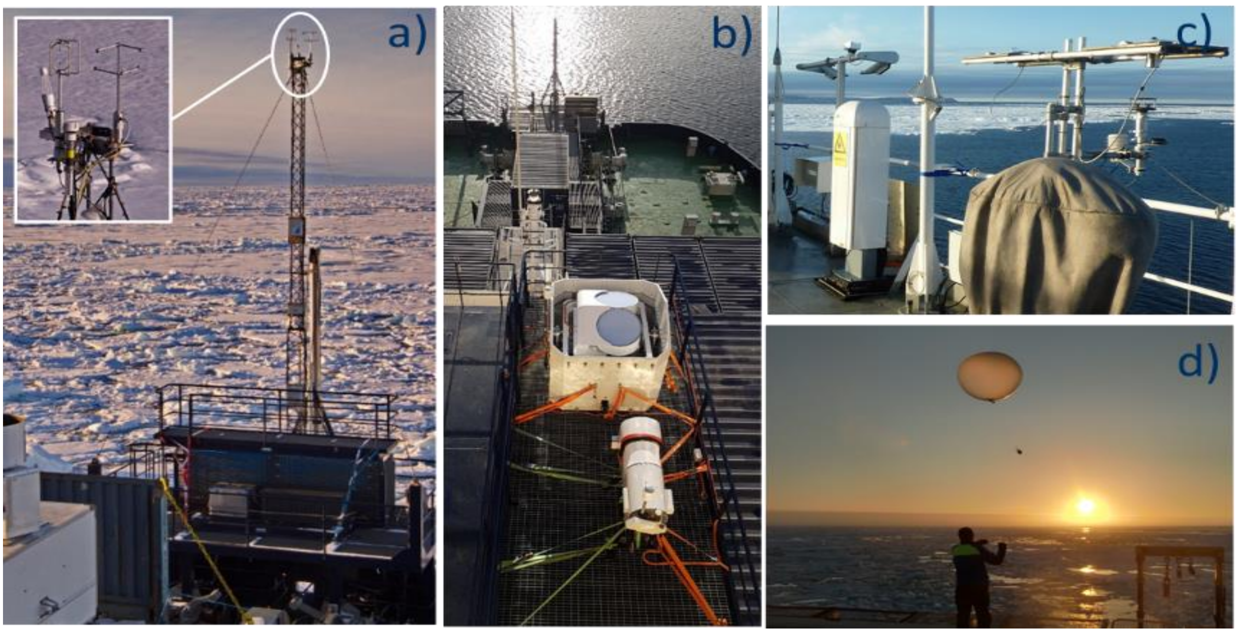


Figure 14. *Photos showing the atmospheric observatory on the research icebreaker Oden: (a) the foredeck mast with eddy-covariance flux instrumentation, (b) cloud radar and microwave radiometer on the 4th deck container roofs, (c) 7th deck weather station with gimballed radiation sensors in front and visibility and cloud lidar in the back, and (d) a radiosonde being launched from Oden's helipad. Photos are provided by Michael Tjernström.*

Platforms with standard sensors and instruments that are proven in lower latitude observatories often fail when deployed in the extreme Arctic conditions. Long polar night and severe storms prevent use of solar panels and windmills as power supply for autonomous sensors and platforms. Decline in sea ice extent in the Arctic Ocean makes it more challenging to deploy ice-based platforms that survive longer than a year. To overcome these difficulties, it is necessary to improve technical solutions to be used in Arctic conditions. For example, 1) develop robust solutions for de-icing of atmospheric and terrestrial instruments or innovative power supplies for surface instruments operating during polar night; 2) facilitate new platform design for ice-based installations that will allow to withstand the melt-out, open water drift and freeze-in periods in the Arctic Ocean.

5.2 Under ice observing capabilities

Ocean physical and biogeochemical variables in general, especially beneath the sea ice, are under-resolved in the Arctic Ocean. The measurements that do exist are typically localized and widely separated in both space and time. Sea-ice cover prevents surface access for autonomous moving platforms, collecting measurements in the water column under the ice. The most robust observing system for ice-covered oceans are sea floor installations and bottom-anchored moorings standing vertically in the water column (Fig. 15).

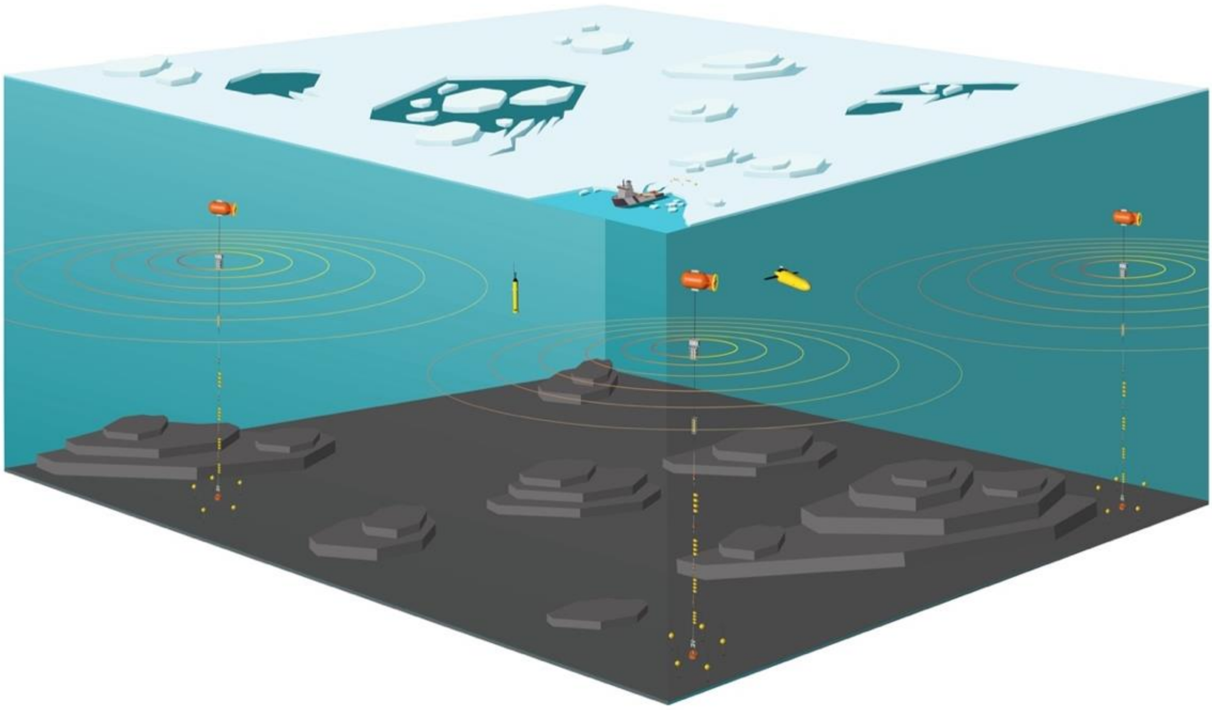


Figure 15. *Concept of multipurpose mooring system. The moorings are anchored to the sea floor and kept vertical with floatation elements e.g., the orange buoy at the top, and yellow floatation elements along the mooring wire. The grey elements (with circles around) are the low frequency sources that provide acoustic signals for geo-positioning of underwater floats and gliders. Acoustic signals from one source are received on 1000 m long hydrophone arrays on the other moorings for acoustic thermometry and passive acoustics. In addition, the mooring will include instruments for collection of ice-ocean parameters (e.g., upward looking sonars, acoustic doppler profilers, biochemical measurements, and standard instruments for temperature, pressure, and salinity measurements. (Copyright: H.Sagen, Nansen Environmental and Remote Sensing Center, 2022).*

