Integrated Arctic Observation System

Research and Innovation Action under EC Horizon2020
Grant Agreement no. 727890

Project coordinator:
Nansen Environmental and Remote Sensing Center, Norway

Deliverable D1.11

Final synthesis report

Start date of project:	01 December 2016	Duration:	63 months
Due date of deliverable:	28 February 2022	Actual submission date:	24.04.2022
		Resubmission after review:	29.08.2022
Lead beneficiary for preparing the deliverable:		NERSC	
Person-months used to produce deliverable:		na	

Authors: S. Sandven, H. Sagen, R. Pirazzini, A. Beszczynska-Möller, F. Danielsen, P. Gonçalves, G. Ottersen, D. Zona, E. Buch, D. Gustavson, P. Voss, L. Iversen, T. Hamre, M. Sejr, R. Higgins

Report No: 417, NERSC Technical Report Series
https://doi.org/10.5281/zenodo.7033824

.

Version	DATE	CHANGE RECORDS	LEAD AUTHOR
1.0	01/03/2022	First version	S.S
1.1	22/04/2022	Final version	S.S.
1.1	22/04/2022	Reviewed	TH, HS
2.0	29/08/2022	Revision after comments by external reviewers	SS, HS, TH

Approval	Date: 29.08. 2022	Sign. Stein Sandven

USED PERSON-MONTHS FOR THIS DELIVERABLE					
No	***Beneficiary***	***PM***	***No***	***Beneficiary***	***PM***
1	NERSC	*1*	**24**	Terradue	*X*
2	UiB		**25**	GINR	
3	IMR	*X*	**26**	UNEXE	
4	MISU		**27**	NIVA	
5	AWI		**28**	CNRS	
6	IOPAN	*X*	**29**	U Helsinki	
7	DTU		**30**	GFZ	
8	AU	*X*	**31**	ARMINE	
9	GEUS	*X*	**32**	IGPAN	
10	FMI	*X*	**33**	U SLASKI	
11	UNIS		**34**	BSC	
12	NORDECO	*X*	**35**	DNV GL	
13	SMHI	*X*	**36**	RIHMI-WDC	
14	USFD	*X*	**37**	NIERSC	
15	NUIM		**38**	WHOI	
16	IFREMER		**39**	SIO	
17	MPG		**40**	UAF	
18	EUROGOOS	*X*	**41**	U Laval	
19	EUROCEAN	*X*	**42**	ONC	
20	UPM		**43**	NMEFC	
21	UB		**44**	RADI	
22	UHAM		**45**	KOPRI	
23	NORUT		**46**	NIPR	
			47	PRIC	

DISSEMINATION LEVEL		
PU	Public, fully open	X
CO	Confidential, restricted under conditions set out in Model Grant Agreement	
CI	Classified, information as referred to in Commission Decision 2001/844/EC	

EXECUTIVE SUMMARY

The overall results of INTAROS are summarized for each WP as follows:

WP1 The requirements for integrated Arctic Observing Systems" Existing requirement documents have been reviewed and consolidated. Links have been established with various stakeholders, rightholders and user groups including international bodies, public administration, private sector, Indigenous and local communities, and science communities. Collaboration has been developed with several other projects, programmes and institutions working with Arctic observing systems in Europe, North America and Asia. A data management plan and data governance framework for Arctic data has been developed and a Roadmap for future sustainable Arctic Observing System has been prepared.

WP2 Exploitation of existing observing systems. The term "observing system" was defined as an observing asset consisting of a data collection component (physical infrastructure) and a data management component (e-infrastructure). An observing system can be multidisciplinary or focused on a specific discipline, and it serves a clearly identified scientific or operational purpose. A survey was conducted among the partners providing information about 50 in situ observing systems ranging from large pan-Arctic programs such as International Arctic Buoy Programme to local observations at a single station. A part of the survey was to assess characteristics of the systems (e.g. documentation, data management, uncertainty handling, sustainability) using a maturity score from 1 to 6. Systems with highest maturity were those with sustainable funding for the whole data production and data management chain. The online survey system was further developed in a spin-off project, resulting in the ARCMAP system, which will be operated as a service after INTAROS. Many of the assessed observing systems, including satellite data products, were used to build the INTAROS data catalogue (WP5) and in case studies demonstrating integrated use of observing systems and modelling systems (WP6).

WP3: Enhancement of multidisciplinary in situ observing systems. The work has focused on developing and implementing new solutions and novel technologies to fill selected gaps identified in the existing Arctic observing systems. Novel instruments and sampling methods were integrated with mature components of existing observatories to increase temporal and geographic coverage of in situ observational data in the Arctic and to include missing key parameters. New clusters of sensors have been integrated into a variety of platforms, and several experimental setups have been tested and implemented. The field work was conducted in different marine and terrestrial regions to collect important data to understand ongoing climate and environmental changes and their consequences for the Arctic. The field implementation of new ocean and sea ice observations was supported by use of icebreakers, research vessels, ships of opportunity, ocean column and seafloor observatories provided by collaborating national projects. The data collection from ice sheets, glaciers and terrestrial stations was based on existing reference sites and other research sites in the Pan-Arctic region. New collected measurements have been processed and formatted to provide standardized data sets ready for integration into existing data repositories and registered in the INTAROS data catalogue. Metadata and data formats for observations made with multidisciplinary platforms have been developed in collaboration with WP1, WP2, and WP5. Selected data sets have been exploited in demonstration actions (WP6) and in consultations with stakeholders in (WP7).

WP4: Community-based monitoring (CBM) programs have been strengthened. The project co-organized 40 workshops which brought practitioners of CBM together and enabled them to share and discuss their experiences. Six hundred people attended the workshops inc. representatives from 5 Arctic Indigenous Peoples. Existing Arctic CBM programs have been analysed and capabilities, "good" practice

and challenges have been identified. A website has been set up with tools to cross-fertilize local knowledge with scientific knowledge. New and expanded existing CBM programs have been initiated in Svalbard, Greenland, Yakutia and Kola Peninsula, to inform decision-making and action. Datasets derived from the programs have been registered in the INTAROS data catalogue. Lessons from CBM were made broadly available through a large number of physical and online events, policy briefs, proceedings, scientific reports and articles.

WP5. Data integration and management. Work has focused on deploying and demonstrating a cloud platform with geo-statistical tools for services as part of the integrated Arctic Observation System (iAOS). The objectives were to demonstrate integration of data and provide tools for data analysis, transformation, and visualization, in the cloud platform. Selected applications in WP6 have been used as showcases for the services and tools provided by this cloud platform. In addition, work has concentrated on improving data integration from existing repositories, along with metadata, so that it is findable and exploitable by iAOS applications. Extensive efforts have been devoted to streamline the data flow between data producers, data managers and data users. A major outcome of the project is the iAOS Portal and the INTAROS Data Catalogue, providing access to multidisciplinary data from a wide range of data repositories containing Arctic data. The portal and catalogue will be maintained and used for promotion of data and services in other projects after INTAROS.

WP6. Applications towards stakeholders. Work has focused on studies of how data from various observing systems can be used to develop useful results to the benefit for different stakeholders on local, regional or pan-Arctic scale. The results demonstrate how the Arctic observing system can be applied to further develop the accuracy of climate models, improve the understanding of biogeochemical cycles and ecosystem functioning, enhance fisheries and environmental management, increase the level of preparedness towards natural hazards, and develop better management and decision-making for selected local communities. The following topics are addressed: (1) Improving skill of climate models in the Arctic, with examples from sea ice prediction and hydrological forecasting; (2) Applying observations and models for environmental and fisheries management, with case studies in the Barents Sea and west Greenland; (3) Ice-ocean statistics using examples from Observing System Simulation Experiments (OSSE), preparation of a 10 year reanalysis, development of a risk assessment system, studies of ocean sound, oceanographic and sea ice time series, sea level studies from altimeter and tide gauge data, sea ice data from ice mass balance buoys, sea ice remote sensing applications; (4) natural hazards, (5) greenhouse gas studies, (6) enhancing community-based observing systems in Greenland and Svalbard, and (7) summary of ocean observing benefit for blue growth in the Arctic.

WP7. Communication and outreach. Work has been focused on planning and conducting various communication activities to inform projects, programmes, user, rightsholder and stakeholder groups, agencies, and policy makers about INTAROS. The consortium members have promoted the project and its objectives through several hundred meetings, workshops, conferences, publications, and other dissemination activities. Much of this communication and dissemination work has been done in collaboration with WP1 and WP4. Various online tools were employed to maximize the visibility and communicate the project activities including: a public project website, Twitter and other social media, videos on YouTube, blogs, printed materials (brochures, factsheets, posters, policy briefs, photos), project identity toolkit (graphical image, logos, lettering, templates, and branded materials). Furthermore, several training and education activities have been organized, focused at early career scientists and students, public resource managers, and Indigenous community members.

Project websites: http://intaros.eu, http://intaros.nersc.no

Table of Contents

Introduction

The Arctic is undergoing the most rapid changes in the climate system worldwide. This is clearly demonstrated by the thinning and reduction of sea ice, the melting of ice sheets and glaciers, thawing permafrost, and the potential for more extreme weather events. The warming leads to improved access to the Arctic and its resources, offering new opportunities for communities and for economic development related to exploration of natural resources, transport, and other industries. This presents extraordinary requirements for planning and decision-making based on scientific and economic assessments and predictions. To meet these challenges, we need improved systems to enable better-informed decisions and better-documented processes within key sectors (e.g. local communities, shipping, tourism, fishing), in order to strengthen the societal and economic role of the Arctic region.

The EU's strategies for the Arctic emphasize the need to implement monitoring programmes to underpin sustainable development in the region. To build and sustain an integrated system of many discipline-specific observing systems requires agreement among the major players from Europe, North America and Asia who can contribute to this system. Many countries related to the Arctic have invested in infrastructure and logistical services to support various observing systems with a long-term perspective, which is an important condition for sustainable observing programmes.

On this background the INTAROS project has made a significant contribution to develop an integrated Arctic Observation System serving different user groups such as climate and environmental research, management of fishery resources, national and European agencies, local communities, Arctic shipping and tourism. The results from INTAROS have been obtained in collaboration with many other projects, programmes and institutions developing observing systems in different regions of the Arctic. INTAROS has focused primarily on strengthening the in situ component of the observing systems, with case studies demonstrating the importance of integrating in situ observations with satellite remote sensing and modelling. The results are obtained in the following categories:

- Extensive field work with collection of atmospheric, ocean and terrestrial data
- Development and improvement of observing sensors and platforms
- Provision of data in support to long-term observing programmes and for operational services
- Strengthening and promotion of community-based monitoring and citizen science
- Demonstrating use of data in various application studies towards stakeholders
- Established and maintain a common data catalogue for all data from the project
- Improved data services and access to data repositories
- Conducted a number of education and outreach activities
- Strengthening international collaboration with partners in North America and Asia

The report gives a synthesis of the results obtained in the workpackages of the project:

WP1: Requirements and strategy for Pan-Arctic Observing systems
WP2: Exploitation of existing observing systems
WP3: Enhancement of multidisciplinary in situ observing systems
WP4: Community-based observing programmes
WP5: Data integration and management
WP6: Applications towards stakeholders
WP7: Dissemination and outreach

The detailed results of these seven WPs are reported in 97 deliverables, which are listed in Appendix and are available at https://intaros.nersc.no/list-of-open-deliverables

1. WP1: Requirements and strategy for Pan-Arctic Observation systems

The main objectives of WP1 have been to (1) Review and consolidate the high-level requirements for integrated Arctic Observation Systems, (2) Establish and maintain links to various stakeholders, rightholders and user groups including international bodies, public administration, private sector, shipping, Indigenous and local communities and science communities, (3) Establish collaboration with other projects, programmes and institutions working with Arctic observation systems in Europe, North America and Asia, (4) Prepare data management plan and data governance framework for Arctic data, and (5) Develop a Roadmap for future sustainable Arctic Observation Systems. In this document Arctic observing system is the infrastructure used to collect data that is delivered together with meta data to a data system for storage and for dissemination. An integrated observation system is about the observing system together with the data system.

1.1 Requirements for integrated Arctic Observation Systems

An Arctic observing strategy needs to build on a set of objectives connected to the scientific disciplines and services which are important both on global, regional, and local scale. The strategy should support the societal benefit areas of the Arctic and be developed in close interactions with the stakeholder groups. The societal benefit areas for Arctic observing have been defined by SAON (Fig. 1.1), showing that a broad range of human activities depend on observation systems. The objectives for a sustained observing system are formulated through a set of relevant phenomena and essential variables for climate, ocean, atmosphere, and other scientific disciplines. The various phenomena require observations on certain time and space scales. Furthermore, they identify which essential variables to be observed and suggest methods for observations.

Societal Benefits Area
1. Disaster Preparedness
2. Environmental Quality
3. Food Security
4. Fundamental Understanding of Arctic Systems
5. Human Health
6. Infrastructure and Operations
7. Marine and Coastal Ecosystems and Processes
8. Natural Resource
9. Resilient Communities
10. Sociocultural Services
11. Terrestrial and Freshwater Ecosystems and Processes
12. Weather and Climate

Figure 1.1 *List of Societal Benefit Areas developed by SAON*

The high-level requirements of an integrated Arctic Observation System (iAOS) have been reviewed based on identification of the major societal drivers of such an observing system. The requirements are expressed through international policy documents, conventions, treaties, and other agreements (i.e. climate, environment, biodiversity, sustaining ecosystem services, improving the livelihoods of Indigenous and local communities, support to maritime safety, etc.). These requirements have been analysed on a practical level, describing spatiotemporal resolution, timeliness and quality of observations and the applicable technologies.

Based on requirements from global scale programmes such as EU Copernicus Programme, WMO and IOC a set of concrete requirements for in situ observations in the Arctic have been formulated. The requirements to time resolution, quality, and timeliness, is similar in the Arctic as on global scale while the definition of spatial resolution for in situ data raises two questions:

- What is the balance between what is "nice to have" and what is "feasible to do" because of technical, logistical, and economical constraints

- How should spatial coverage and resolution be solved? Two approaches are most common: (i) Use of gridded format with fixed horizontal and vertical distances between observation points. This is the standard method for satellite remote sensing and 3D modelling, but not for in situ observations. (ii) In situ observing points are spread irregularly and with large gaps. Model simulations can be used to find optimal locations where the data can have significant impact and representativeness in their model systems. Other specific needs for observations in an area might be introduced by other stakeholders in private and public sectors.

Gaps in the observing systems and assessment of the existing systems are discussed in WP2. The location of in situ observing sites is a key issue in the implementation of an Arctic Observation System, because it involves logistical, technical, financial, and political issues.

1.2 Stakeholder interaction

An integrated Arctic Observation System will provide essential data and knowledge of Arctic environmental processes to underpin a knowledge-driven society that can advance the Arctic economy whilst ensuring environmental sustainability. Successful delivery of products for societal benefit critically depends on interactions between many centres of competence operating across the boundaries between knowledge, society, and policy. Societal requirements for timely and adaptive policy responses are important for e.g., climate mitigation and adaptation and ecosystem health. The information to support these policy responses is provided through two channels (1) Scientific advisory and assessment and (2) Operational services delivery. Both channels rely on sustained in situ observations delivering data in line with essential variables (e.g., Essential Climate Variables, Essential Ocean Variables).

An integrated Arctic Observation System must be capable of providing physical, biogeochemical, and biological state and evolution as basis for research, services and informed decision making. The observing systems need to adapt to evolving user needs, technological advances, and funding mechanisms. Technological improvements in observing capabilities are important for making new measurements feasible and interoperable data systems are crucial for the data accessibility.
The development and implementation of sustained observing systems must be done through a consultation process with the user groups and stakeholder groups. During INTAROS consultations have been done through

- Three stakeholder meetings (WP1)
- Events and dialogue with Indigenous Peoples and local communities (WP4)
- Several one-to-one meetings, workshops, or larger events with dedicated stakeholders (WP6)

More than 350 dissemination and outreach events have been performed to promote INTAROS results towards international and national agencies, organisations and programmes as well as towards schools and the public. (All WPs).