Autonomous underwater platforms (profiling floats, gliders, AUVs) are more frequently deployed under sea ice in Arctic, but generally limited to the periphery of the Arctic icepack. Technological progress should be boosted to allow full use of moving autonomous platforms in a larger area of the ice coved Arctic Ocean. A main limitation is the lack of position for the data obtained when the platform cannot surface for geo-localization due to ice. Under-ice positioning of autonomous platforms under the ice remains a challenge and requires technological and methodological developments. Year-round operation of moving autonomous platforms would nicely complement the sampling efforts from ships especially during the poorly sampled winter months.

Moorings provide long timeseries of observations at the fixed location, but they do not yet provide real time observations. These installations are deployed and maintained by research vessels or icebreakers in ice covered regions. Furthermore, downloading of data, replacing batteries, and checking status of the instruments can only be done by recovering and re-deploying the moorings, which is costly and represent a barrier for extensive use of moorings in the Arctic.

To operate floats and gliders under ice, it is necessary to install a mooring network facilitating for geo-positioning system. Such a network will transmit acoustic signals which Argo floats can receive if they have hydrophones installed, and their position can be triangulated, as shown in Fig. 15.

The multipurpose acoustic mooring network should be designed to provide measurements of ocean and sea ice variables combined with instruments for active and passive acoustics. The acoustic network can be used for acoustic thermometry, geo-positioning of underwater vehicles, detection of marine mammals, geohazards and human generate noise (Lee et al 2019, Howe et al. 2019a).

5.3 Biological and biogeochemical observing capabilities

Biogeochemical and biological observations are extremely scarce in the Arctic Ocean. Our understanding of under-ice carbon cycle dynamics is particularly limited due to a lack of maturity in sensor technology that is suitable for extended deployments on fixed moorings or mobile platforms. Reagent-based biogeochemical sensors may not be robust enough for deployment in Arctic conditions. Biological observations still mostly originate from ship-based sampling which is limited in time.

It is required to accelerate a development of robust and reliable sensors for biogeochemistry and biology to be routinely used for long-term ocean observations in the Arctic environment. Solid-state sensors may be more suitable, but both sensor types would require co-located validation samples during extended deployments. Furthermore, integration of new technologies (e.g. optical imaging) for biological observations on autonomous platforms and adapting world-wide used sensors and samplers for marine biology should be promoted for operating autonomously in Arctic environment. (Fig. 16).

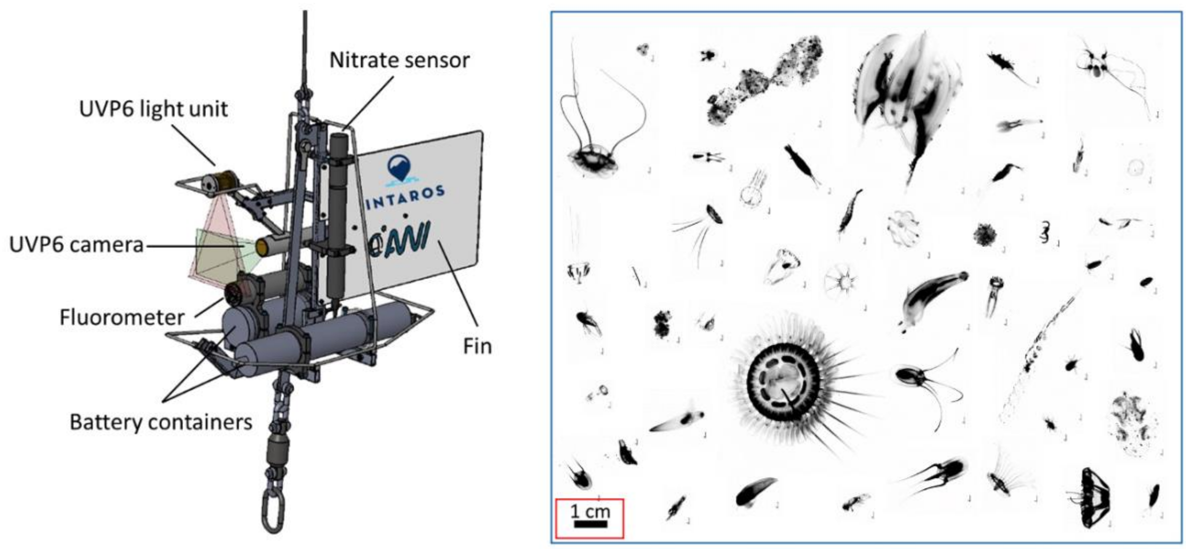


Figure 16. *Left: Sensor package setup with an Underwater Vision Profiler 6 (UVP 6), which acquires particle sizes and quantities as well as zooplankton and aggregate images. The fluorometric SUNA sensor measures nitrate concentrations, the Ecotriplet sensor acquires chlorophyll-a, cDOM, and particle backscatter. Right: example of image showing of Arctic zooplankton from the location north of Svalbard. Figures are provided by A. Rogge, AWI.*

New promising approaches to observe ocean acidification, and anthropogenic carbon uptake and changes in ocean physics autonomously, should be further developed and implemented in important regions in the Arctic e.g. North of Svalbard, Barents Sea opening, and Arctic fjords. Combined with conventional research cruise-based observations, autonomous observations (e.g. moorings and floats) will give better seasonal, annual, interannual and decadal coverage of the carbonate system and ocean acidification. There is also the need to improve observations related to phytoplankton blooms and biological production to fully characterize and understand carbon system dynamics.

5.4 Geohazard observing technologies

A common approach to observe the ground motion on the seafloor is to install ocean bottom seismographs (OBS), which typically contain three seismometers recording in two perpendicular horizontal directions and in vertical direction as well as a hydrophone that records acoustic signals. During the INTAROS project OBS data collected in ice-free areas west of Svalbard showed that seismic wave arrivals are clearly visible in the hydrophone data. In the high Arctic, however, it is not possible to use the traditional deployment method for OBS systems because of the sea ice and the risk of loosing the instrument. A possible solution is to deploy and recover the OBS with an ROV, but that will require a two-vessel operation for ROV deployment to be safe in the sea ice. For landslides, snow avalanches and iceberg calving, high-resolution satellite remote sensing data have already been established in many regions where these hazards are present. But dedicted local observations with in situ instruments are needed to collect data that cannot be observed from satellites.

5.5 General technical developments

Power supply. Traditional batteries limit the sampling capability and life time of autonomous instruments operating in low-temperature Arctic conditions. For terrestrial and ice-based platforms, long polar night and severe weather prevents using solar panels and windmills. For autonomous mobile underwater platforms, battery capacity restricts the range of operations. Limited power supply also often prohibits implementation of the near real-time data transmission, from terrestrial observatories. It is of high priority to improve power supply to autonomous systems in the Arctic Observing system. The power supply should have high capacity, high performance, and improved tolerance for low temperatures, and if possible, allow for recharging. This together with less power demanding instruments will enable longer and more efficient use of autonomous systems in the Arctic.

The way forward for subsea installations in ice covered regions is to develop technology which enables data download and recharging instrument batteries without recovery of the installation. These developments would be a step towards incorporation of subsea installations in the future commercial communication cables in the deep oceans and thereby receive power and transmit data in real time, e.g., the Smart Cable – Arctic Express (Howe et al. 2019b). Research communities should work closely with industry within subsea and cable communication to benefit from developments made for offshore industry.

The **satellite data transmission** in the Arctic has up to now been very limited in terms of geographic coverage, bandwidth, quality of service and affordability. This situation severely hampers near-real time data retrieval and two-way communication. Two-way communication is needed for remote control of autonomous observing infrastructure including controlling the sensors operations (e.g. scheduling of the sampling).

There is now a rapid development of new broadband satellite services covering the Arctic region (https://spacenews.com/arctic-connectivity-competition-is-heating-up/). These services will facilitate for significant amount of data to be transmitted from a network of observing platforms in any location in the Arctic. The new broadband will also facilitate for realtime data transmission from observing platforms, which will support operational monitoring and secure the data without recovery of the platforms.

The research communities should collaborate with the telecommunication companies to adapt observing platforms for broadband communication. This will require robust, low-power hardware for data transfer (e.g. modems, antennas, terminals). Furthermore, cost-efficient data services will be needed from the telecom service providers for near real time data transmission.

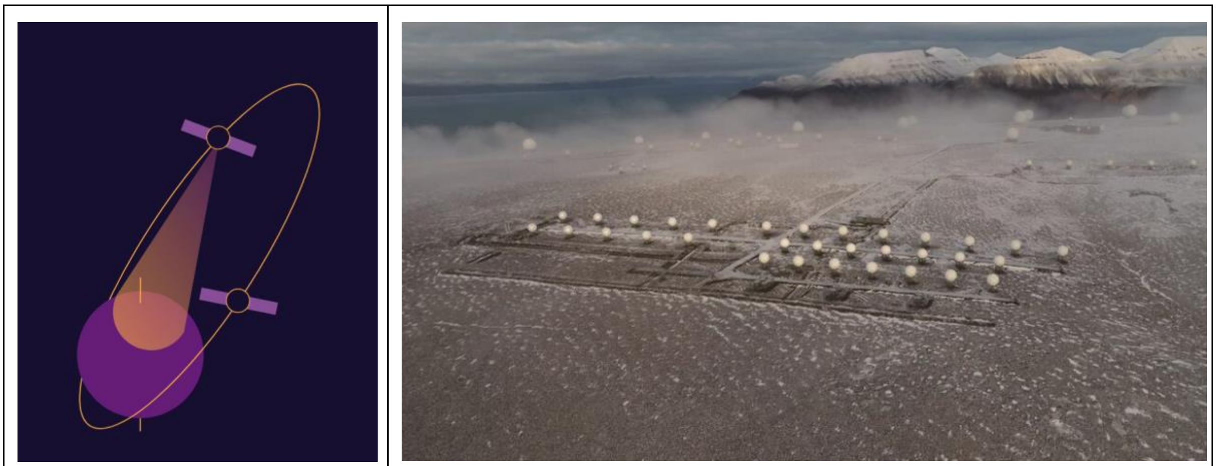


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Figure 17 (a) *Illustration of the two new Norwegian satellites in the Arctic Satellite Broadband Mission thatwill be launched in a High Elliptical Orbit (HEO). The satellites will provide mobile broadband communication in the Arctic. Illustration: Northrop Grumma;* ***(b)*** *OneWeb antennas installed at the Svalbard archipelago between mainland Norway and the North Pole are hosted by KSAT, a Norwegian ground services provider. Credit: OneWeb/KSAT*

6. Data systems in the data value chain

Data systems are critical for implementing the FAIR principles, but they depend entirely on data from a large number of research programs and infrastructures. However, there are many barriers and challenges in having a common understanding of how the data flow can be optimised and sustained between data collectors, data managers, and those using data for services and research. In this section, we provide the perspective of those providing data to data systems, and those managing data systems. Challenges for service developers are addressed in the next section.

An increasing amount of data from satellites, in-situ observing systems, and model systems are available through different data systems. Efficient extraction of information from these vast amounts of diverse data needs efficient and scalable digital techniques. Geo-statistics, machine learning, and other artificial intelligence techniques enable deeper extraction of hidden connections and patterns in these data. The challenge is to use this information to build new and useful knowledge for a variety of users. This requires co-development between experts in digital techniques, scientific domains, and the final users of the results. The development is not done in a single step, but through several phases with frequent interactions.

In future work, user requirements for domain specific applications, as well as workflows including tools and methods, must be defined, and validated early in the project. Scientists, data providers, software developers, and users must be involved to ensure focus on usability and performances expected by user communities. Understanding the stakeholders' expectations and requirements is the key point for co-developing services. Thereafter, the domain experts must define what data, models, and algorithms, are needed. Based on this the experts in digital technologies propose suitable frameworks and tools. This is then presented for the stakeholder to decide if this is according to his/her expectations. It can be demanding to establish a fruitful dialogue due to differences in professional background and terminology. Dialogues entail organising a series of meetings between stakeholders, scientists, and software developers. If reliable and well documented online data services exists, then data can be used directly in the service development. However, if data come from data systems with low technical maturity, then data managers must be involved in the service development. Research infrastructures (RI) and monitoring programs are obliged to provide data and they are funded to do so, and therefore they have a generally high score on data management procedures.