- Private sector
  - Transport
  - Tourism
  - Fishery
  - Energy – oil, wind
  - Instrument producers
  - Service providers
- Public administration and decision making
  - Environment – EEA, AMAP
  - Climate change
  - Fishery – ICES
  - Natural hazards
  - Met. Services
  - Ice services
- Search and rescue
- Science community
  - Copernicus services
  - ESA and EUMETSAT
  - EU Polar Expert Group
  - EU polar cluster projects
  - Research Infrastructures
  - Selected universities
- Indigenous people organisations
- International bodies
  - WMO, IOC/GOOS + ocean Decade, GEO, GCOS, GCW,

Figure 1.2 *User groups*

In the first period of the project the stakeholder consultation was devoted to a dialog with the scientific community regarding a common understanding on which phenomena, essential variables and observing requirements a future Arctic Observing System should address. Later in the project efforts were focused on a wider group of users, in particular the private sector such as transport, energy, tourism, fishery, insurance, and the coast guard regarding safety of ships in the Arctic (Fig. 1.2). Before starting to work in the Arctic, the companies need for basic information on the physical environment that can support decisions on the feasibility of the engagement considering security, investments, operational cost, educations etc. key products to be used in this phase are:

- Statistics and analysis based on existing data or start new and tailored observing programs
- Projections on the long-term (years) development produced by a validated model systems
- Risk assessment associated with safe navigation, deployment and recovery of equipment, seabed mining, hydrocarbon extraction etc.

For companies who already are active in the Arctic the requirements include (1) operational Services – real-time observations and/or short-term forecasts, (2) ship routing services, and (3) risk assessment

Indigenous People and local communities represent important user group because their daily life depends directly on nature and the environment. They specifically require information on:

- Long-term trends in changes of the environment that will influence their living conditions. This can be used for planning of development of their society.
- Dedicated operational products that can help them performing their daily occupation, fishery, hunting, reindeer breading, etc.

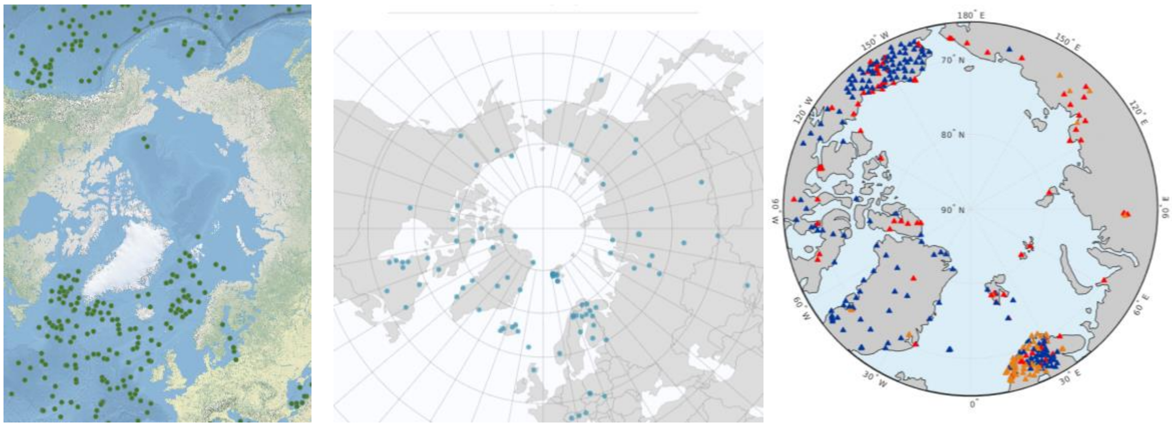
The local communities/Indigenous People have built up a detailed knowledge of and experience with the Arctic environment over many years, which is complementary to scientific data. Cooperation with Indigenous Peoples is therefore an important component in the planning and design of a future sustained Arctic Observing System partly to draw on their knowledge and experience, partly to involve them actively in observing activities. Community-based observations and citizen science are addressed in WP4.

During the COVID 19 pandemic period the possibilities to meet stakeholders were significantly reduced. Alternative methods using video conferences and online questionnaires were used, but this is not very effective in establishing new contacts. The best way to communicate with stakeholder is via in person meetings, preferably in smaller groups of the same type of stakeholders.

1.3 Establish collaboration with other projects and programmes in the Arctic

The development of collaboration with other projects, programmes and institutions working with Arctic observing has been a continuous process during the project. The collaboration included the EU Polarnet and other H2020 projects within the Polar Cluster regarding joint sessions at conferences, promotion material, and policy briefs. In Europe, collaboration was established with the Copernicus programme and research infrastructure programmes with activities in the Arctic. European research infrastructures of importance for the Arctic include ACTRIS, EuroARGO, ICOS, EPOS and the INTERACT network of stations (Fig. 1.3). In addition, the Svalbard Integrated Arctic Earth Observing System (SIOS) has been established as a regional observing system providing long-term measurements and data management in the Svalbard area. These programmes have long-term funding perspectives and support on research, but their support to Arctic Observing depends on the priorities of the national funding agencies and ministries. Through Copernicus services and Polar programmes under the Space Agencies, the production and delivery of satellite data for Arctic observing is growing strongly. Partners in INTAROS are well-connected to these programmes and have exploited satellite data in several Arctic studies reported in other WPs.

Collaboration with other projects and programmes regarding field work has been important on national level as well as with institutions in Europe, North America, and Asia. INTAROS partners participated in and contributed to the MOSAIC expedition, which was a major international field experiment lasting for more than a year from 2019-2020. Communication, dissemination, and outreach activities have been performed in collaboration with SAON, Arctic Science Summit Week, Arctic Observing Summit, and EGU sessions. INTAROS has also given presentations at conferences and workshops in USA, Canada, Russia, China, Japan and South Korea. As a result, the project has established collaboration with the main Arctic institutions in these countries. Several MOUs have been signed to ensure that collaboration will have long-term perspective. Such collaboration is required to build a sustained integrated Arctic Observation System covering the pan-Arctic region. Furthermore, several spin-off projects have been established to follow up activities that were initiated in INTAROS.



a b c

Figure 1.3 *Network of in situ observations in the Arctic. (a) Argo floats with almost no coverage in the Arctic Ocean; (b) INTERACT network of 89 terrestrial field stations, and (c) Seismic stations in the Arctic, red: no data are transmitted, orange: data are restricted, blue: data are transmitted.*

INTAROS has made great progress to develop collaboration with Arctic shipping operators, in particular the Norwegian Coast Guard icebreaker KV Svalbard and tourist companies offering expeditions in the Arctic. There are more and more vessels sailing in Arctic waters, ranging from schooners to expedition vessels and large icebreakers. These vessels provide opportunities to collect data and thereby contribute to the observing network. Citizen science projects are developing worldwide where data collected from tourist ships can contribute to the scientific data collection. In the Arctic, the possibility to develop citizen and community-based observations in collaboration with ship operators will be further developed in new projects.

INTAROS partners have been active in OceanObs'19, which is major decadal event involving the ocean observing community ranging from scientists to end users to lay out plans for the next decade. INTAROS partners are also involved in the preparation of the Arctic Action Plan under the UN Decade for Ocean Science for Sustainable Development (https://www.oceandecade.dk/decade-actions/arctic-process).

1.4 Data management plan and governance framework

The Data Management Plan describes how new datasets collected or generated by partners in the project, are managed according to guidelines for FAIR data management in Horizon 2020. This includes the procedures for planning and conducting data management within the project, i.e., the data governance framework. Data governance in INTAROS is pragmatic and geared towards supporting partners in preparing and publishing their data collections. Close collaboration between data managers and data providers has been key to implementing sound data management in the project.

INTAROS is pan-Arctic in scope and collects *in situ* observations, extract parameters from satellite data and model projections in several regions and across multiple spheres (themes). The focus areas of INTAROS include Coastal Greenland, Fram Strait, North of Svalbard, the Eurasian Basin, and selected sites in Siberia, Finland, Canada and Alaska. Within these areas, INTAROS partners are collecting new observations and generating high-level data products from different spheres: (1) Atmosphere, (2) Ocean, (3) Sea ice, (4) Marine ecosystems, (5) Terrestrial, (6) Glaciology, (7) Natural hazards, (8) Community-based monitoring.

Datasets collected or generated within these spheres are published in open repositories that ensure long-term storage and access of the data. The published datasets have been registered in the INTAROS Data Catalogue, available at https://catalog-intaros.nersc.no/. This data catalogue is updated as new datasets are prepared.and The catalogue will be maintained by NERSC after the INTAROS project ends. This will enable INTAROS partners to update their dataset descriptions, e.g by adding a DOI or a direct data download link when their datasets are published. The data catalogue can also be used in new projects.

The Data Management Plan recommends metadata and data standards that INTAROS partners should use to prepare their datasets, to make it easier for other scientists and stakeholders to reuse the data. There are no community standards for ocean mooring data. Thus, data managers from WP1 and WP5 joined forces with ocean scientists from WP3 and WP6 (e.g. acoustics) to define a structure and format of metadata and data for this kind of data, based on widely accepted standards such as CF, ACDD, CMEMS and OceanSITES. Templates were defined for time series of point measurements (e.g., from CTD sensors) and time series of profiles (e.g. from ADCP sensors). These templates were used by partners within INTAROS to publish their ocean mooring data in a standard compliant format. The first set of templates were published in the Data Management Plan and will be made available through the iAOS portal together with the second set of templates. For data access, repositories that support the OPeNDAP standard protocol is recommended to facilitate data extraction from distributed sources, selection of subsets of large datasets and accessing data as a stream.

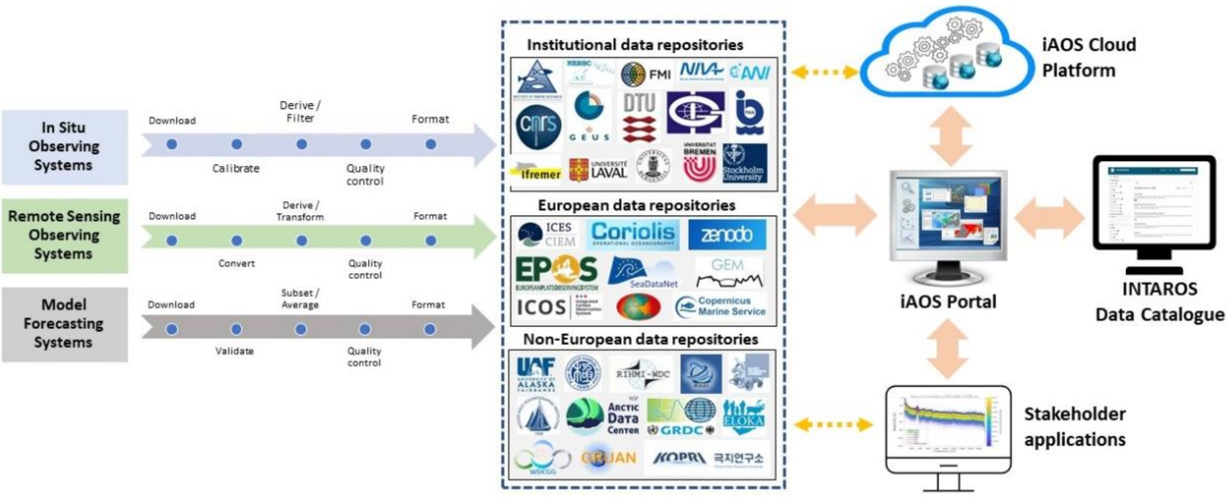


Figure 1.4 *Data value chains for integrating INTAROS data sets into various applications*

1.5 Roadmap for a future sustainable Arctic Observation System

A Roadmap document has been prepared describing the main components of developing a sustainable Arctic Observation System addressing the whole data delivery chain (Fig. 1.4). Such system consists of many subsystems serving different purposes ranging from global climate research to operational weather and ice forecasting, resource management, support to commercial activities, and services for local communities. This implies that there are many stakeholders with different requirements to what an observing system should provide, regarding type of data, sampling in space and time, data delivery chain and responsible organization. The sustainability of each subsystem varies, depending on the funding mechanism. Most of the observing systems are driven by scientists working under research strategies and programmes, providing short term funding. Another important part are the operational observing systems for weather, hydrology, earthquake, and other public services. These are operated by national and international agencies, resulting in more sustainable funding of the observing systems compared to the research-funded systems. In addition to scientific and operational observing systems, there are Community-Based Monitoring (CBM) and citizen science observing systems where data are collected by local communities or visiting cruise guides and guests. The CBM and citizen science observing systems in the Arctic generally lack sustainable funding and depend on volunteer efforts.

Satellite-based remote sensing has become the major observing system in the Arctic due to the Sentinel satellites and other earth observation programmes. The in-situ component of the observing system is poorly developed in the Arctic, but it is required for collecting a variety of data that cannot be obtained from satellites. The in-situ systems are built on many observing sensors and platforms. For land-based observations, several instruments and sensor are operated from stations around the Arctic. For ocean-based observations, there is a difference between ice-free and ice-covered areas. In open ocean, ships, Argo floats, drifters, gliders, moorings, and various surface platforms are commonly used, but in the ice-covered areas it is required to use icebreakers which can deploy ice-based platforms and underwater moorings. Argo floats and gliders are not yet operationally used in the ice-covered regions of the Arctic due to lack of underwater geo-positioning. Common for all the in situ observing systems are the logistical and technological challenges of deploying and operating the systems in the Arctic.

The Roadmap document (D1.10) points out the requirements that need to be fulfilled to have a sustainable in situ observing systems in the Arctic. These include:

- Access to the Arctic: infrastructure, transport, logistical services must exist to enable personnel to deploy and operate the observing systems in the areas
- Observing platforms, instruments and sensors for data collection need to be designed and built to operate autonomously over long time in a harsh environment
- The full data delivery chain, including observing system, processing, dissemination, and management of the data must be standardized and documented to ensure that high quality data are available for the users
- Interoperability of the data systems must be improved to establish an integrated Arctic Observation System.
- Collaboration between countries and institutions should be improved to make best possible use of resources, personnel, and secure continuity of the system
- Funding mechanisms to support both development and operation of the observing systems should be established

1.6 Expected impact, challenges and recommendations

On requirements and gaps, INTAROS has created a better understanding of the barriers to building and maintaining the in-situ components of the observing systems. The barriers are of technological, logistical, geopolitical, and financial character, which need to be identified and resolved.

Space agencies have responsibilities for the overall planning, implementation, and operation of large satellite observations programmes with funding committed at governmental level in the participating countries. This is in strong contrast to the in-situ observing systems which depends on national research programmes and priorities. Even European research infrastructures are to large extent dependent on time limited national funding from research programmes. The countries have own responsibilities and priorities within their territorial areas, and the requirements to observations are very heterogeneous, because there are many user groups who need different data. The in-situ observing systems and their data systems are therefore less coordinated and very often not sustainably funded.

A major impact from INTAROS is the enhanced collaboration between countries within Europe and with countries in North America and Asia regarding Arctic field experiments, data collection, and data management. Such collaboration is essential for consolidating the requirements and making agreements on developing Arctic observation systems. Identified gaps such as missing observations, lack of free data exchange, sustainability and technology are challenges that must be addressed separately and collectively in the planning of a future Arctic Observation System. Especially the lack of observations from the central Arctic is a matter of great concern.

Recommendations regarding requirement and stakeholder interaction are the following:

- Since a regular grid of in situ observations is not feasible to operate in the Arctic, other methods to enhance the spatial coverage should be used. These include cost-benefit analysis for various social-benefit areas, local to global scale scientific priorities, and targeted numerical simulations (Observing System Simulation Experiments).
- International coordination and governance structure are developing under several organizations including WMO, IOC, EU Copernicus, SAON, and Indigenous people organizations. However, there is a gap between the wish to coordinate and the reality. This is because the actual funding of in situ observing systems is dependent on each country priorities and needs. Funding of establishment and operation of the in situ observing systems should be strengthened from national as well as European funding sources. .
- Maintain dialogue between stakeholders and data providers to understand the technological development of observing system and how this leads to changes in observing capabilities, capacity, and thereby requirements
- Support and fund data providers and data managers to deliver open data exchange following the FAIR principle
- Support capacity building, teaching and training within the full data delivery chain in Arctic observing including new observing technologies, data formatting and standards, methods and tools in data processing and analysis including new digital technologies (e.g., machine learning)

2. WP2: Exploitation of existing observing systems

There is limited effort to coordinate physical, chemical, biological, and ecological observations from in-situ and remote sensing platforms in the Arctic, except in frameworks of specific projects and for limited regions. Observations are usually organized discipline by discipline and stored in scattered data repositories, many of which have limited capability for search and access to data. The objective of WP2 was to assess, exploit, and standardize observations from the existing Arctic observing systems. The first step was to identify strengths and gaps in the current set of observing systems. This assessment should serve as background for preparing the multidisciplinary, integrated Arctic Observation System (iAOS), which is further described in WP5.

2.1 Assessment of existing observing systems

Several existing in-situ observing systems and satellite products were analysed, primarily those provided by the INTAROS partners. The analysis addressed observation systems for ocean, atmosphere, cryosphere and land including physical, chemical, biogeochemical and biological parameters.

2.1.1 Definition of in-situ observing system

Although the term "observing system" has been widely used by WMO referring to the "WMO Global Integrated Observing system" (WIGOS), there was no clear definition of "observing system" or of its components at the start of the project. To proceed with a systematic and consistent analysis across different atmosphere, ocean, and terrestrial disciplines it was necessary to formulate a clear and workable definition of the targeted in-situ observing systems. **We defined an "in-situ observation system" as an integrated asset that consists of a data collection component (observing system - infrastructure) and a data management component (e-infrastructure)**:

- The data collection component is comprised of multiple sensors belonging to common fixed or mobile platforms, which can be a single unit or part of a network. It stores the datasets internally or transmits them to the data management component.
- The data management component includes hardware and software for data repository, processing, discovery, and visualization services. It can be centralized or distributed among several institutions, with common standards for data and metadata formats, documentation, and management.

An observing system can be multidisciplinary or focused on a specific discipline, and it serves a clearly identified scientific or operational purpose. With this definition it was possible to collect coherent and consistent information from a large variety of observing systems with different technical solutions, maturity, and organization. Data from field experiments at land stations, ships, ocean and ice platforms, aircraft and satellites were included in the analysis.

Arctic in-situ observing systems also include Community-Based Monitoring (CBM) and citizen science observing systems. Some of these observing systems are established by local communities in bottom-up processes, while other are established by research institutes or non-governmental organisations. CBM and citizen science observations consist of environmental and climate data as well as socio-economic data, frequently obtained on local scale, and they are often collected and disseminated because they are important for the livelihood of the local communities. CBM and citizen science data represent valuable information that complement scientific data. These data are presently not integrated in the data systems for scientific and operational data, but efforts were done in WP4 to register a number of CBM and citizen science systems in the INTAROS data catalogue.

2.1.2 Definition of requirements for the assessment of in-situ observing systems

In the assessment of Arctic observing systems, it is important to take into account that different systems serve different purposes with different requirements. For large-scale operational systems such as weather and climate services organised under WMO or Copernicus there are specified requirements for the observed variables in terms of uncertainty, horizontal resolution, vertical resolution, observing cycle and timeliness. These requirements apply to key, global variables observed from in situ and satellite platforms, and mainly reflect the needs of models that require gridded input on global scale.

However, the individual in situ Arctic observing systems serve several scientific programmes as well as operational services. Some of the in-situ systems are part of regional networks operate over longer time, while others are time-limited field campaigns. Requirements for spatial coverage and temporal duration of the observations can therefore be different for the science-based systems compared to the operational systems. It means that in situ observing systems most often provide data collection in points or in sections in a variety of time windows. The spatial coverage is determined by the location of the stations on land and the sailing route of the ships.

2.1.3 The survey

The information needed to assess the observing systems and their datasets was collected through an online survey divided into 3 questionnaires, addressing in-situ observing systems (Questionnaire A) and their individual datasets (Questionnaire B), and satellite products (Questionnaire C). The content of the survey built upon similar efforts to assess the maturity of climate data record (FP7 CORE-CLIMAX project), measurement series (H2020 GAIA-CLIM project), and data management of Polar observing systems (H2020 EU-PolarNet project). Figure 2.1 summarizes the various characteristics of the observing systems and datasets that were addressed in each questionnaire.

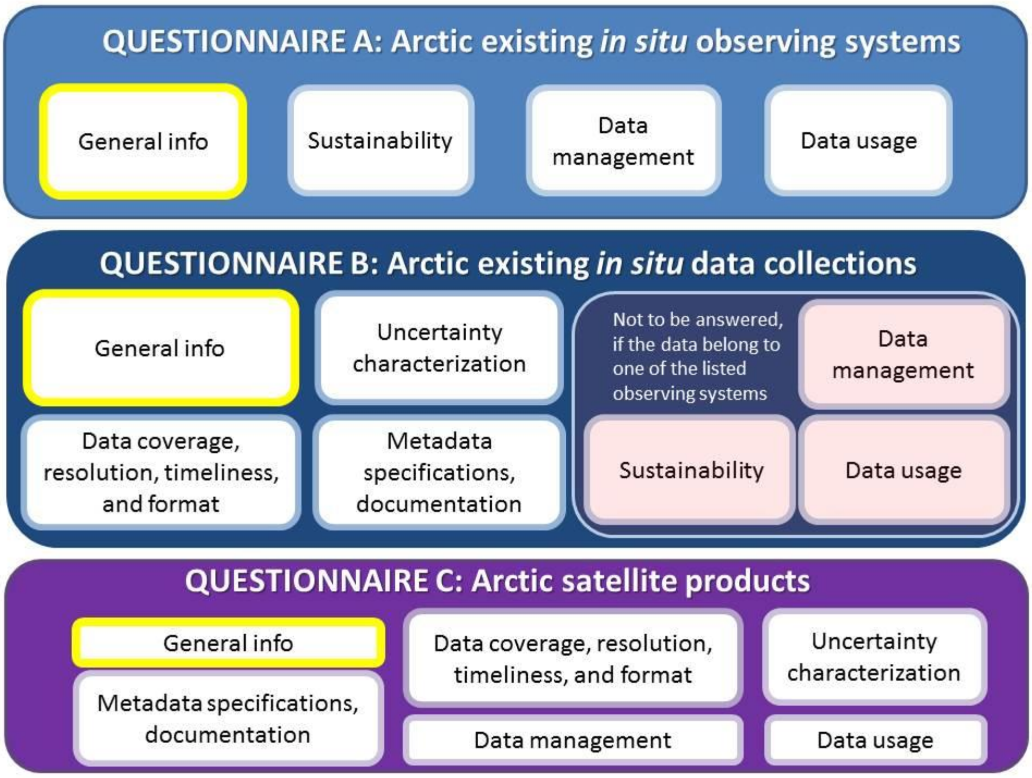


Figure 2.1 *Schematic illustration of the topics addressed in the questionnaires*

"General info" described the measured variables with temporal and spatial coverage. The set of questions were formulated to be applied on observing systems for atmosphere, ocean, land, and cryosphere, including physical, chemical, biological, ecological variables. The community-based monitoring systems are mostly addressing direct observations, for example how many whales of different species are observed in specific regions.

The information collected through the survey was important because (1) it gave an overview of the registered observing systems (what is measured, where and when, by whom, funding sources, etc.) and (2) it provided statistic for assessing each of the criteria: sustainability, uncertainty handling, data management, metadata handling and documentation. For each of the criteria a score between 1 and 6 was given as an estimate of the maturity of all the analysed observing system. Some examples of results are presented in section 2.1.5.

To enable online access to this information, updates to the answers, and ingestion of additional metadata, the online tool ARCMAP (https://arcmap.nersc.no) was created under a spinoff project funded by the Norwegian Directorate for Environment and Climate and NERSC. The ARCMAP tool is now operated as a service by NERSC, described also in WP5.

2.1.4 Model sensitivity studies

Three case studies were conducted using model experiments to assess the impacts of observational gaps:

Atmosphere: The analysis of model outputs indicated that forecasts made with the European Centre for Medium Range Weather Forecasts (ECMWF) Integrated Forecasting System (IFS) numerical model strongly improved when accurate soundings in areas without other data were assimilated, such as data from field campaigns in the central Arctic. On the other hand, in other regions with reasonably dense sounding network, the impact of sounding was limited by the data quality, as in the case of Siberia.

Ocean: Potential effects of satellite altimetry and mooring observing systems on monitoring Arctic changes was evaluated, using a suite of forward and adjoint model simulations. Satellite altimeter data combined with tide gauge and bottom pressure data provide sea level data which are crucial for ocean circulation studies. Moorings, available in very few locations, provide time-series and depth profiles of temperature, salinity and currents that are crucial for estimates of circulation, heat and freshwater fluxes. Results are described in WP 6.

Land: The spatial representativeness of the data coverage provided by a network of 29 pan-Arctic atmospheric monitoring sites was assessed. The sites provided continuous, well-calibrated observations on atmospheric greenhouse gas mixing ratios. The network representativeness analysis demonstrated that the current infrastructures provide a basic footprint coverage for most regions in Canada, Europe, and Western Russia, which extend also to most the Arctic Ocean. Only Russian Far East, Western Alaska, and the Eastern Canadian Provinces have significant gaps in spatial representativeness.

2.1.5 Gap analysis and maturity assessment of the Arctic observing system

The gap analysis and maturity assessment of the Arctic observing system included mostly in-situ systems, supplemented by selected satellite systems. The in-situ systems consisted of measurements from land stations, ships, ocean/sea ice platforms, surface-based remote sensing and data from aircraft and unmanned aerial vehicles (UAV). The detailed analysis of individual observing systems and data collection were followed by a cross-disciplinary synthesis of atmosphere, ocean, and terrestrial in-situ systems as well as the satellite systems. The application areas for the observing systems are presented in Fig. 2.2., which shows that climate research and monitoring is dominant: 52 % of the in-situ systems and 29 % of the satellite systems. It is expected that satellite observations will play an increasingly important role in Arctic observing systems because Sentinel and other satellite programmes provides huge amount of data every day. The Sentinel satellite under Copernicus deliver operational data which will be sustainable in the future.

For the in-situ observations there are different considerations for the terrestrial systems and the ocean systems. In the Arctic Ocean there is essentially no infrastructure for atmospheric in-situ observations, except for data provided by shipborne or airborne scientific expeditions. A network of ice buoys under the International Arctic Buoy Program delivers surface data but no vertical atmospheric profile data. Automated observing infrastructure, such as land stations, provide continuous measurements over time, but most often they collect data of a few variables and cover only a limited part of the Arctic areas. A few places in the Arctic have advance land stations with personnel operating many instruments and collects a wide range of measurements. Examples are the Sodankylä station in Finland and Ny-Ålesund in Svalbard. For ocean observations, there are time series of multi parameter data sets from instruments at fixed moorings and drifting ice tethered profilers providing observations of the ocean interior in ice covered regions the Arctic, whereas operational systems such as Argo floats and gliders are not yet applicable in ice-covered areas. During field campaigns with ships and aircrafts scientists can operate many instruments and therefore collect much more data (ice, ocean, and atmosphere), but only for a shorter period, usually in summer or early autumn when access to the Arctic is easier. An exception was the MOSAiC expedition which was extensive campaign lasting for more than one year.

Regarding Community-Based Monitoring (CBM) and citizen science in the Arctic, the maturity of 30 programs was analyzed, as described in WP4. The results showed that the CBM and citizen science observations usuallly lack stable funding and long-term strategies. On the other hand, CBM citizen science observations can provide data that are not possible to obtain through standard science projects (https://intaros.nersc.no/sites/intaros.nersc.no/files/NORDECO-EGU2020-22212_presentation.pdf). This suggests that CBM can help increase observational coverage in space and time with often low-cost approaches, while also adding value through the introduction of holistic perspectives - such as Indigenous knowledge-based - into the observing process.

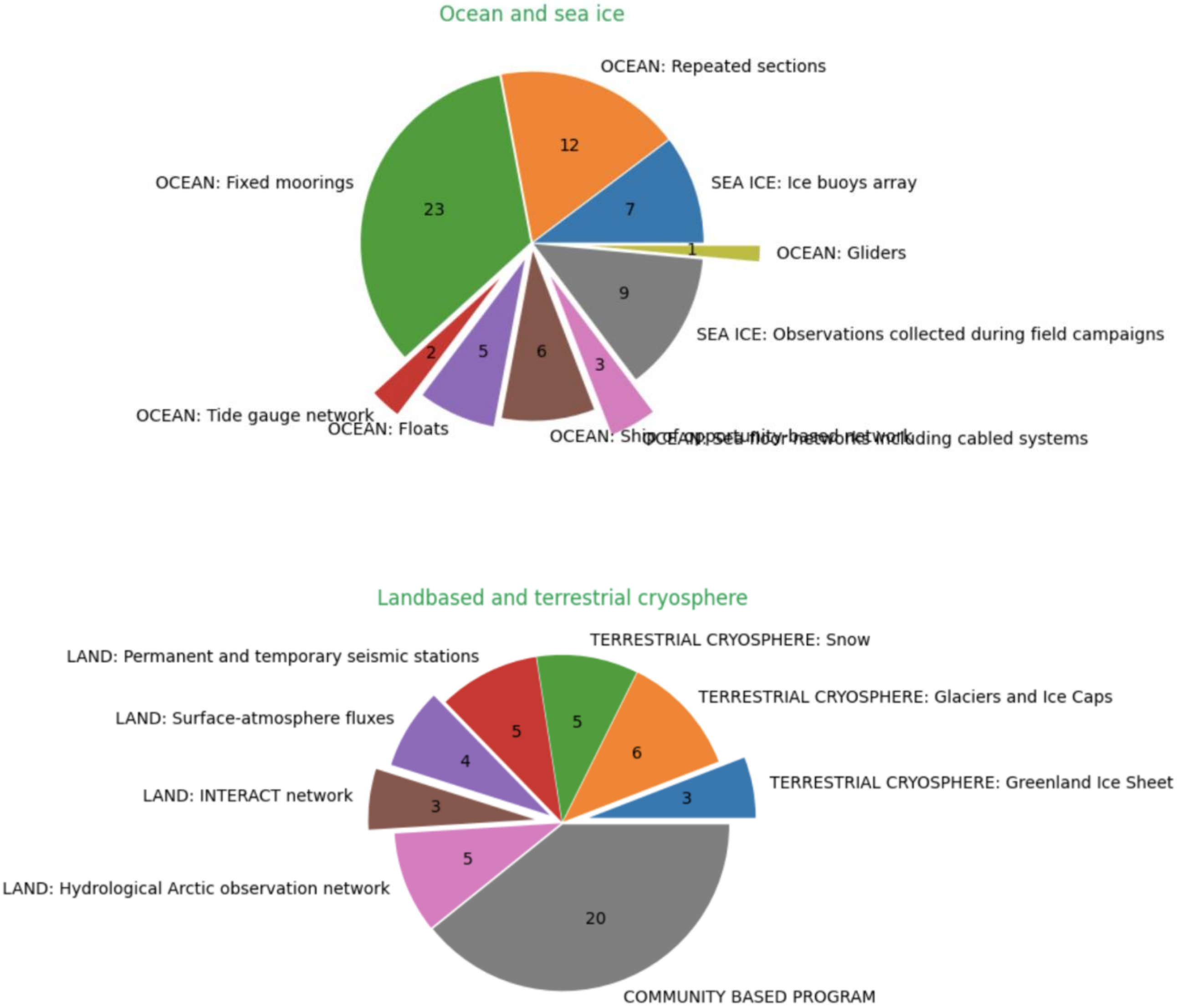


Figure 2.2 *Types of observing systems or networks – percentage distribution. Data from ARCMAP, March 2022*

The assessment of a number of scientist-executed monitoring programs show that sustainable funding all the way from the *infrastructure investment* to *data handling*, through *international agreement* and *national commitment*, is required for a well-functioning observing system. Sustained funding leads to high score on the other criteria which are uncertainty handling, data management, metadata handling and documentation. Examples of successful observing systems are European research infrastructures, such as ICOS and ACTRIS. These systems have well-defined requirements to observations, and they are operated on global or European scale. However, they are poorly represented in the Arctic. The observing system that are most important in the Arctic have lower maturity scores, but they deliver essential data for climate research, weather forecasting, fisheries management, and other societal benefit areas. It should be of high priority to expand European research infrastructures (ESFRI) into the Arctic region. This depends on the willingness of the member countries to invest in Arctic components of the observing infrastructure.

Observing systems under the national meteorological institutes through WMO agreements are required to be operational and deliver specific data in near-real time to the weather services. However, the quality of these observations can be variable and less documented and safeguarded. This is likely due to national budget constraints together with less rigorous international constraints. There are numerous monitoring networks to support climate research and other applications. They often have lower scores on all the maturity criteria because they struggle to secure sustained funding. Many of these systems were originally set up for science rather than operational monitoring and they try to continue the monitoring based on research funding.