Distributed data system will continue to be the solution for the researchers to share in situ observations and other data products. This facilitates for close collaboration between scientists and data managers ensuring well documented data are ingested into data systems. To build an integrated Arctic Observation system requires interoperability between the distributed data systems. This is the responsibility of the data systems, but funding at national and European level are needed to make these systems interoperable.

6.1 Technical perspectives

Standards for data and metadata storage and access. INTAROS has worked in many scientific disciplines as well as with community-based monitoring (CBM) and citizen science (CS). The wide variety of data from different scientific domains, CBM and CS, meant that many standards for metadata and data formats had to be accommodated. Some categories of data did not have community accepted standards. This urged INTAROS to develop metadata structures and data formats based on standards from the wider scientific or user communities. One example is a joint definition of metadata for ocean mooring data based on Climate and Forecast (CF) and Attribute Convention for Data Discovery (ACDD) conventions, complemented by requirements from the Copernicus Marine Service and SeaDataNet. To support data search across the disciplines, we used a simple metadata schema in the INTAROS portal and data catalogue. This allowed users to look for relevant data from distributed data centres in a common user interface, and reduced the effort needed for registering their own data. The INTAROS portal harvested metadata from non-partner data systems using standards protocols, enabling the same search functionality for external data useful for science or service development (Fig. 18).

Figure 18. *Homepage of the iAOS portal (https://intaros-portal.nersc.no).*

Combining data from multiple disciplines and sources are needed to address important scientific, societal, and business issues. Therefore, we recommend Arctic scientists, local communities, data managers and stakeholders to work together to harmonise and standardise metadata and data formats used in Arctic data systems and promote open and well documented interfaces for search and retrieval of metadata and data across disciplines and data systems. Special focus is needed to adopt common formats and protocols with wide support in the various disciplines and communities. This will facilitate federated search across distributed data systems bringing together relevant metadata and data in a joint data portal. This work should be carried out in collaboration with ongoing Arctic data initiatives and programmes, e.g. the Arctic Data Committee (ADC).

FAIRness of data systems. Most data repositories operated by research institutes do not fully comply with the FAIR principles, and for example do not assign a DOI. International and discipline-based data systems (such as those of EU RIs) provide support to standardize formats and request that data comply with the FAIR principles, but this request is difficult to satisfy for many research institutions that do not have sufficient resources. Moreover, FAIRness of data requires a close collaboration between the data providers/curators, the technology experts who maintain the data repositories, and the user of the data to understand and support their capabilities and requirements. This is often lacking since scientists in many cases have insufficient knowledge on information technology, while data manager experts often lack understanding of structure and characteristics of scientific data. The collaboration between data collectors and data managers should be improved. This can be done by training data managers to act as mediators uniting science and technical terminology, or by data managers providing simple guidelines with clear instructions on how to document and format data.

Data traceability in services. Services producing value added data products frequently use data from multiple sources. However, tracing the data used to generate such products back to an individual data provider's institute or a person in the data value chain is not fully implemented in many data services. This is a particular challenge for dispersed Arctic data. The lack of traceability leads to insufficient acknowledgement of different contributors who have a crucial role in data and product generation. In a longer run, this lack of traceability may jeopardise the long-term sustainability of the data systems providing input data to data services. Therefore, we strongly recommend data to be published through data systems that issue a persistent identifier (e.g. DOI) and include a data license specifying accepted use of the data. In addition, data systems should implement tracking services showing citations of their data by other data systems or services and follow up any discrepancies between expected FAIR and actual usage of data.

Upstream and downstream services. To enhance the use of Arctic data systems the data delivery chain must be improved by providing better services for upstream (e.g. observers, scientists) and downstream (e.g. service developers and research) users. Upstream and downstream users have different professional backgrounds and expertise, but often little or no formal training or experience with data management and standard metadata/data formats. Therefore, it is necessary to acknowledge and strengthen the mediator role between the data provider and the data managers as well as between the data managers and the service developers and between the service developers and the end users. Arctic data systems must be responsible for providing support and competence building tailored to the different categories of users.

It is important that the role and responsibilities are given for each step in the data value chain to advance the implementation of FAIR and CARE (Collective benefit; Authority to control; Responsibility; Ethics) (https://www.gida-global.org/care)). Data observers are responsible for providing the necessary meta data for inclusion into data systems to ensure that the data are reusable and that their rights are respected through licences and proper credit. Data systems are responsible for making the data findable and accessible, through standard formats and protocols for meta data and data. Furthermore, the data systems are responsible for developing interoperability between different data systems through common interfaces e.g. community vocabularies, machine to machine communication. Common interfaces such as OpenDAP will facilitate for data sharing and simplify the development of tools for ingesting data into user applications including Cloud services.

Respecting and acknowledging observers and other actors generating data is important in order to keep the trust of the different user and stakeholder communities. Advancing user support and competence building should be carried out in joint projects where the data and rights holders have an equal position of data managers and data system operators. Work should be aligned with ongoing initiatives and practical implementation of FAIR and CARE principles, e.g. with ESFRI projects and ERICs, EOSC initiative and projects, as well as CBM and CS programs.

7. Services and application development

Data from the observing systems are used in services and applications to serve various actors in the Arctic including local communities. Services and applications depend on standard-based and timely access to data from models, remote sensing, and in situ observing systems. Furthermore, they rely on efficient tools for integration, analysis, and visualization of massive amounts of data from a variety of sources, including different model and data systems. To make the services and applications trustworthy for use in decision making the data must be quality controlled and the model systems must be properly validated. With this in place useful services ad applications can be developed. The services and application should build on a holistic approach seamlessly integrating and exploiting data from in situ observations, satellite remote sensing, reanalysis products, and a range of models. Services and application cover a wide range of domains, and in the following we address selected topics with importance for different actors in the Arctic.

7.1 Climate projections and services

Climate model predictions are providing projections to help the society to plan and to adapt to the ongoing climate change. The projections must be translated into useful information to the actors in the arctic together with realistic uncertainties. It is therefore important that these models are validated with data from various observing systems, and that the validation procedures are clearly documented and explained. Climate validation requires long term timeseries of the essential climate variables. It is important that the climate communities come with requirements for the in situ observing systems. However, it is important that these communities follow up actions to implement the requested monitoring.

7.2 Natural hazard risk assessment

With climate change comes extreme weather events, thawing permafrost, and melting glaziers. These changes increase the probability of severe natural hazards such as avalanches, landslides, tsunamis, and earthquakes. For local communities and actors, such hazards can be life threatening, and risk assessment systems and warning systems and are needed for planning and mitigation. Long time series is the backbone for increased process understanding and improved predictions of natural hazards. Availability of data in (near) real time is important for operational services to allow authorities to respond timely, e.g., in the event of an earthquake or an increase in the risk of an avalanche. Risk assessment system will support local councils and constructors to take measures to reduce the risks from natural hazards. For example, a risk assessment can enable municipal councils to assess whether critical infrastructure is secured against natural hazards including strong earthquakes, landslides, snow avalanches, and floods. Systems should include evaluation of the potential consequences and prepare action plans in case they occur. Local and national authorities should have the main responsibility for monitoring, responding to risk assessment, and prepare actions for mitigation. As part of the mitigation, private companies, especially construction firms should follow up recommendations given by authorities.