Most national and international research projects today have a contractual obligation to make their data openly available. Unfortunately, scientists get little credit for making their data available and their funding limits the efforts they can allocate on data curation. The problem can be solved if the data infrastructures can provide services to help the data providers to make the data available for re-use. The observing systems with high scores on data management and metadata handling have also good support from their data infrastructures.

2.2 Exploitation of existing data

The exploitation of existing data consisted of upgrading of some in situ dataset through improved data processing, data quality check, metadata, and data management. This work resulted in generation of new datasets, some of which were applied in the case studies in WP6.

Upgrade of selected in-situ datasets included acoustic data, hydrographic data, and datasets in AREX, A-TWAIN, Argo, and UDASH (unified database for Arctic and Subarctic Hydrology) and Greenland Ecosystem Monitoring Programme. For the land areas_upgraded datasets included atmospheric black carbon, soil temperature measurements and hydrological dataset under Arctic-HYCOS. Some statistics of observing systems registered in ARCMAP are shown in Fig. 2.3.

Generation of new datasets was done by processing in situ and satellite data applying novel methods. For ocean and sea ice the new derived parameters included a sea-ice displacement satellite product, a multiyear sea ice concentration product, thickness of thin sea ice retrieval, and total atmospheric water vapor over ice and open water, For the land areas the new derived parameters included front positions of tidewater glaciers in Hornsund, Svalbard, cloud products from in-situ ceilometer data, SMOS soil frost satellite product, and ice velocity maps and ice mass balance of the Greenland ice sheet.

2.3 Compilation of data products from distributed databases

The exploitation of existing Arctic data was further enhanced by harmonizing format and metadata of sparse data, and in most cases by making them available through open data repositories. The collation of sparse data also resulted in the creation of thematic catalogues such as the Earthquake and Focal Mechanism Catalogue, the PEEX catalogue, and the Arctic eddy-covariance flux stations catalogue. These catalogues, together with the upgraded and new datasets were linked to and described in the INTAROS data catalogue, which is a major component of the iAOS portal (described in WP5).

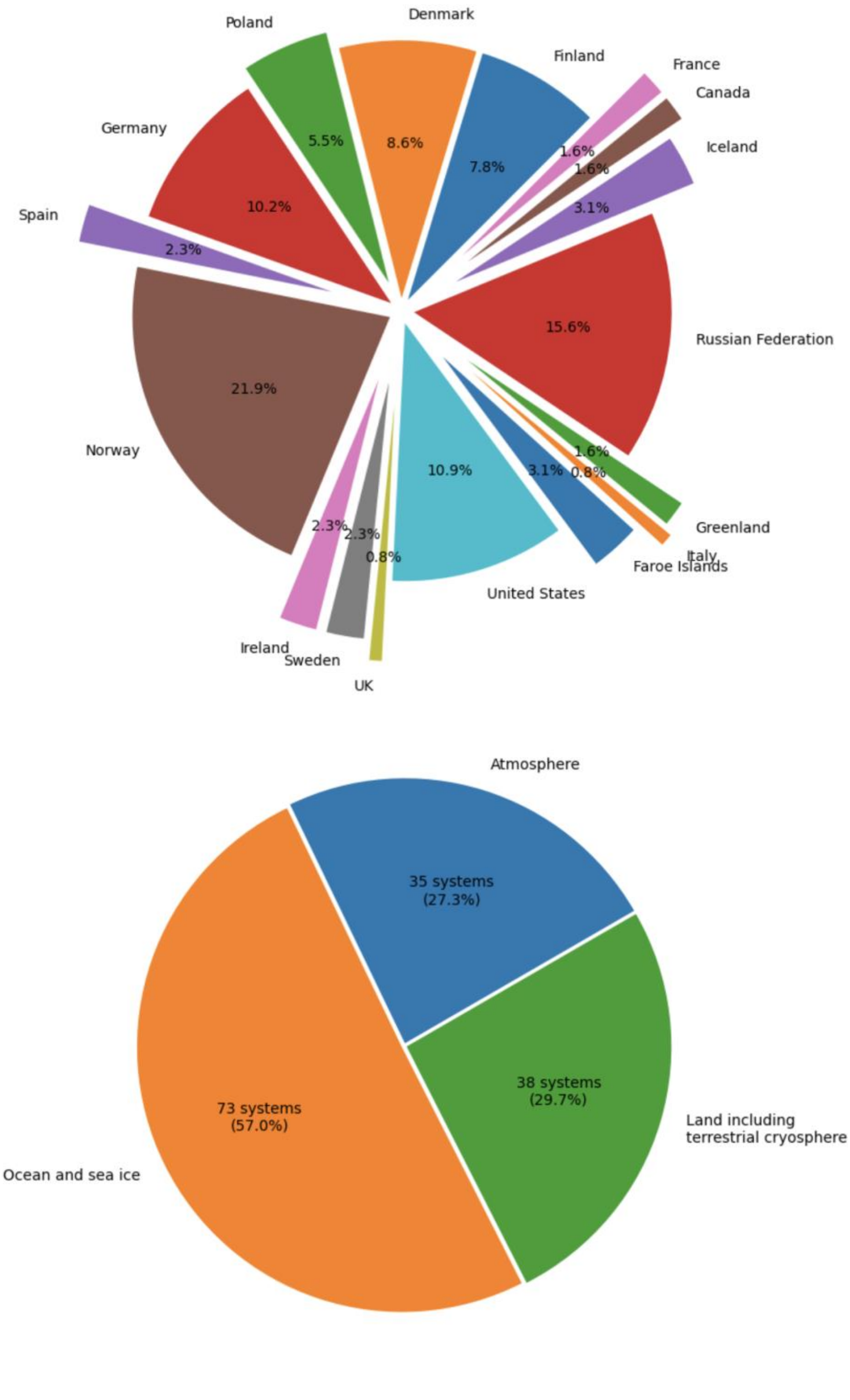


Figure 2.3. *Statistics on Arctic observing systems registered in ARCMAP. Upper graph: distribution of systems by country; lower graph: distribution of systems by sphere (https://arcmap.nersc.no/).*

2.4 Expected impact, challenges and recommendations

The survey and assessment of the observing systems, which was developed into an online tool in the ARCMAP project, will be provided as a service by NERSC after the end of INTAROS. The service can be used by other projects and initiatives to map and assess new observing systems. One such initiative is the Polar Observing Assets Working Group (POAwg), working to identify standard metadata for the polar observing systems (https://www.polarobservingassets.org/). POAwg was established in 2020 under the SAON Committee on Observations and Networks (CON).

INTAROS has improved the access to data produced within the project as well as from other projects by supporting partners to upload their data in established repositories. For some partners and institutions, this effort has led to establishment of a state-of-art data repository compliant with FAIR principles, which will have long-term impact. Also, efforts to publish data as part of scientific articles or as data publications has improved the access to data.

Data from INTAROS has also contributed to extend time series for climate monitoring, which will be useful in the future as the time series become longer. The generation of updated and new sea-ice, atmospheric water vapor above sea-ice, and hydrological data is expected to have an impact on weather, hydrological and sea-ice services in the Arctic, while the new glaciological data on Greenland ice sheet and Svalbard glaciers and the new SMOS permafrost data are expected to be used to improve the Greenland climate modelling and Svalbard glacier modelling, with impact on climate change and sea-level rise projections.

The major challenge regarding the in situ observing systems in the Arctic is to make the systems more sustainable and thereby raise the quality and usefulness of the systems. Based on results from WP2 the following recommendations are formulated:

- The Arctic in situ observing systems require stronger national and European funding in order to be sustainable and contribute more significantly to the global observing systems (e.g. WMO, GCOS, GOOS)
- The in-situ component should have more focus on providing necessary data for satellite algorithm development and validation to enhance the quality of the satellite data products
- Better collaboration should be established between the research communities providing satellite data, in situ data, data management, and model assimilation products (e.g. re-analysis). This collaboration is necessary for building an integrated Arctic observation system
- European Research Infrastructures, which have high scores on all the maturity criteria, need to strengthen their observing capacity in the Arctic. It means that they should establish collaboration with existing observing networks and research infrastructures that are present in many regions of the Arctic
- The collaboration between the observing infrastructures and the data infrastructures needs to be improved. Now there is a gap between these two groups, resulting in barriers in accessing the data. The data infrastructures should provide services to help the data providers to ingest the data into established repositories and thereby offer a well-functioning data delivery chain.

3. WP3: Enhancement of multidisciplinary in situ observing systems

WP3 has focused on developing and implementing new solutions and novel technologies to fill selected gaps identified in the existing Arctic observing systems. Novel instruments and sampling methods were further integrated with mature components of existing observatories to increase temporal and geographic coverage of in situ observational data in the Arctic and to include missing key parameters. Three reference sites (Coastal Greenland, North of Svalbard, Fram Strait and Svalbard fjords) and two distributed observatories (for ocean and sea ice, and for land and atmosphere) were selected within INTAROS as providing critical data to understand ongoing climate and environmental changes and their consequences for the Arctic.

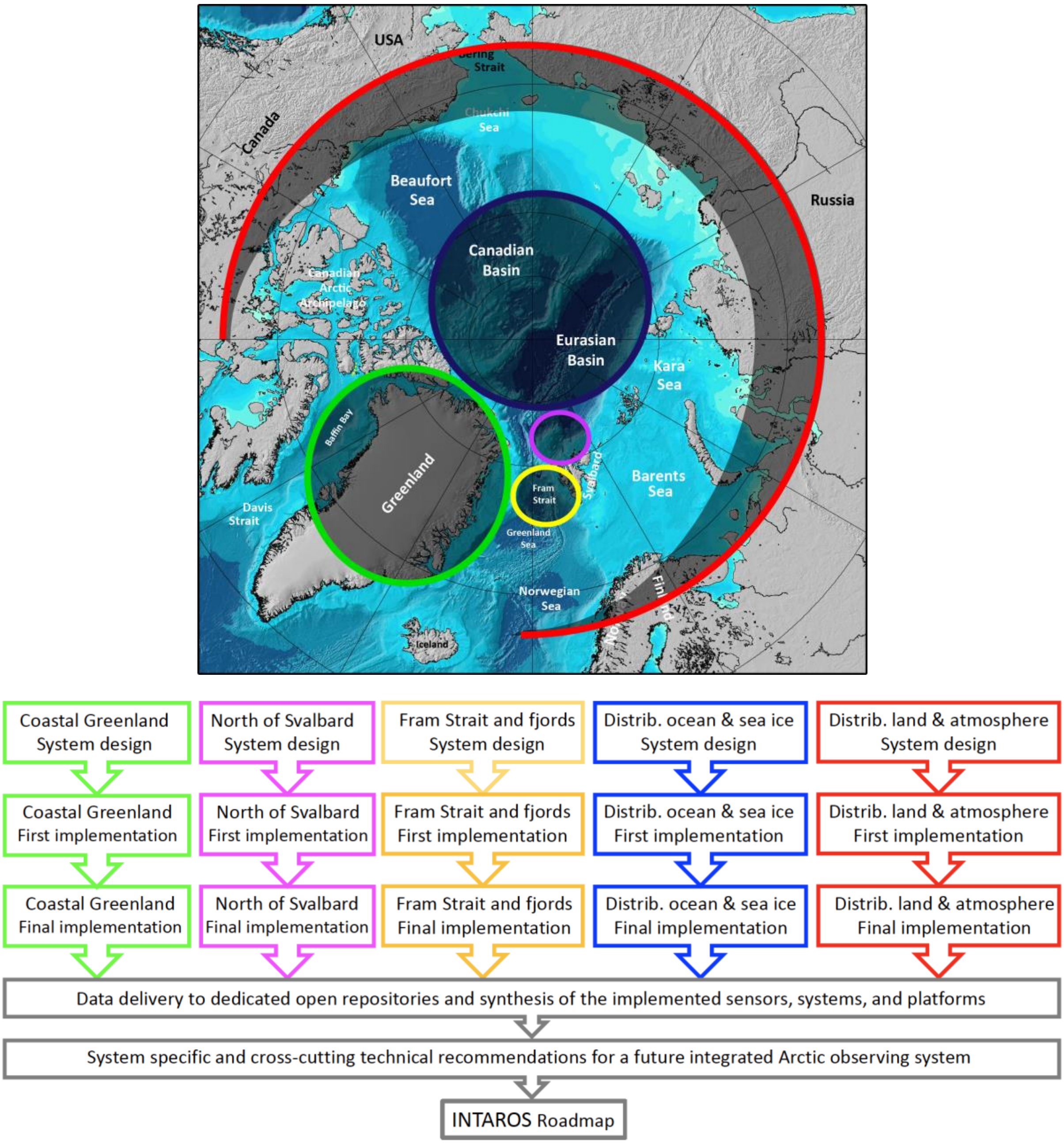
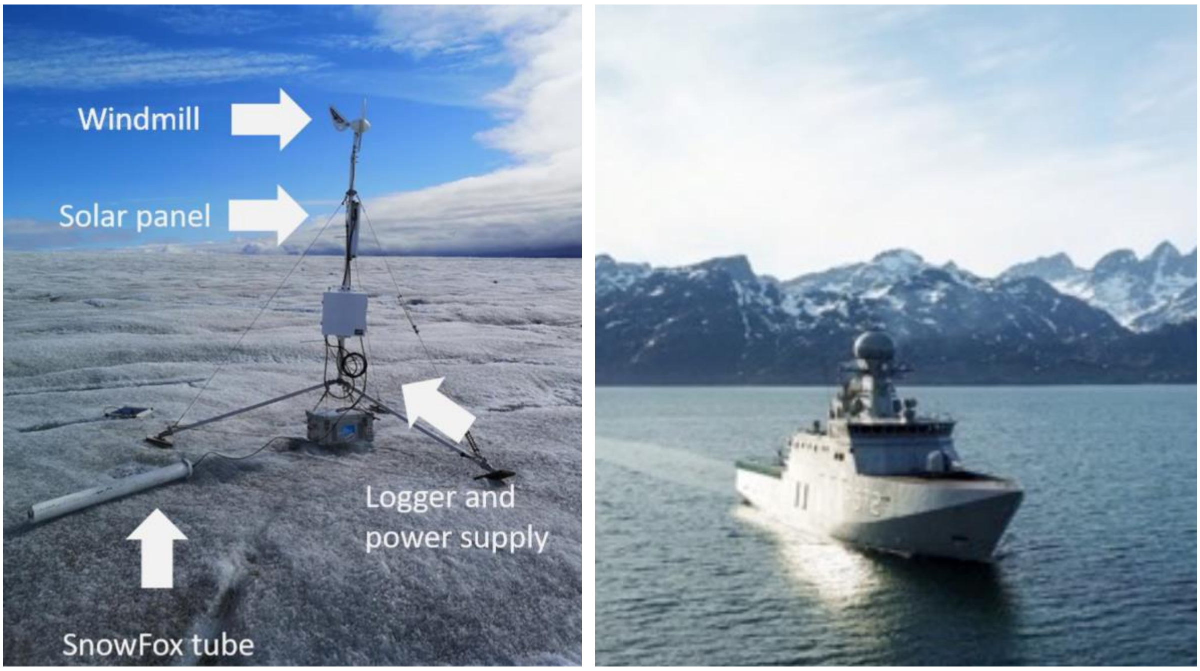


Figure 3.1 *Geographical range of in situ observing systems implemented under five WP3 tasks (upper panel) and a schematic of the workflow during different phases of WP3 activities (lower panel).*

To optimize the fieldwork effort and maintain the integrity of new data, we have built on and effectively extended infrastructure already existing in selected reference sites and distributed observatories. New clusters of sensors have been integrated into a variety of platforms, and several experimental setups have been tested and implemented. The field implementation of new ocean and sea ice observations was supported by use of icebreakers, research vessels, ships of opportunity and seafloor observatories provided by collaborating national projects. The data collection from ice sheets, glaciers and terrestrial stations was based on existing reference sites and other research sites in the Pan-Arctic region. New collected measurements have been pre-processed and formatted to provide standardized data sets ready for integration into existing data repositories and registered in the INTAROS data catalogue. Metadata and data formats for observations made with multidisciplinary platforms have been developed in collaboration with data managers in WP1 and WP5. Selected data sets have been exploited in demonstration actions in WP6 and provided for the consultations with stakeholders in WP7.

3.1 Marine and ice sheet observations in coastal Greenland

Observing systems for the Greenland ice sheet and the coastal waters around Greenland have been improved. New ocean mooring was installed and new sensors added to existing mooring in Young Sound, NE Greenland, to observe freshening of the fjord environment. A baseline dataset on surface pCO2 and ocean acidification was established for the entire Greenland coastal zone. New instruments and improved sensors (instruments for snow-water equivalent, rain gauges, precision GNSS and tilt and azimuth sensors) were added to the network of PROMICE automatic weather stations (Fig. 3.2). New correction methods were developed for in situ ice sheet albedo measurements. An innovative ice-penetrating radar system was improved for generating ice thickness data. INTAROS also contributed to automated monitoring of the spring bloom processes and the bio-optical and biogeochemical properties under the ice pack of the coastal ocean at the Baffin Bay Observatory.



a b

Figure 3.2. *(a) Instruments deployed on the Greenland Ice Sheet for in situ observations; (b) Danish navy vessel contribution to data collection in the coastal areas around Greenland.*

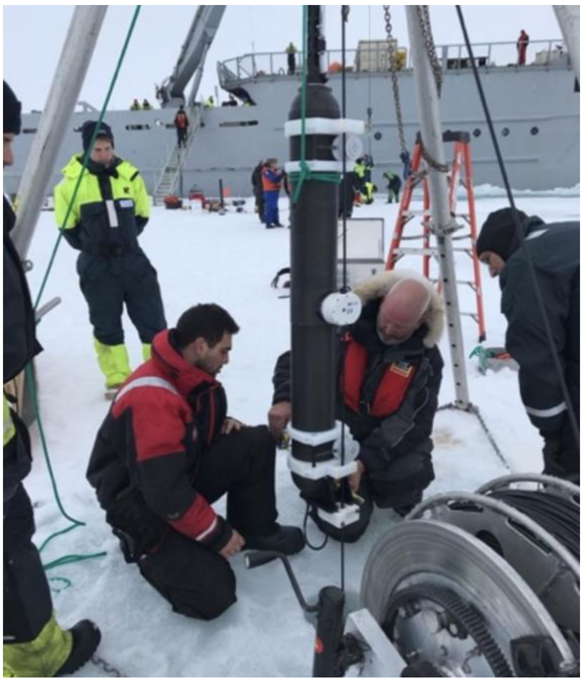
3.2 Moored observatory north of Svalbard towards the deep Nansen Basin

The area north of Svalbard towards the deep Nansen Basin is a key location for Atlantic water inflow to the Arctic Ocean and a hotspot for ocean-atmosphere-sea ice interactions with a strong impact on Arctic ecosystem. The existing ocean observatory was extended with a new array of moorings, deployed for three subsequent years for the continuous year-round collection of physical, biogeochemical, and biological ocean observations. Numerous up-to-date instruments for autonomous measurements of temperature, salinity, ocean currents, bottom pressure, and sea ice drift and draft were implemented on new ocean moorings. Additionally, new sensors for biogeochemical measurements (dissolved oxygen, pH, pCO2, nitrate sensors, contaminant samplers) and biological observations (acoustic and optical imaging) were installed in selected locations. Complementary ship-borne ocean measurements were collected during the mooring operations cruises. Ocean bottom seismometers were deployed in Fram Strait and in Storfjorden to observe solid Earth processes and extended the earthquake monitoring network.

3.3 Marine observations in Fram Strait and Svalbard fjords

The observations of ocean acidification, carbonate system, and underwater sound in the Fram Strait and in Kongsfjorden have been continued. In the Fram Strait the arcFOCE system was used to study impacts of ocean acidification on benthic organisms and communities (Fig. 3.3a). The autonomous observatory at the AWIPEV station was used to conduct real-time measurements of pCO_2 and pH measurements, supplemented by weekly discrete measurements of dissolved inorganic carbon and total alkalinity. A passive acoustic system was used in Kongsfjorden to monitor natural sounds like the activity of benthic species (bivalves) and those produced by icebergs (including localization and detection) as well as anthropogenic sounds, e.g. introduced by fishing vessels or tourists ships.

a



b

Figure 3.3 *(a) Use of the ROV PHOCA to deploy and recover the arcFOCE system in the Fram Strait; (b) Deployment of the ITP from WHOI at the North Pole in August 2019 with KV Svalbard in the background.*

3.4 Distributed observing systems for ocean and sea ice

Distributed observing systems for ocean and sea ice measurements were extended and improved in different parts of the Arctic. The systems included autonomous instruments and platforms that drifted freely on the sea ice or in the water column (ice tethered platforms, ice buoys and floats), moved along pre-programmed tracks (gliders) or measured autonomously at fixed locations (deep ocean moorings). A network of SIMBA buoys and one Equipex-IAOOS platform were deployed in the central Arctic Ocean to collect observations of sea ice, snow on ice and ocean variables. Endurance glider sections were established in the northern Fram Strait for high resolution ocean measurements. In the Baffin Bay INTAROS contributed to the network of the under-ice BGC Argo floats. New sensors and samplers (a microplastics sampler, a combined pH/CO_3 sensor, and an integrated sphere absorption meter sensor) were developed and implemented for the FerryBox measurements between Norway and Svalbard. Use of drones for observing snow and sea ice radiation and albedo measurements on local scale has been demonstrated.

3.5 Distributed observing systems for land and atmosphere

New observing systems for terrestrial and atmospheric measurements were used in different areas across the Arctic. Improved observation techniques were tested and contributed to advancing the Arctic observing capacity for climate gas fluxes. An automated system with flask sampler for atmospheric trace gases was used first in Siberia and thereafter at Station North in Greenland. Vertical profiles of atmospheric boundary layer state variables have been collected during the Polar-5 aircraft campaigns in several Arctic areas. New heating system was designed, tested, and implemented to enable year-round measurements with sonic anemometers on eddy-covariance towers in the Barrow cluster on Alaska. High spatial and temporal resolution temperature profiles with high-resolution thermocouples were installed at the Barrow cluster, extending the existing network for GHG monitoring in the Arctic. Observing stations for permafrost have collected data in the Canadian Arctic. Ground-based optical and microwave remote sensing data of snow and soil has been collected in the northern Finland. The semiautonomous observing system for atmospheric measurements was further developed and implemented on IB Oden operating in the central Arctic.

Figure 3.4 *Photo of an observing station at Bylot Island in Baffin Island in Canadian Arctic.*

3.6 Collaboration with other programs and projects

International collaboration with common scientific and logistical planning is crucial for successful research based on observations in the Arctic. This requires specific tailored observing systems suitable for Arctic conditions (Lee et al., 2019). Therefore, INTAROS field work has made extensive efforts to collaborate with various international and national programs and projects collecting in situ observations in the Arctic, both on land and sea (Table 3.1). The collaboration has been two-way, where other projects have contributed to INTAROS and INTAROS has supported other projects.

INTAROS contributed to several existing observing systems or networks by bringing in new sensors or platforms, developing new methodologies of observations, improving existing sensors and adapting them to Arctic conditions, and establishing data delivery chains from INTAROS observing assets to dedicated data repositories of established international observing networks. At the same time, INTAROS field activities largely benefited from using shared logistics and infrastructure, provision of ship time or access to terrestrial locations, and support of highly qualified professionals, provided by collaborating projects and programs. Collaboration with other projects also comprised a joint participation in the large-scale field campaigns, bringing the benefits of shared field logistics, access to collocated auxiliary measurements, intercalibration activities, transfer of useful operational knowledge and even support with instrumentation or hardware in emergency situations. Collaborative efforts allowed maximizing the cost-efficiency of field operations and optimal use of infrastructure for the mutual benefits of all partners. A total of 27 such collaborations with other programmes and projects have been part of the project (Table 3.1).

Table 3.1. The list of other field programs and projects contributing to and/or supported by INTAROS and the scope of collaboration.

Program or project	Domain	Scope of collaboration
CAATEX (Coordinated Arctic Acoustic Thermometry Experiment) *Norway, US*	Ice and Ocean	CAATEX contributed to deep water mooring design and operation. It provided ship time for INTAROS for mooring operations, in situ measurements, deployment of ice buoys, and drone operations. INTAROS contributed to CAATEX field operations, standardization of data processing, formatting, and delivery of oceanographic data. Joint activities on defining practices and recommendations for further technological development of regional to pan-Arctic Ocean observing systems.
MOSAiC (Multidisciplinary drifting Observatory for the Study of Arctic Climate) *International*	Sea ice, ocean, atmosphere	MOSAiC provided space and infrastructure on Polarstern and access to interdisciplinary data for the participating partners. INTAROS contributed to radiation measurements and SIMBA buoy deployment during the MOSAiC field campaign.
A-TWAIN (Long-term variability and trends in the Atlantic Water inflow region) / Nansen Legacy *Norway*	Ocean	A-TWAIN/Nansen Legacy provided ship time for INTAROS mooring operations and support during the field operations. A-TWAIN also provided mooring infrastructure for two INTAROS instruments (ADCP/echosounder and ADCP/ice) Collaboration on instrumentation, data processing, and scientific use of observations.
PROMICE (Programme for monitoring of the Greenland ice sheet). *Denmark and Greenland*	Ice sheet, atmosphere	PROMICE sharing field logistics and infrastructure with INTAROS. INTAROS contribution to development and implementation of new or improved components of the PROMICE observing system (SnowFox instruments, rain gauges, GNSS positioning, tilt and azimuth sensors).
GC-Net (Greenland Climate Network) *Denmark and Greenland*	Ice sheet, atmosphere	GC-Net contributed field logistics and infrastructure with INTAROS. INTAROS contributed to development and implementation of new or improved components of the GC-Net instrumentation (SnowFox instruments, rain gauges, GNSS positioning, tilt and azimuth sensors).
GEM (Greenland Ecosystem Monitoring)	Ocean	GEM provided field logistics and infrastructure to mooring operations. INTAROS contributed to ship-borne carbonate system

Denmark and Greenland		measurements in coastal waters and added new mooring and instruments to moored observatory in Young Sound.
LTER Hausgarten Observatory in FRAM (FRontiers in Arctic marine Monitoring) *Germany*	Ocean	INTAROS contributed to development and implementation of a new platform (ArcFOCE) in the FRAM observing system. FRAM provided ship time, field logistics and infrastructure for the new INTAROS platform.
Equipex IAOOS (Ice-Atmosphere- Arctic Ocean Observing System) *France*	Ocean, sea ice	Equipex IAOOS provided know-how, logistics, infrastructure and technician support for development and deployment of the IAOOS ice-based platform contributed by INTAROS for ocean, sea ice, and atmospheric measurements.
COSYNA-AWIPEV Underwater Observatory *France, Germany*	Ocean	INTAROS contributed to implementation of new sensors (pH sensors) as components of the observing system for continuous measurements of carbonate system variables. COSYNA-AWIPEV observatory provided infrastructure and logistics for new sensors.
EPOS-N (European Plate Observing System - Norway) *Norway*	Natural hazards, ocean	INTAROS contributed to EPOS-N with deployments of new OBS systems for earthquake monitoring. EPOS-N provided instruments and data management infrastructure for the OBS data.
GLISN (Greenland Ice Sheet Monitoring Network) *International*	Natural hazards, land and ice sheet	The GLISN project has established a real-time sensor array of 33 stations to enhance and upgrade the performance of the scarce existing Greenland seismic infrastructure for detecting, locating, and characterizing glacial earthquakes and other cryo-seismic phenomena, and contribute to our understanding of Ice Sheet dynamics.
DanSeis *Denmark*	Natural hazard, sea floor	Danish national research infrastructure providing access to cutting edge seismic research equipment to scientists from research institutions in Denmark and worldwide.
ICOS (Integrated Carbon Observation System) Atmospheric Monitoring Program *International*	Atmosphere	INTAROS contributed to development and implementation of autonomous system for GHG sampling and to enhancement of Station North facilities as the European ICOS observation network for GHG. Station North provided infrastructure for new sampling platform.
FMI Sodankylä-Pallas Observatory (cal/val site for the NASA SMAP and ESA SMOS missions). *Finland*	Atmosphere land	INTAROS contributed to development and implementation of ground-based sensors for microwave and optical remote sensing of snow. Sodankylä-Pallas Observatory provided field logistics and infrastructure for new instruments.
SnowAPP (Modelling of the Snow microphysical-radiative interaction and its APPlications). *Finland*	Land	SnowAPP provided part of the resources to process the observations and develop the observation routines of the SVC spectro-albedometer and the full-polarized SodScat radar.
ACAS (Arctic Climate Across Scales) *Sweden*	Atmosphere	INTAROS contributed to implementation of semiautonomous system for atmospheric measurements on IB Oden that was developed and established by ACAS.
Year of Polar Prediction (YOPP) under Polar Prediction Project (PPP) *International*	Atmosphere	INTAROS provided near-real-time Arctic observations on the WMO Global Telecommunication System during the Arctic Ocean 2018 and Synoptic Arctic Survey 2022 expeditions, both on the Swedish icebreaker Oden, as well as participated in the YOPP outreach program with popular science articles

DINGLAC, project funded by Spanish Polar Programme *Spain*	Ice sheet, glacier	DINGLAC project co-funded the ground-penetrating radar developments performed under INTAROS by the UPM team.
Norwegian Ocean Acidification monitoring project. *Norway*	Ocean	Norwegian Environment Agency project on monitoring ocean acidification and INTAROS have collaborated and both contributed to the carbonate system observations in the Barents Sea Opening.
INTAROS_SVALBARD (2018-2021), funded by French Polar Institute (IPEV) *France*	Ocean	INTAROS-SVALBARD provided support for glider rental and logistics in Svalbard for the endurance glider lines operated under INTAROS.
APT (Accelation of permafrost thaw), funded by the BNP-Paribas Foundation. *France*	Land	APT co-funded instruments and field work for multi-disciplinary monitoring of snow and vegetation properties in the Canadian High Arctic.
ESCAPE-Arctic (Ecosystems – Snow – ClimAte – Permafrost feedbacks) *France*	Land	ESCAPE co-funded instruments and field work for multi-disciplinary monitoring of snow and vegetation properties in the Canadian High Arctic.
PCSP (Polar Continental Shelf Program) *Canada*	Land	PCSP provided logistical support for field work related to multi-disciplinary monitoring of snow and vegetation properties in the Canadian High Arctic.
Amundsen Science *Canada*	Ocean	Amundsen Science manages all the scientific operations aboard the icebreaker NGCC Amundsen. Through a collaboration, Amundsen Science contributed ship time and berths for the deployment of BGC-Argo floats over the entire INTAROS time frame.
Baffin Bay Observatory *France, Canada*	Ocean, sea ice	Shared field logistics and infrastructure with INTAROS. INTAROS contribution to implementation of under-ice BGC Argo floats and new sensors for sea ice properties.
Sentinel North *Canada*	Ocean	Sentinel North supported the BGC-Argo float work through post-doctoral fellowships as well as ship-time for the deployment of the floats in 2021. INTAROS contributed to operating the BGC-Argo floats and data analysis.
FACE-IT (The future of Arctic coastal ecosystems – Identifying transitions in fjord systems and adjacent coastal areas) *International*	Ocean	FACE-IT contributed to analysis of time series data and design of perturbation experiment in mesocosms in Kongsfjorden observatory. INTAROS contributed with new sensors and measurements to carbonate system observations from Kongsfjorden.

The COVID-19 pandemic starting in March 2020 has reduced the INTAROS field activities in the last two years. There have been restrictions in mobility, organization of field expeditions, and access to remote places as well as a shortage of qualified manpower. Several research cruises or land expeditions were cancelled or postponed, risking loss of valuable instruments and data. Only thanks to extensive collaborative network and support provided by other projects and programs, much of the fieldwork could still be done, but with delays and reduced data collection. Field work and data collection will continue in many of the study areas after the end of INTAROS.

3.7 Summary of challenges and achievements

The main achievements in WP3 are represented by

(i) new sensors, platforms and observing infrastructure that were added to existing key sites and distributed observatories,

(ii) new and extended in situ data collections provided by implemented observing assets, and

(iii) improved methodologies for data processing and delivery chains.

Novel instruments, platforms and sampling methods were integrated with mature components of existing observatories to enhance collection of in situ data in three reference sites (Coastal Greenland, North of Svalbard, Fram Strait and Svalbard fjords) and two distributed observatories (for ocean and sea ice, and for land and atmosphere).