7.3 Marine ecosystem understanding and management

Climate change affects the marine ecosystems, and thereby affect the livelihood of people living in the arctic as well as commercial activities such as fisheries. To support sustainable management of natural resources risk assessments systems should be developed for marine ecosystems. Variability and changes in the physical and biogeochemical conditions influence Arctic marine biology and ecosystems. It is therefore important that risk assessment systems are developed to include the analysis of a broad range of variables covering the whole water column. To improve the reliability of the assessments it is important to validate the integrated products from the reanalysis and the ecosystem models with observations, and to provide uncertainty estimations. Presently many, but relatively simple, indicators are used in marine management plans e.g., as used in Norway for the Barents Sea. More advanced indicators, utilizing information also from models and reanalyses, will give better foundation for understanding of the ecosystem and advice towards environmental and fisheries management. This should be followed up both at the national level (e.g., within the Norwegian management plan system, led by the Norwegian environmental agency) and Internationally (e.g., within AMAP and other Arctic Council working groups and ICES).

7.4 Shipping in the Arctic

Increased ship traffic in the Arctic lead to higher risks of accident, and therefore insurance companies, tourism, and search and rescue agencies are for better informed risk assessment systems. The present assessment systems do not yet fully benefit from the huge amount of information from reanalysis and forecasting systems, in situ observations, and more advanced products from satellite data. Currently, the assessments have been focused on bringing information about the position the ice edge to support ships operating in open sea. In the years to come more traffic of ice strengthened ships and small to medium sized ice breakers are expected to operate in ice covered regions (Figure 19). These operators will need information and risk analysis about the ice thickness, compression and decompression of the ice field, and the age of the sea ice. The development of better risk assessment systems for Arctic shipping should be followed up by coast guards, national authorities, and international maritime organizations in collaboration with researchers and the PAME and EPPR working groups under the Arctic Council.

7.5 Human impact on the Arctic environment

There is growing concern regarding the human impact on the natural environment in the Arctic. Our impact is manifested through observations of micro plastic and toxic substances in the marine and terrestrial eco systems. Most of the pollution is transported from lower latitudes with the ocean currents and the weather systems. It is therefore important to have a large-scale approach with a strong link to the ecosystems when assessing the potential risk and finding mitigation measures. This is an extremely complex task because it contains many interlinks requiring expertise from several disciplines. Processes are ongoing in the Arctic Council working groups, but to resolve the issues needs binding commitment at international and national level.

Figure 19. *Regular tourist cruises are taking place in the interior of the Arctic, as well as research cruises and commercial shipping activities. The photo shows a Russian atomic ice breaker (2019) (Photo: H. Sagen, CAATEX/NERSC)*

Increased human activities in the Arctic (e.g., shipping and tourism) are influencing the environment at local to regional scale by contributing to air and water chemical pollution and spreading of sound in the water and on land. These sources of unwanted affect on the environment can be identified and mitigation actions can be taken to directly reduce the problem. A sustainable development is not necessarily obtained by conservation of the environment. Therefore, we recommend conducting broad environmental assessments building on scientific, sectorial, and local knowledge to document potential severe negative impact on the Arctic environment and to develop mitigation actions.

7.6 Digital solutions for extraction of information from observations

Massive amounts of heterogenous data from numerous data systems and data providers are being produced and made available for users. This includes satellite remote sensing data from space agencies, and 3D timeseries of climate variables from model simulations, predictions and reanalysis. In situ data are available from different observing systems at a much sparser geographical coverage and often with unregular coverage in time. The advantages of in situ data include high measurement accuracy and many parameters not observable by other means. The volume, variety and variability of data sources is complex and introduces several technical challenges. Cloud technologies can help in accessing, organizing, and processing the massive amounts of data in a scalable and vendor independent manner.

Tools for preparing diverse data from different Data Systems are needed to support efficient integrated analysis. These tools must include methods for transforming data to common formats, aggregation and reprojection to a shared grid (time and space), and quality control of the data (e.g., uncertainty in the data set). Currently, several digital methods are available for advanced data analysis such as geo-statistics, data assimilation, machine learning, neural networks. Before applying digital methods, domain experts must clearly define the objective of the integrated analysis, develop the workflow, and based on this make the choice of suitable technology. The development of digital solutions is supporting the establishment of digital twins for different users of environmental data and models. Development of Digital twins need to combine the expertise of end users, domain specialists, and technology providers. Digital twins are addressed in several programs under the HORIZON Europe.

8. Further development of Arctic observing

This section has focus on observing systems for the Arctic Ocean, especially the ice-covered areas, where there are large gaps in the observing capacity. Terrestrial observing systems are more thoroughly addressed in other H2020 projects (e.g. INTERACT and NUNATARYUK). Important drivers for further development of sustainable Arctic observing systems are research, climate services, forecasting systems, local communities, and stakeholders operating in the Arctic. However, it is up to national and international funding mechanisms to make this happen which means that politicians should be informed about the need for in situ observing systems. Many important variables are not available from remote sensing and the models are not able to reproduce them. Coordinated efforts should be made to forward the message that satellite remote sensing and model systems do not tell the full story about the Arctic. Also, decision makers and funding agencies should be informed about the resources needed to make the data delivery chain FAIR, and that sufficient resources should follow the requirements imposed. In this respect they should learn about the difference between observing systems operated as part of research infrastructures with long-term funding and observing systems maintained by research projects with time-limited funding.

8.1 Research-driven observing systems

Climate and Arctic research are an important driver for continued implementation and expansion and sustaining research infrastructures and monitoring programs in the Arctic. Curiosity driven research and innovation is important for moving forward towards improved observing systems. Innovative observing technologies include new sensors and ways to improve measurements of key parameters and thereby advancing the Arctic observing capacity.

Dedicated funding should be earmarked to streamline data management within research driven observing systems, to ensure collected data are made available in line with the FAIR principles. Funding should be provided by both national and international bodies, with focus on coordinating use and distribution of resources to maximize growth in Arctic observing capacity.

These funding mechanisms should promote shared use of long-living observing infrastructure and coordinated and optimized field logistics. As an example, most of autonomous platforms operated in the central Arctic Ocean are single use and are not retrieved after the end of life. Increasing efforts to recover autonomous platforms such as Argo-type floats or ice-tethered platform would reduce pollution of the Arctic Ocean. This will have an added benefit of enabling redeployment after refitting, significantly extending the lifetime of such platforms and maximize return on operating expenses.