Major challenges in implementing new in situ observations were related to inadequate robustness of available sensors under harsh Arctic environmental conditions, high sensor/platform costs thus no redundancy of critical measurements, limited power supply for autonomous platforms, limited access to critical services (GPS positioning, satellite data transfer), extremely demanding field operations, complex and expensive logistics, and limited availability of trained technical personnel. High costs and high risks in implementing new observations translate to challenging scalability, it is therefore difficult to sustain broad, long-term observing activities as defined by requirements and gap analysis. Figure 3.5 gives an overview of *in situ* observations collected during INTAROS field campaigns in different regions of the Arctic.

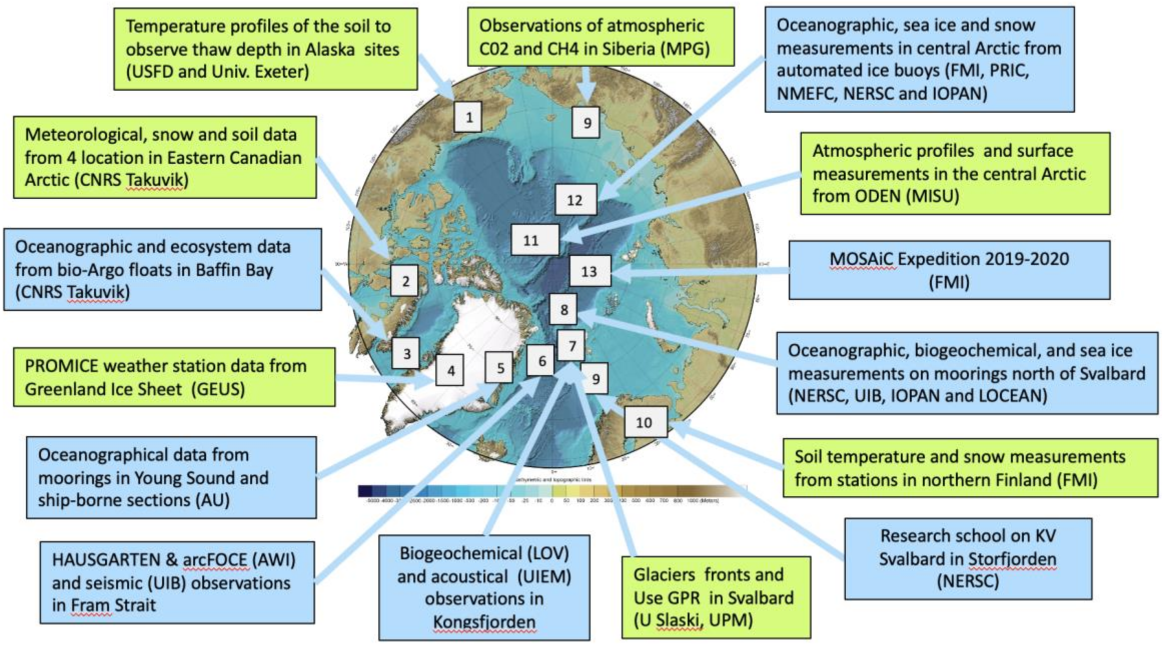


Figure 3.5 *Spatial distribution of observing system, networks and platforms providing in situ observations during INTAROS field campaigns in 2017-2021. Blue boxes and arrows indicate measurements collected in ocean and sea ice domains while green boxes depict atmospheric and terrestrial observations.*

3.8 Expected impact and recommendations

3.8.1 Expected impact

New observations of key ocean, ice, atmospheric, and terrestrial variables have been collected, processed and delivered to open data bases. Thereby the availability of in situ measurements from poorly observed areas has improved with positive impact on research, operational services, climate monitoring, and decision-making processes.

Extension of long-term in situ time series of observations or establishing new time series will improve climate and environmental monitoring under on-going climate change and provide a baseline to assess numerical forecast and prediction models for the Arctic.

Novel sensors and systems developed for measuring new variables or improving quality of existing measurements will enhance observational capacity of the current Arctic observatories and provide solutions for a future development of observing systems.

Existing observing systems improved and extended with new sensors or technologies will deliver multidisciplinary collocated observations that are expected to improve current understanding of the complex Arctic climate system

Improved data processing algorithms and data delivery chains for different types of in situ measurements (from raw data processing to submission into open data repositories) will potentially enhance the uptake of in situ observations for different applications and increase efficiency of using new data collections by different user groups.

Enhanced collaboration with different projects and programs that was established with different models of sharing observing infrastructure, field logistics and personnel resources will enable more interdisciplinary research, improve cost efficiency of in situ measurements, and promote an exchange of technological know-how for the benefit of a future Arctic observing system.

3.8.2 Technical recommendations

All INTAROS field experiment where many different sensors and platforms were used for collecting in situ measurements have provided invaluable experience in operating these assents. Furthermore, INTAROS has collaborated extensively with other field programs such as MOSAiC and CAATEX. From this collaboration a number of technical recommendations have been elaborated and are summarized in the following points:

1. Improve the sustainability of existing observing system by integrating and upgrading fragmented networks with new instrumentation
2. Implement multipurpose observing systems, enabling multidisciplinary observations and providing additional services for different platforms and systems (e.g. acoustic geo-positioning or data telemetry in the ocean).
3. Promote development of relatively simple (miniaturized if necessary), low-cost and low-power sensors to be deployed in larger quantities and thereby improve spatial coverage
4. Develop robust and reliable sensors for biogeochemistry and biology to be routinely used for ocean observations in the Arctic environment.
5. Improve use of autonomous systems for atmospheric measurements over land, sea ice and ocean, including radiative fluxes, winds, aerosols, and clouds.
6. Provide solutions for de-icing of instruments, in particular during polar night
7. Improve power sources to enable longer and more efficient autonomous measurements in the Arctic
8. Develop data transmission using broadband services from new communication satellites

9. Increase the use of ships of opportunity for autonomous collection of standard measurements
10. Advance best practice documentation for operating different *in situ* sensors, platforms and systems in the Arctic and open technical trainings to professionals from involved in Arctic observing
11. Promote further development of common data standards for new measurements collected

The most important technical requirements for future Arctic observing systems can be summarized as:

(i) Build standard sensors designed for Arctic conditions as well as new, low-cost and low-power sensors,

(ii) Develop more autonomous observing systems, capable of long-term operations under changing conditions with less sea ice cover, melting glaciers and thawing permafrost,

(iii) Develop and implement new generation of improved power supplies, and

(iv) Provide reliable, high bandwidth, and cost-effective services for satellite data transfer

Several of the technical recommendations are addressed in ongoing research and innovation projects (new sensors and platforms, power supply, satellite broadband communication). Future Arctic observing systems should take advantage of the technology development in these projects to build and operate sustainable systems.

4. WP4: Community-based observing programs

The goal of WP4 was to enhance community-based observing programs (CBM) for participatory research and capacity building. Many experience-exchange workshops have been organized, and the status of several ongoing community-based observing programs and their capabilities, "good" practice and challenges have been analysed. Furthermore, a set of tools to cross-fertilize local knowledge with scientific knowledge have been developed. New CBM and citizen science initiatives have been initiated, and several existing CBM programs have been strengthened as so as to inform local and national decision-making. Datasets from CBM and citizen science projects have also been registered in the INTAROS data catalogue.

4.1 Survey and analysis of existing community-based observing programs

Based on identification of 170 CBM programs in the Arctic, 45 CBM of the programs were selected for in-depth analysis. A major effort was to organise 40 workshops with 600+ people including representatives from Inuit, Sami, Evenk, Gwi´chin and Komi Izhma to discuss and exchange lessons on CBM, as described in D4.1. The CBM programs are contributors to key economic sectors in the Arctic, as shown in Fig. 4.1. The results from the analysis and the discussions at the workshops, together with the CBM program organizers, were presented in the book "*Community-Based Monitoring in the Arctic*" (University of Alaska Press, 2020), The lessons from CBM programs were also broadly disseminated through a large number of physical and online events (presented in D7.14), policy briefs (presented in D6.6), proceedings, scientific reports and articles. A joint analysis of the observation capacity of scientists' observing and CBM programs in the Arctic, using a common frame of assessment topics among scientist- and community-led programs, see section 2.1.5). This analysis constitutes an important concrete step towards better integrating the two approaches.

4.2 Tools for cross-fertilizing Indigenous and local knowledge with scientific knowledge

A web library with examples of Arctic CBM manuals and CBM program organizers' reflections of key lessons learnt has been established (https://mkp28.wixsite.com/cbm-best-practice; D.4.2). Moreover, with co-funding from the Government of Denmark, a UArctic Thematic Network on Collaborative Resource Management and Community-Based Monitoring has been initiated. This network organized an experience exchange workshop in Hokkaido, Japan, and a course on Collaborative Resource Management and CBM tools for 25 public resource managers from Greenland's five municipalities. The course material was made publicly available at https://www.uarctic.org/organization/thematic-networks/collaborative-resource-management/. A second course is scheduled in 2022, funded by the Government of Denmark.

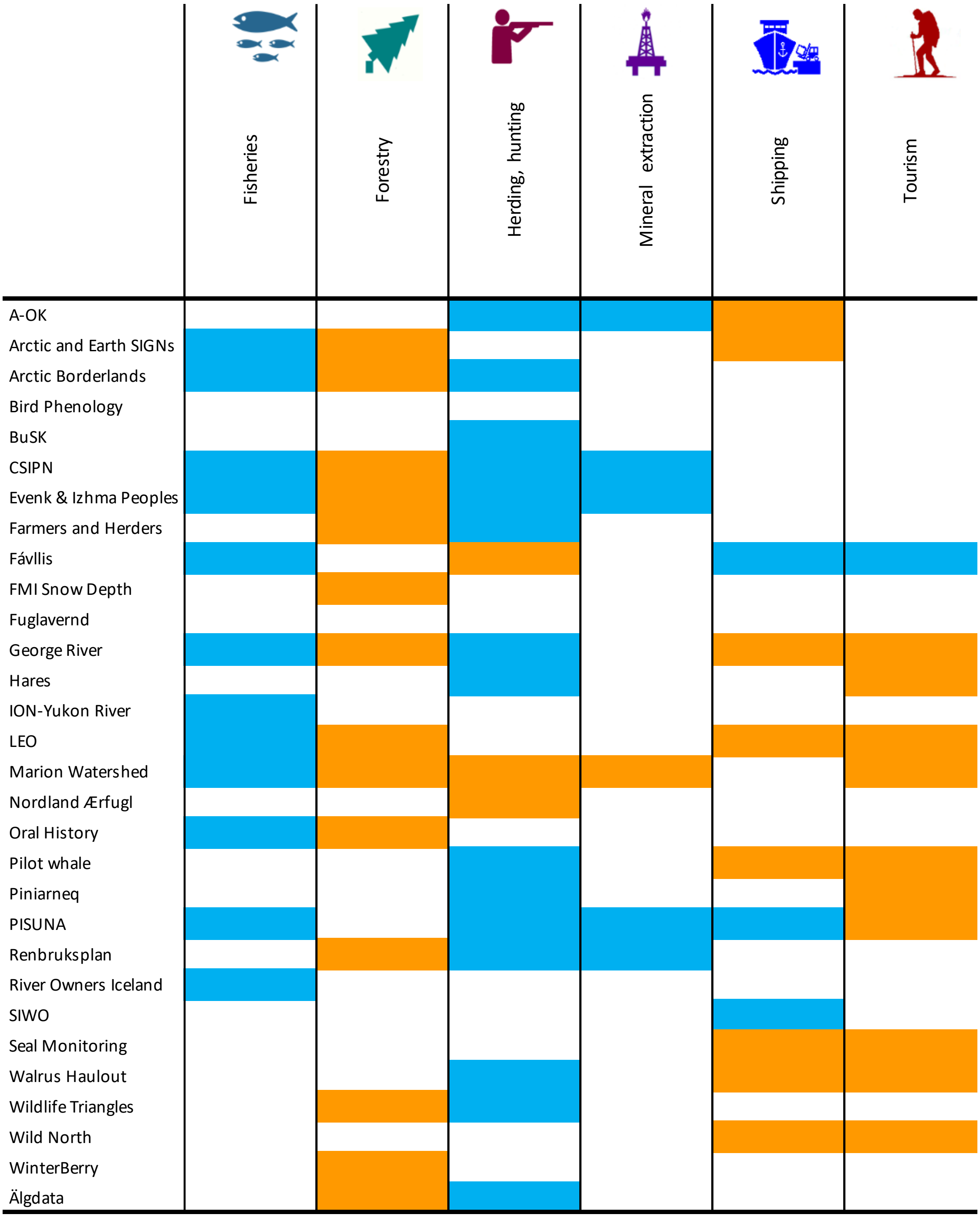


Figure 4.1. *The contribution of Arctic community-based monitoring programs to key economic sectors in the Arctic (blue = contributed; orange= probably contributed; n = 30), Excerpt from "Community-Based Monitoring in the Arctic", UAF 2020, p. 18).*

To stimulate increased use of local knowledge to inform decision-making in the international management bodies that advise the authorities on resource management in the Arctic (e,g. NAMMCO; North Atlantic Marine Mammal Commission), the project organized a dialogue workshop with representatives of small-scale fishermen and hunters in Greenland and Nunavut, the NAMMCO Secretariat and public resource managers. Subsequently, the project developed a Catalogue of Actions for NAMMCO with concrete suggestions for how to increase the integration of user and hunter knowledge into the way NAMMCO is operating. This work was also supported by the Nordic Council of Ministers.

In a series of four review papers in *BioScience*, key topics and tools were explored with regard to the use of CBM in the Arctic and beyond (https://academic.oup.com/bioscience/pages/community-based-monitoring-2021). The results were met with great interest: in just three months, the papers in *BioScience* were downloaded more than 3,000 times.

The team in WP4 has also contributed with descriptions of tools and approaches to support participatory resource management in the Central Arctic. The Central Arctic Ocean Fisheries Agreement, ratified by Russia, Greenland, Canada, USA, and the EU, requires decisions on living resources in this region to take into consideration Indigenous and Local Knowledge (ILK) as well as scientific knowledge. By invitation of government staff from two of the Arctic countries, the WP4 team provided suggestions for relevant approaches that could contribute to interweaving ILK and scientific knowledge for decision-making.

Moreover, by invitation of the United Nations Environment Programme, the WP4 team helped co-found the Global Citizen Science Partnership (http://www.globalcitizenscience.org/). This is a one-step entry point for governments and other partners seeking to collaborate with, and use tools from, the global citizen science community. The CBM work will continue through the H2020 CAPARDUS project with focus on capacity-building in support of 'good' CBM practice and sustainable development in the region (http://capardus.nersc.no) .

4.3 Initiate community-based observing networks to support decision-making processes

The work has been conducted in five different activities.

Activity 1: Rural communities in Greenland use the environment on a daily basis for their livelihood and represent a vast. largely untapped source of knowledge on the environment. In Greenland's Disko Bay, focus group discussions were set up with 30 fishermen and hunters in the PISUNA program (*Piniakkanik Sumiiffinni Nalunaarsuineq*). The project supervised the PISUNA program on a weekly basis through skype, phone and physical meetings, and regularly updated the website and database of observations. The fishermen and hunters made observations during 4,300 field trips (Fig. 4.2). They discussed their observations among themselves and with local government staff, and they used the findings to forward 197 management proposals to the authorities (D4.3). In 2018, the fishermen and hunters in the PISUNA program received the Nordic Council Environment Prize.

In 2020, with many partners inc. Ilisimatusarfik (University of Greenland) and Greenland Association of Fishermen and Hunters (KNAPK), a policy brief was prepared, urging the government to incorporate the use of such Local Knowledge into the new Fisheries Law (Section 6.6). Moreover, led by Dr Christine Cuyler from Greenland Institute of Natural Resources, we co-developed with muskox hunters from Ivittuut a muskoxen demographic model that enables community observers – independently from scientists – to undertake multiannual harvest planning of muskoxen stocks. Importantly, this harvest planning ensures both a supply of meat for subsistence and quotas of old bulls for trophy hunting.

Activity 2: Environmental observation by tourists on expedition cruises has been enhanced in Svalbard. This kind of volunteer data collection is also called Citizen Science. The tourists are already collecting observations of birds and cetaceans, however, the attributes observed, and the volume of records are limited and few of the observations are used by decision-makers. Collaboration was initiated with expedition cruise operators to develop such observing systems further (D7.14, p.13). Four citizen science programs used by cruise operators in Disko Bay and Svalbard were analysed (D4.3; policy brief in D6.6). A total of 165 people contributed observations during one cruise season to *eBird* (Fig. 4.3), which is a well-developed global Citizen Science project (https://ebird.org/home). Also, marine mammal encounters were documented through photos and reported to *Happywhale* (https://happywhale.com/home). Plans for further development of citizen science for documentation of cultural heritage sites in Svalbard are prepared as part of the CAPARDUS project.

***Figure 4.2** Left: The communities involved in the resource observations in Northwest Greenland. Centre: Registration of local resources in Disko Bugt (Photo: F. Danielsen). Right: Overview of data from 357 monthly reports on resource observations (D4.3).*

***Figure 4.3.** Records of Atlantic puffin Fratercula arctica (n = 622 records) from Svalbard 2002-2019 in the eBird database (D4.3). Puffin is listed as globally threatened by the World Conservation Union in the category Vulnerable. Records highlighted with a white flame are from eBird hotspots, areas with "many" checklists. Insert photo by Henrik Kisbye.*

Activity 3. The WP4 team has initiated a dialogue with decision-makers and other local actors in Svalbard regarding environmental observing. The dialogue is important for so building trust and long-term collaboration while addressing ethical, democratic, and cultural dimensions. The activities included interviews, workshops, and public outreach in collaboration with Svalbard Social Science Initiative (SSSI). Focus of the activities was to identify knowledge gaps and how to share knowledge between local actors and scientists.

A digital platform was set up for communication between scientists, business actors and decision-makers (https://svalbardsocialscience.com/). These initiatives contributed to important community dialogues during the Covid-19 crisis in Svalbard. The first community science panel to mobilize citizen science in Longyearbyen and Svalbard was organized in collaboration with "Hearts in the Ice" (https://www.heartsintheice.com/?lang=no). The collaboration with community actors and the SSSI network, now established as an organization, has received funding from the Svalbard Strategic Grant for a workshop to develop a proposal for Horizon Europe on citizen involvement in knowledge co-creation.

Activity 4. A citizen science seismology demonstration was conducted in Greenland. Large parts of the region have few or no seismic stations. We have been testing citizen seismology for the first time in the Arctic. In the Greenlandic settlements of Akunnaaq and Attu, fishermen Gerth Nielsen and Per Ole Frederiksen put small seismometers on the bedrock under their houses (Fig. 4.4). The data from the instrument enable location of 23 seismic events and improved the location of 209 events, significantly enhancing our understanding of both ice-generated and tectonic events in the area (D4.3). The citizen seismology test was led by GEUS and the University of Bergen. Citizen seismology is useful where buildings are constructed on bedrock and trusted relationships exist between government agencies, scientists, and residents (Section 6.2.2). It may help build community awareness of natural hazards. A policy brief was developed (D6.6).

***Figure 4.4**. Gerth Olsen, Akunnaaq (left) with the seismometer (middle) before placing it on the rock below his house (D4.3). Photo: F. Danielsen. Righ: a seismogram showing the recording of a magnitude 2.0 earthquake located 122 km South-West of Akunnaaq on 21 May 2018.*

Activity 5: In many areas of Arctic Russia, current land management systems are not able to include Indigenous perspectives. For Indigenous Peoples, CBM can be not only a tool for ensuring sustainable resource use, but it can also provide a means for protecting their rights to land and resources. In Kola Peninsula and Yakutia, Sakha Republic, the WP4 team has supervised community organizations in their efforts to facilitate CBM on a monthly basis through skype, phone and physical meetings (D7.14, p.10). Eight groups of reindeer herders, fishermen and hunters are monitoring the environment and the mining that is being undertaken or planned on their traditional territories (Fig. 4.5). The CBM also enables dialogue between the extractive industries and the owners and users of the traditional lands. The CBM has led to a number of natural resource management actions (see the technical report available at http://www.intaros.eu/media/1650/process-report-yakutia-cbm-dec-2019-final.pdf) . As an example, a community in Zhigansk District obtained the rights to a traditional fishing ground in part because of its active participation in the CBM.

4.4 Make community-based observations accessible in the INTAROS data catalogue

Most data catalogues and international data repositories are not suitable for hosting CBM data collections. Therefore, only a small proportion of the CBM programs register the data in international data catalogues. INTAROS has established a data catalogue (https://catalog-intaros.nersc.no/) with ca. 150 data collections with links to each dataset. The catalogue includes meta-data for PISUNA-net and

14 others Arctic CBM and citizen science data collections. It is recommended that the major Arctic data repositories enable their systems to ingest CBM data collections.

Figure 4.5. In the tributaries to the Lena River in Yakutia, Russia's Sakha Republic (left), Evenk community groups have documented that Siberian and Arctic cisco (Coregonus sardinella, C. autumnalis; top right) are increasingly found at greater water depths than before. The fish are therefore difficult to catch with the permitted net types. This finding has been used by the Republic Indigenous Peoples organisation to influence changes in permitted net types. (Bottom, right) A visitor welcome ritual in the Evenk community. Photos by Martin Enghoff and David M. Runfola, FishBase.

4.5 Expected impact, challenges and recommendations

By invitation, the WP4 team organized a "Grand Challenges Session" at the First European Polar Science Week to discuss challenges and recommendations for moving forward with CBM in the Arctic (Oct 2020). The session included several presentations, a panel of five experts, and had 30+ participants. On the basis of the presentations and discussions, it was concluded that substantial theoretical work and demonstration activities have been made on the needs for cross-weaving knowledge approaches. In the coming years, it will be very important to move further from theory to practice with cross-weaving of knowledge approaches in the Arctic. The whole session is available on YouTube: https://youtu.be/ljUTNlw4slM. Below we summarize the key conclusions.

Impact. In recent years it has been demonstrated by INTAROS and related initiatives in the Arctic that mobilizing all relevant knowledge, observations, and data on the Arctic environment from local communities can make a significant contribution to the overall environmental and climate data collection in the Arctic (e.g., D.4.3). It is expected that in the future the contribution of knowledge and observations from local communities will continue to grow and to contribute to a better understanding that over time may be able to transform natural and social science research and natural resource management in the Arctic. This has great potential to impact the lives of Arctic peoples.

Challenges and recommendations. There are many barriers at the level of the individual CBM and citizen science program in the Arctic (see e.g. D4.1, D4.2, D4.3, D6.6, D7.14). The challenges and recommendations related to CBM and citizen science observing programs are summarized as follows:

- Insufficient respect among scientists for the knowledge and observations of community members, in particular Indigenous Peoples
- Incomplete understanding of how to obtain and use data from different people (with varying beliefs, epistemologies, rationalities, and cosmologies) and different knowledge systems in mutually beneficial ways.
- Lack of shared protocols enabling cross-weaving, and insufficient dialogue on how to ensure knowledge synthesis.
- Lack of government policies in support of cross-weaving knowledge.
- Asymmetric power relationships (and financial resources).
- Digital divide.

Key research recommendations are (see also the roadmap in D1.11):

- Develop a holistic data 'ecosystem': bridging conceptual, political, and geographic distances.
- Establish an understanding of how to obtain and use data from different people and different knowledge systems.
- Develop ways to enable knowledge production and monitoring across scales.
- Explore appropriate ways for combining Indigenous and local knowledge, CBM, and citizen science data, and science data for improved 'real-world' decision-making.
- Improve coordination of research efforts (related to cross-weaving knowledge) and mobilize all research results for operational contexts.
- Further develop observing-logistics and research infrastructures, including cyber infrastructure for cross-weaving knowledge.

5. WP5: Data integration and management

Work has focused on developing: (1) a cloud platform (the iAOS cloud platform) and a set of showcase application integrating, processing and analysing data from distributed repositories, and (2) an Integrated Arctic Observing System portal (the iAOS portal) which provides access to observations and derived parameters from multidisciplinary data repositories.

5.1 The iAOS cloud platform, processing services and geostatistical tools

The work has focused on deploying and demonstrating the IAOS cloud platform for user applications (iAOS Showcases) using data from online data repositories. It is required that the data repositories provide access to data through standard APIs allowing software clients to extract parameters, geographic areas, and time range of interest. These APIs must support data delivery in standard formats, including ample metadata, such as NetCDF/CF, Shapefiles and GeoTIFF.

A data processing service powered by Terradue's Ellip Solutions was implemented by ARMINES using CTD datasets in the North Sea, provided by IMR. The service used a RGeostats-based data interpolation application, providing gridded fields based on APIs of the iAOS cloud platform (Fig. 5.1). This API empowers the application with an interoperable data access mechanism (based on OpenDAP), scalable data processing capabilities (based on Hadoop MapReduce) and standard processing invocation and results retrieval (based on OGC WPS), for integration with the iAOS Portal or other Geobrowser applications.

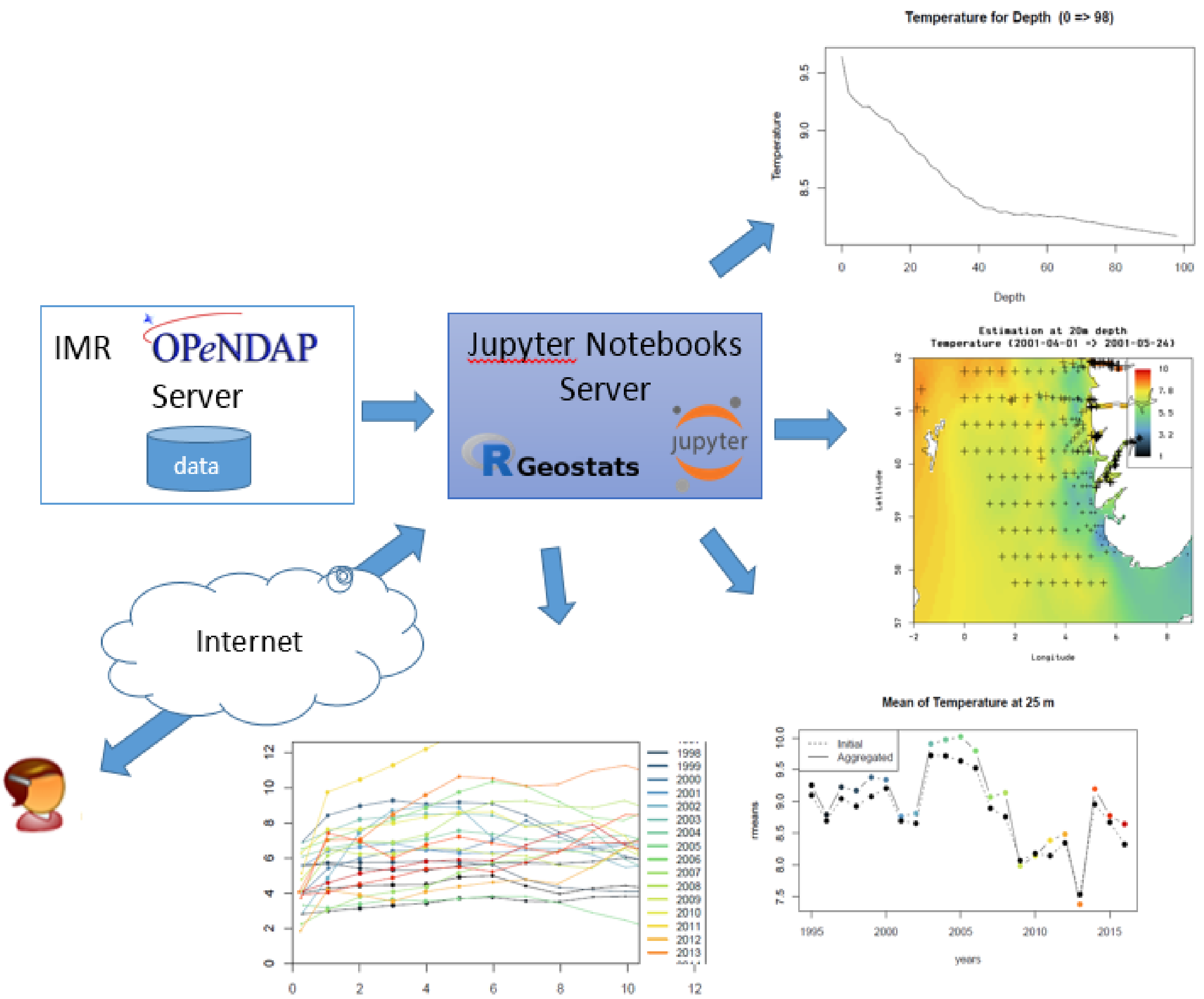


Figure 5.1 *Application design based on remote data access and Cloud-based Jupyter Notebooks*

Another successful use of data processing services powered by Terradue's Ellip Solutions has been implemented by NERSC in collaboration with the EC NextGEOSS project, where processed Copernicus Sentinel-1 data permitted to deliver sea ice classification products and Sea ice drift products, then published in an open data repository for exploitation in the INTAROS Data Catalogue. These two services have made use of the Cloud Computing resources funded by the NextGEOSS project on the EGI.eu Federated Cloud, and both processing services have transferred output files from the processing campaigns run on the NextGEOSS-funded Cloud Production environment, to their publishing through the OPeNDAP data server at NERSC.

NERSC developed the iAOS service "Characterization of Passive Acoustic Data (C-PAD)", which enables users to analyse and present passive acoustic data, to support detection and classification of different sources of noise pollution in the ocean. The generated data products include noise level statistics and spectrograms. NERSC implemented the C-PAD service in R, utilizing Jupyter Notebook as a rapid development and interactive testing tool. C-PAD draws upon several open-source tools and libraries for acoustic data processing, analysis, and visualisation. This enables other scientists and service developers to quickly put the service into use, without committing resources to commercial tools. The C-PAD service is based on the PAMGuide software, a tool for analysis of passive acoustic data. This tool was initially designed to process audio files (WAV files) but has now been augmented to support vector input. This allows for processing of data stored in e.g., NetCDF format without converting to WAV before processing, which potentially could lead to loss of data, as well as adding computational time.

Fig.5.2 shows the spectrogram and noise statistics for an acoustic recording collected during the WIFAR project in August 2012. The spectrogram shows a strong, constant signal around 20 Hz throughout the 10-minute recording. This dataset is publicly available through the Norwegian Marine Data Centre (NMDC).

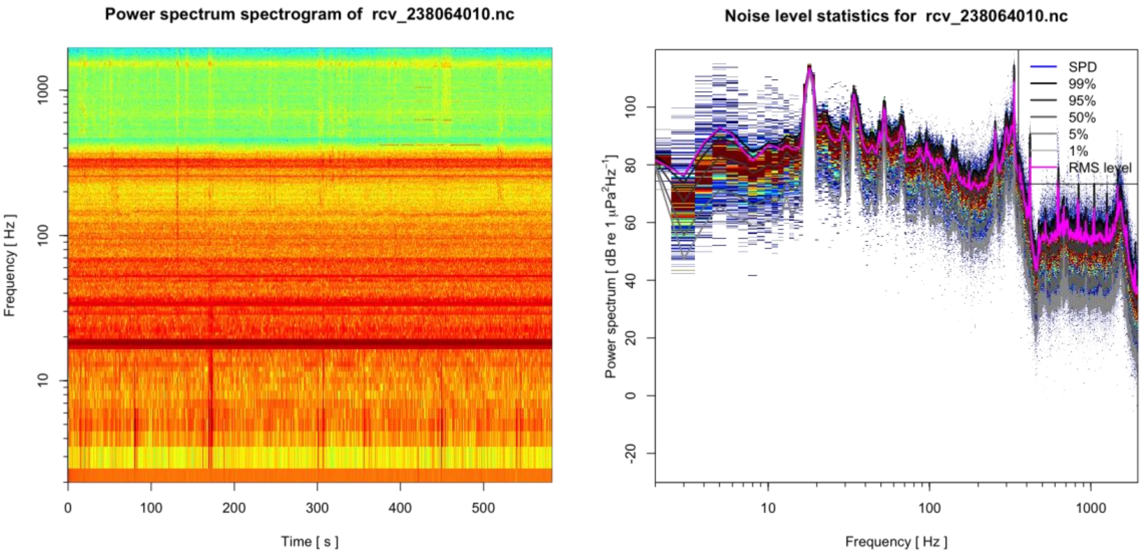


Figure 5.2 *Examples of power spectrum spectrogram (left) and noise statistics plot (right) generated by the C-PAD Service when analysing passive acoustic data from the previous WIFAR project.*

The iAOS Service "Time Series of Sea Ice Concentration (TS-SIC)" developed by NERSC enables iAOS users to extract a time series of sea ice classification maps for a selected time period in the Fram Strait and North of Svalbard. Data in the time series can be used to generate different statistics for sea ice concentration in the region.