Observing technologies developed for science, early warning, and offshore industries (e. g., power, communications, and electric vehicle charging nodes) should be used to develop robust fixed and mobile infrastructure for arctic observing, especially so in the ice-covered regions of the polar oceans. Ocean observing can benefit from commercial submarine cables to obtain data in real time (Fig. 20). Cables can host basic sensors in the optical amplifier repeaters every 70 km or so (the concept of SMART – Scientific Monitoring And Reliable Telecommunications, Howe et al., 2019 and 2022).

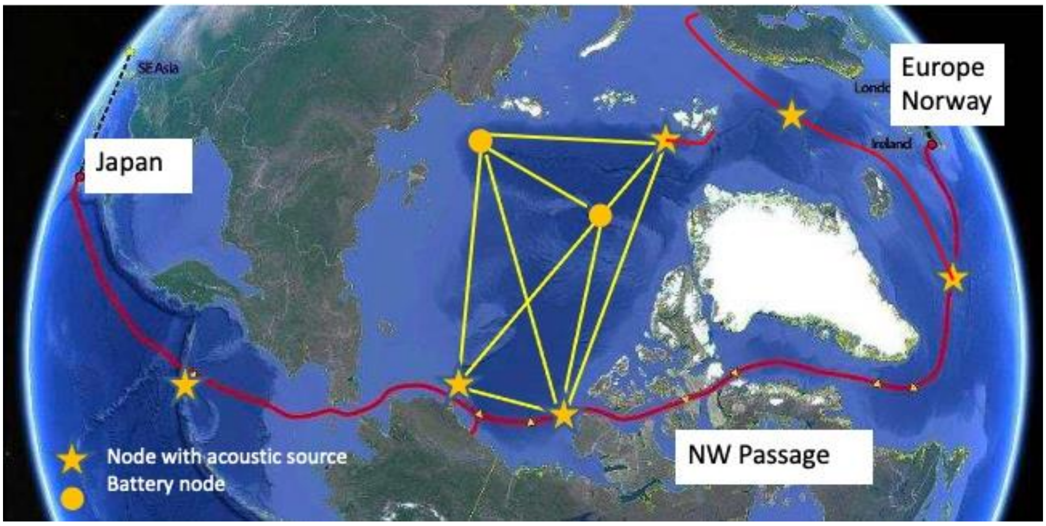
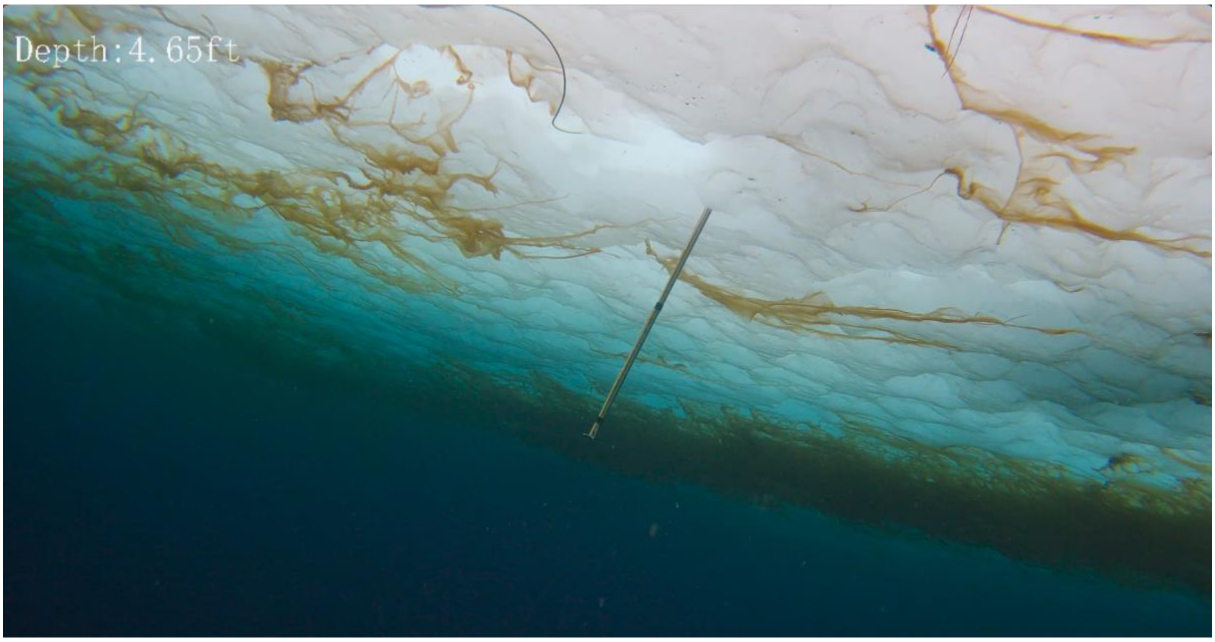


Figure 20. *Conceptual description of a multipurpose acoustic network for the central Arctic integrated with the planned Far North Fiber SMART cable system from Norway to Japan. The red line indicates the Far North Fiber cable route, and the yellow STARS indicate branch nodes with multi-disciplinary instrumentation including acoustic transceivers and AUV docking stations; large yellow dots are autonomous battery-operated nodes (some to be ultimately cabled). The cable will provide broadband communication to Indigenous communities along the route (via standard telecom branches, small yellow dots), while providing high-speed, low-latency communication between Europe, North America, and Asia. As shown here, the cable from Svalbard would be a dedicated cable for science. Stars outside the Arctic will support anticipated science needs in the other ocean regions. (Figure from Howe, Icard, and Sagen, 2022).*

The cables can also provide branches to host more complex subsea nodes with more capability (e. g., docking stations for Autonomous Undersea Vehicles (AUVs), acoustic transceivers, cameras, lights and other ocean observing instrumentation). The cables would provide data in real time and over the nominal telecom engineering life of 25 years. A conceptual network drawing is shown in Figure 20. This network includes as the foundation cables (SMART and nodes), but also cable-connected and autonomous moorings in the Arctic that can be used for ice-ocean observations and facilitate an acoustic positioning system which will expand the use of AUVs, Argo floats and gliders in central Arctic. The initial capital costs are high, but the annualized costs are modest when considered over the long-expected lifetimes ~25 years. These investments would be small compared to the costs of observing satellites.

ROVs and AUVs equipped with different sensors are being tested under ice conditions, as well as the development of Argo floats with biogeochemical sensors. Furthermore, drones are getting widely used to observe land, ocean, and ice (See Fig 21). These platforms are very promising for obtaining detailed observations below and above the ice and can be equipped with different sensors. The ROV technology is used to perform very complex operations in offshore industry, and in the future this is technology can be simplified for serving marine research. The airborne drones can be used collect detailed information about the sea ice with various coverage depending on the size and the weight of the payload. If the drone has broadband communication, it can operate in a large area with real-time data transmission.



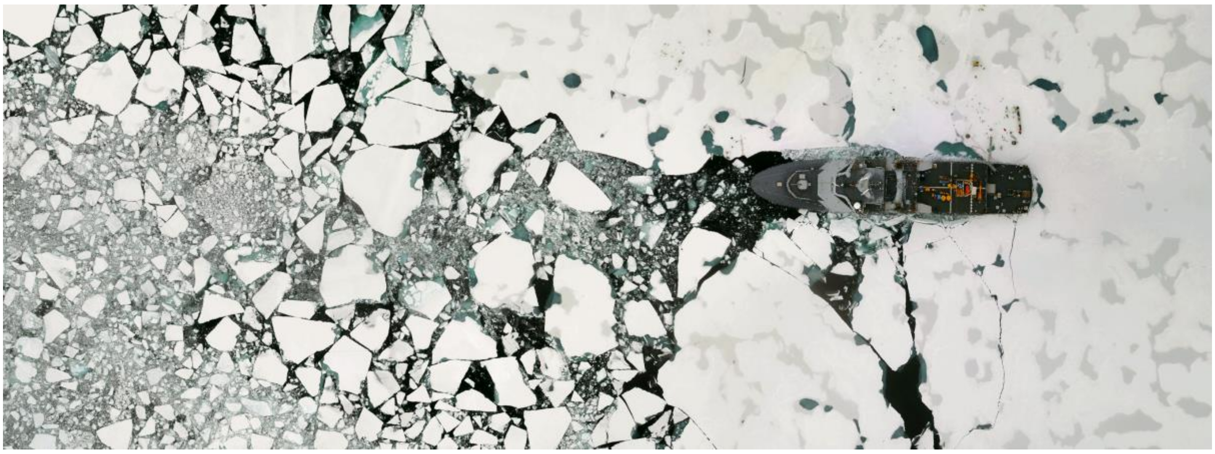


Figure 21. *The upper photo shows the ice algae below the ice obtained by a ROV operated by a PhD student Laust Færch during the UAK 2021 cruise North of Svalbard. The lower photo shows the KV Svalbard at the North Pole in August 2019 as part of the CAATEX cruise. The photo was obtained by a drone operated by Tom Rune Lauknes, NORCE*

Funding agencies should support cross-disciplinary projects and development of formal frameworks to co-design, co-develop and co-use observing infrastructure by different groups with interests both in research-driven and operational observations. Specifically, collaborative networks to assure efficient exchange of technical know-how and operational schedules to support joint field operations in the Arctic regions should be established. This would for instance enable enhanced recovery of autonomous platforms in the Arctic Ocean or installation of terrestrial observing infrastructure in the remote and inaccessible Arctic areas.

Our recommendation for funding bodies is to initiate a dialog with owners of commercial infrastructure in the Arctic and explore possibilities of a secondary use of existing nodes or installations for implementing new observing assets for autonomous data collection. Likewise, we recommend initiating a dialog with commercial Arctic operators (on land and at sea) to explore the potential to use their logistics (e.g., tourist ships' traffic) to collect voluntary observations or deploy simple sensors in the Arctic areas not covered by regular observing systems. Identified themes of mutual benefit should be followed up through dedicated calls for collaboration.

8.2 Observing systems co-developed between researchers and stakeholders

To make research and observing systems useful for the society it is important to involve all the relevant stakeholders and rightholders, including Indigenous and local communities, government agencies, the private sector and service providers. Funding agencies should facilitate for collaboration between researchers and stakeholders to co-develop programs that combine research objectives with stakeholder needs. Collaboration builds on jointly agreeing on monitoring priorities and objectives, sharing of knowledge and data, and mutual competence building between scientists and stakeholders. Broad stakeholder involvement will ensure that research programs support sustainable development of the Arctic and strengthen research that is important for the Arctic society.

Future projects need to address the challenge of sustaining community members' interest for long-term commitment to CBM and CS efforts. Their commitment is influenced by both community perceptions of relevance and reward - and by factors related to community capacity. Programs in which observing protocols are too time-intensive or researchers provide insufficient feedback to communities about outcomes risk burnout over time (Eicken et al. 2021). It is recommended that organizers of CBM and CS programs (1) incorporate data collection into routine activities; (2) prioritize regular feedback to community members about the use of CBM and CS data; (3) consider how to motivate all parties, including community members as well as authorities; and (4) strengthen the involvement of young people and women. For many participants, there is a strong incentive if the CBM program gives them the right and power to influence decision-making – having a 'voice' in society because of their effort.

Furthermore, long-term funding must be established to resolve the challenge of insufficient organizational structures in the communities to support CBM and CS programs over time (Danielsen et al. 2020). Efforts to remedy this would contribute to "ensure responsive, inclusive, participatory and representative decision-making at all levels" (UN SDG 16, Target 16.7). It is recommended that prospective CBM and CS organizers (1) assess local institutional capacity prior to establishing CBM and CS programs; (2) develop the capacity of local institutions; and (3) pool resources among CBM, CS and other observational programs so that funds for capacity-building and local incentives such as job creation can be coordinated.

8.3 Sustaining data systems and reuse

The data systems hold relevant data for Arctic science and business development and play a crucial role in making data FAIR. To sustain storage and access to Arctic environmental data, it is necessary to maintain tools for data extraction adapted to the APIs of data systems used by the research infrastructures. This enables researchers, service developers and end-users to carry out their work more efficiently.

To leverage advances in standards and vocabularies, data systems must support standard metadata and data formats and protocols. Inclusion of new categories and increasing amounts of data need close collaboration between data managers and observing system operators. Data systems can benefit from technological developments through collaboration with international organisations such as ADC (Arctic Data Committee), and RDA (Research Data Alliance).

A barrier in operationalization of data delivery chains is the lack of common terminology and understanding across disciplines including data management. Earmarked funding is needed for supporting competence building and sharing knowledge between data collectors and data managers. To achieve this data managers and research communities should work together to put focus on the mediator roles int the data delivery chain towards funding agencies.

Interoperable data systems form the backbone for making value added data products. Development of new data products through services may extract and integrate data from several data systems. This requires stable data access APIs. If the service uses massive amounts of data, the hardware capacities of the computing infrastructure a limiting factor. This can be solved either getting access to a more powerful computer (e.g., HPC) or to a network of computers (e.g., cloud computing).

To develop services the following considerations of the computing infrastructure must be made: (1) cost assessment, (2) legal aspects of data, methods, and tools (e.g., licences), (3) trust in infrastructure providers, (4) privacy policies (e.g., GDPR), (5) security policies (e.g., to avoid hacking), and (6) usability criteria (e.g, user friendliness). These considerations must be addressed by project proposers and be part of the evaluation process in funding agencies. Competence building in use of cloud computing is needed to increase the use of this technologies within the research communities.

8.4 Competence building and cross-disciplinary bridging

The importance of training and education. Knowledge transfer between generations is essential to continue to develop excellence in science and technology. Several research schools were organized as part of INTAROS on this topic including data management of in situ data (Fig.22). Education is multi-directional, and opportunities for education cannot be limited to transmission of knowledge from academics or public representatives to non-specialist audiences. Indigenous and local communities, citizen scientists and local and regional authorities contributes with a wealth of local knowledge and perspectives. Open fora for communication and mutual learning will enable knowledge and experience sharing between all stakeholders.

***Figure 22**. Researcher schools focused on making and documenting in situ measurments are important in the training of the new generation of scientists. These photos shows master and PhD students partcipating in a researcher school with the KV Svalbard summer 2021. (Photos: H.Sagen, UAK/NERSC).*

Legacy of INTAROS through Open Science. INTAROS has made a significant contribution to sharing scientific knowledge about the Arctic, by providing an INTAROS portal and data catalogue that are openly available to all. INTAROS research has been reported in open access journals e.g., a Science Special issue for INTAROS including a variety of Copernicus Journals. A Zenodo INTAROS community has been established to promote results from the project including data, presentations. Videos from field work have been deployed at the You Tube INTAROS Channel, https://www.youtube.com/channel/UCoegF3QSQe17mmGvj8oNs_g/videos.

It is important for Arctic science and observing that information is shared through open data repositories, open access publishing, co-design and co-creation, science becomes a shared asset that all stakeholders can benefit from and more quickly than in the past. Open Science tools will increase education, engagement, and synergies within Arctic research and observing.

9. Conclusion

The **funding mechanisms** for observing systems can be divided in two main categories according to funding mechanism: (1) established programmes with sustained funding over many years, e.g., ESFRI program, COPERNICUS with the Sentinel and national monitoring programs; and (2) research projects with short-term funding of 3- 4 years e.g., INTAROS, other H2020 project and national projects. Satellite remote sensing programs are implemented by space agencies with funding committed at governmental level in the participating countries. This contrasts with the in-situ observing systems which are normally organised by research institutes depending on European ornational research programmes. At European level the research infrastructures under ESFRI play a role in implementing in situ observing systems (e.g, Euro Argo, ICOS, EPOS), but these infrastructures depend largely on national research programmes. The Arctic countries have own responsibilities and priorities related to funding in situ observing systems in their territorial areas and economic zones. Many other countries conduct research in the Arctic and contribute to the Arctic observing through research funding. In general, the in situ observing systems are less developed and sustainable compared to the space-based systems. This is mainly due to the difference in funding schemes.

It is important that countries with interest and need for sustained Arctic observations work together to provide long-term funding of scientist- and community-led observing systems to follow up the Joint Statement of Ministers (ASM 2021).

International coordination initiatives for Arctic observing are evolving under global programmes by e.g., WMO, IOC, GOOS, GCOS, and Copernicus Specific coordination for the Arctic is done by Arctic Council and its working group, Indigenous peoples' organizations, SAON and many more. As part of the third Arctic Science Ministerial in 2021 a statement about collaboration about the Arctic Observing was developed and signed by 25 countries, 6 organizations, and the EU (https://asm3.org) . The actual funding of in situ observing systems depends on each country's priorities and needs. Funding mechanisms of establishment and operation of long-term in situ observing systems should be strengthened from national as well as European funding sources. Furthermore, coordinated initiatives should be taken to promote the development of a holistic data 'ecosystem' for CBM and CS. Such initiatives should contribute to bridging conceptual, political, and geographical distances, and to strengthen decision-making at various levels of the public sector together with local communities in the Arctic.

It is required to strengthen collaboration and coordination between the initiatives, institutions, and organizations to promote funding for sustained observations at national, European, and international level. The establishment of the Arctic Science Funders Forum is a step in this direction

There are several **technological challenges** in the data delivery chain from the in situ observing system to the delivery of data to a stakeholder. Resolving these are essential for improving in situ observing systems capacities and capabilities. The critical factors are access to logistics, robust and adequate observing technology (e.g., sensors, platforms), improved data telemetry (e.g., underwater and satellite communication), and services from interoperable data systems.

The data delivery chains from in situ observing systems must be operationalised. This requires collaboration between experts from research communities, service, and technology providers.

Operational systems e.g., ESFRI have a more mature **data delivery chain** than research driven observing systems. To improve the maturity of the latter, ample resources must be targeted to streamline processing, quality control, formatting of data and metadata. This will reduce the time it takes before the data are ingested into data systems and made available for users. Interoperable data systems will use international standards to ensure compliance with the FAIR principles and proper traceability of the data. Like wise data systems must adhere to the CARE principles for data ownership and use rights for **community-based monitoring and citizen science programs.**

Mediators between researchers, technology providers, data managers and end users are needed to develop streamlined data delivery chains.

In situ observations cannot be delivered on a regular grid, but they provide the most accurate measurements of key environmental parameters. **Digital methods,** including numerical models and geostatistical methods, can be used to fill the spatial gaps. Observing System Simulation Experiments (OSSEs) can contribute to design of a baseline observing system in support to specific needs. However, it is important that the design analysis is based on validated model systems. The future observing systems must build on existing observing capacity and be able to incorporate new observing capabilities. This must be considered in the design of the future observing systems along with research priorities and cost-benefit analysis for various social-benefit areas for the Arctic. **Stakeholders** with different requirements should be involved in the design and implementation of the in situ observing systems. Furthermore, scientists, local communities and governmental agencies should collaborate to develop CBM and citizen science programs addressing community data needs as well as national and international research priorities.

Observing systems must be adapted to evolving priorities, requirements, and technological developments. This requires regular dialogue between Indigenous and local communities, stakeholders in private and public sector, researchers, and service providers.

Continued development of arctic observing capacity and capability depends on **transferring knowledge and expertise** between generations, disciplines, and communities. This can be achieved through educational programs, training events, and Open Science activities, where documentation of methods, tools, and procedures are key elements. These activities must become integral parts of research and community-based projects.

It is important to provide competence building in relevant observing methods, technology, and procedures across generation, gender, and generations.

The geopolitical situation in the Arctic is changing and can have dramatic impact on research and all other activities where people are present in the Arctic. At present it is assumed that research and implementation of observing systems will go on, but with restriction on what can be done in different parts of the Arctic

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