The TS-SIC service was used to generate monthly mean sea ice concentration (SIC) fields using the CMEMS daily SIC product for the Svalbard region. Fig.5.3 shows the mean SIC fields for June - September 2018.

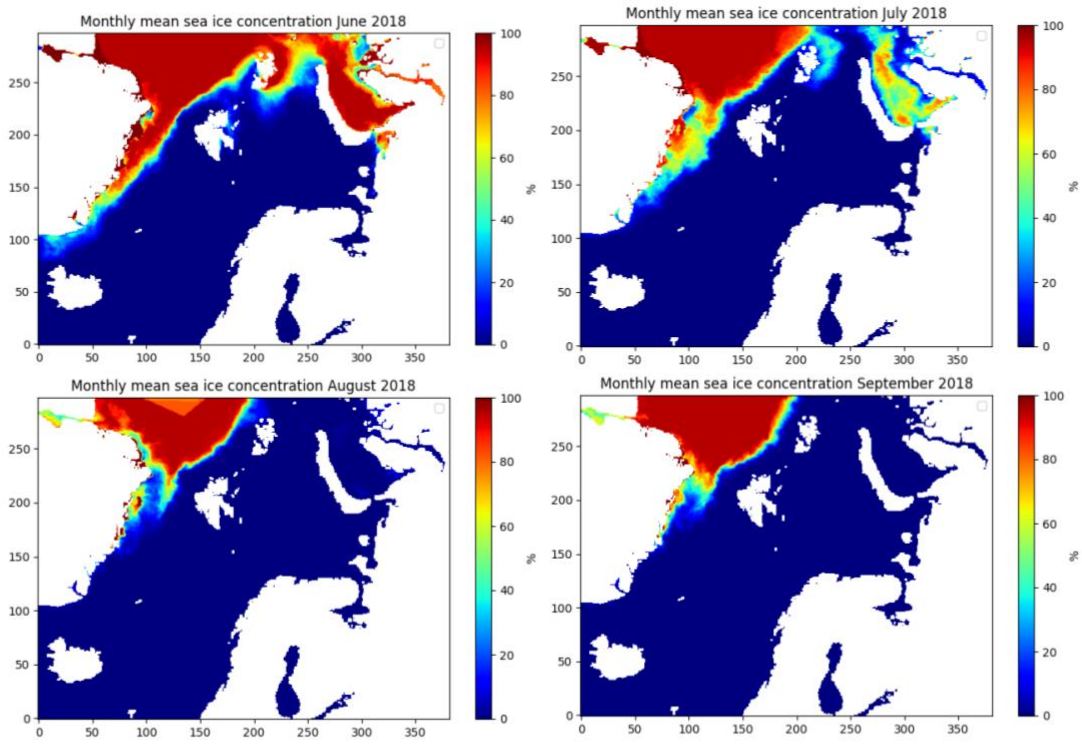


Figure 5.3 *Examples of sea ice concentration statistics, monthly means for June - September 2018 in the Fram Strait of area north of Svalbard, generated from daily CMEMS product.*

5.2 The data catalogue and the iAOS portal

NERSC has developed the iAOS Portal (Fig 5.4, Fig. 5.5) which provides access to selected datasets and services offered by INTAROS partners and by other Arctic data providers and service providers. Required functionality has been identified through dialogue with users and stakeholders. Two main categories of users of the portal were identified: (1) data/service providers and (2) data/services consumers. Providers make their data or services available through the portal and update the descriptions of these if changes are made. Consumers search for and access data or services, with sufficient descriptions (metadata) for both data and services to whether to use them in their work. The population and promotion of the iAOS Portal depends on data providers and consumers including service providers.

The iAOS Portal is implemented using a leading data management system framework named CKAN (Comprehensive Knowledge Archive Network). CKAN offers a broad range of the needed features out of the box and has an active community that develops additional features (plugins). Using the CKAN core components and mature plugins, the following main components of the iAOS Portal have been implemented:

- INTAROS Data Catalogue, holding descriptions (metadata) of datasets collected or generated with support from INTAROS.
- iAOS Portal Data Catalogue, holding metadata harvested from other catalogues offering relevant dataset for the applications developed in WP 6 of INTAROS.
- Services and Applications, describing services and applications developed in INTAROS and by external service providers offering products or functionality that can be exploited in WP 6.
- Tools and Resources, providing links to software libraries and tools, computer platforms, data systems, infrastructures and projects that offer data, information and/or software tools that can

be useful for scientists and stakeholders in Arctic sciences and for local communities in the region.

- ARCMAP – a web application that enables assessment of in situ observing systems and extracting statistics and indicators of the overall observing capacity of these systems.

Figure 5.4 *Home page of the iAOS portal (https://portal-intaros.nersc.no/).*

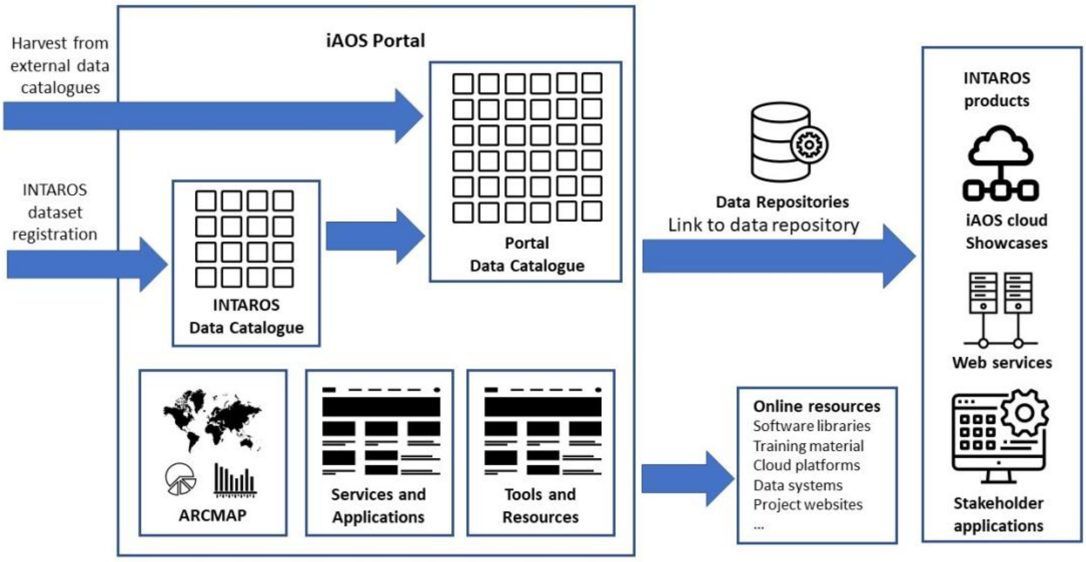


Figure 5.5 *The major components of the iAOS Portal and their interconnections.*

The ARCMAP web application for mapping and assessing Arctic in situ observing systems (Fig. 5.6) is also part of the iAOS Portal. ARCMAP was developed in a spin-off project funded by the Norwegian Ministry of Climate and Environment, and with additional support from NERSC. ARCMAP builds on and extends the INTAROS survey, offering a user-friendly way to update the assessment of Arctic in situ observing systems. By means of standard web frameworks and database technology, NERSC has implemented a methodology and a set of tools for keeping survey information updated and analyzing evolution over time.

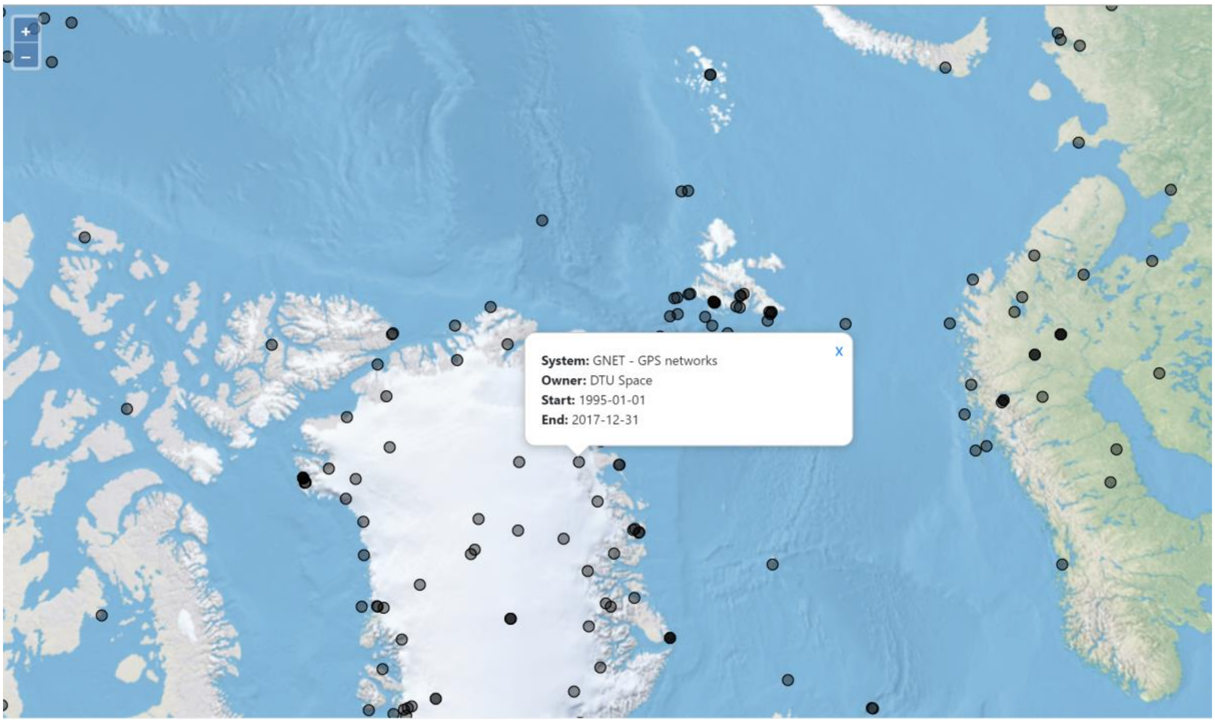


Figure 5.6 *Location of some of the individual stations, ocean moorings and other point-based in situ observing systems in ARCMAP (https://arcmap.nersc.no/).*

ARCMAP development was challenging as there are no standards for surveys requiring compound geographic information for the location of sensors, platforms, and stations. To meet this challenge, we recommend extending an open web framework, WQ.IO, to enable capture of groups of multiple categories of geographic objects as a location entity. Furthermore, the survey design was challenging as detailed information was needed to carry out a comprehensive assessment of observing capacity. This however meant the survey became complex covering a broad range of topics and thus time consuming to complete. The recommendations to alleviate these issues are twofold. First, to divide the survey into several parts that can be completed independently thereby reducing the amount of complexity the responder needs to consider in a single session. Secondly, to focus on formulating the questions in a precise and concise manner, allowing the respondent to concentrate on the key aspects of each question.

5.3 Expected impact, challenges and recommendations

The iAOS cloud infrastructure was used to demonstrate interoperability of data from existing observation systems to support the science community. Working on a set of showcase applications demonstrated that the volume, variety, and variability of data sources are still challenging to handle. The WP5-WP6 collaboration on the iAOS showcases helped to pinpoint the high interest of scientific users for improved and scalable data science capabilities (descriptive, diagnostic, predictive, and prescriptive). In this context, data preparation for inclusion into the application is the main effort to able to assess the suitability and quality of data. There are still only a few platforms supporting this time-consuming step. WP5 focused on an OPeNDAP-related capacity building and consolidating work on the PANGAEA-related tools. Data analysis of semi-structured data sources is time-consuming as well. For exploratory analysis and developing work hypotheses, WP5 focused on capacity building for Geostatistics. Once the previous steps have been completed, efficient orchestration the data processing campaigns is critical to optimize use of cloud computing resources. To address this issue, WP5 used Jupyter Notebooks with needed libraries and execution kernels installed.

Data format standards are generally well established in the software systems used by the iAOS showcases. However, some interoperability protocols (e.g., DAP2, DAP4) do still lack effective online support for software application developers. Therefore, implementing data access can be complex and time consuming. The learning curve is high for an application integrator who needs to leverage all aspects of an infrastructure such as the iAOS cloud infrastructure for efficient data access and reliable data quality assessments, high performance data processing, and easy results sharing. This challenge appeared quite from the start of the WP5 activities in INTAROS. Consequently, several tutorials and training assets were produced. These are publicly shared on the INTAROS community on GitHub: https://github.com/ec-intaros.

Earth Observation (EO) data, in particular Copernicus Sentinel products, have been successfully integrated in the iAOS cloud infrastructure, with tools and platform services demonstrated through iAOS applications. At the UAK research school (December 2018 at UNIS, Longyearbyen, Svalbard), Jupyter Notebook applications were used to introduce EO data processing techniques. The students were introduced to applications using satellite and other data: (1) AIS data to discover relevant Sentinel-1 products, (2) Sentinel-1 for snow and ice classification, (3) offset tracking techniques on Sentinel-1 Level-1 Ground Range Detected (GRD) products to derive glacier velocity maps, and (4) use of multi-year SAR data to study the seasonal dynamic of the snow melt patterns. Furthermore, INTAROS collaborated with the NextGEOSS project, where Sentinel-1 based sea ice classification and sea ice drift products were generated and published in an open data repository by NERSC for exploitation in INTAROS.

Both the INTAROS and the portal data catalogue advocate storing scientific data in sustained repositories that follow the FAIR principles. This ensures long-term data access and the ability to give scientists credit for providing data through a unique identifier (e.g., DOI – Digital Object Identifier) that enables citing datasets in a similar manner to citing papers and books. The generic design of the iAOS Portal (Fig 5.4) makes it well suited for use in future Arctic research and innovation projects. Such projects can draw upon the INTAROS branding and use the iAOS Portal as a mechanism to make their data and services known to the large network of Arctic scientists and local communities established within INTAROS. In this way, the iAOS Portal will become an important element in a Sustained integrated Arctic Observation System and serve as a window to many different systems.

Challenges in the iAOS portal and the INTAROS data catalogue development include: (1) the wide variety of data from different scientific domains, citizen science and community-based monitoring systems, (2) differences in standardization level of metadata and data, (3) data are stored in many Arctic data systems, with different interfaces (APIs) for metadata and data access. For addressing the variety of data and level of standardization, we recommend using a schema with joint discovery metadata as basis for data catalogues and encourage harmonization of metadata and data formats within a discipline. This will enable common search facilities across scientific disciplines and simplify data access and visualization. Furthermore, we strongly recommend long-term storage in repositories that offer standard interfaces, to make it easier to find and access data from different data systems.

6. WP6: Applications towards stakeholders

The work in WP6 consists of several studies where data from various observing systems have been used to develop applications to demonstrate benefits towards a wide range of stakeholder groups. The studies mainly build on in situ observations and model output, a few in addition apply remote sensing data. The applications were focused on selected topics of societal importance for people living and working in the Arctic as well as for the Arctic countries, Europe and the global community.

6.1 Improving skills of model predictions in the Arctic

6.1.1 Climate prediction

The main aim was to demonstrate the potential for new datasets produced as part of a unified Arctic Observation System to positively impact our ability to carry out skilful initialized climate predictions for the Arctic region (and beyond). The climate predictions serve as input or reference for planning and decision-making in various economical and societal sectors via upcoming climate services.

Sensitivity studies were performed by NERSC and SMHI employing their respective seasonal-to-decadal climate prediction systems. They demonstrated the general benefit from initializing sea-ice information for these forecasts: The assimilation of anomalies of sea ice *concentrations* in NorCPM (developed and used at NERSC) was shown to be particularly beneficial for seasonal predictions along the sea-ice edge, while sea ice *thickness* is more important for the central Arctic. A similar study by SMHI in collaboration with the Danish Meteorological Institute using their own seasonal-to-decadal prediction system based on the model EC-Earth3 confirmed this positive result for longer forecast lead times up to several years and even for the temperature predictions over remote areas, such as the North Atlantic Ocean (see Figure 6.1). Hence, assimilation of sea ice concentrations and thickness is complementary and joint assimilation yields the best overall result.

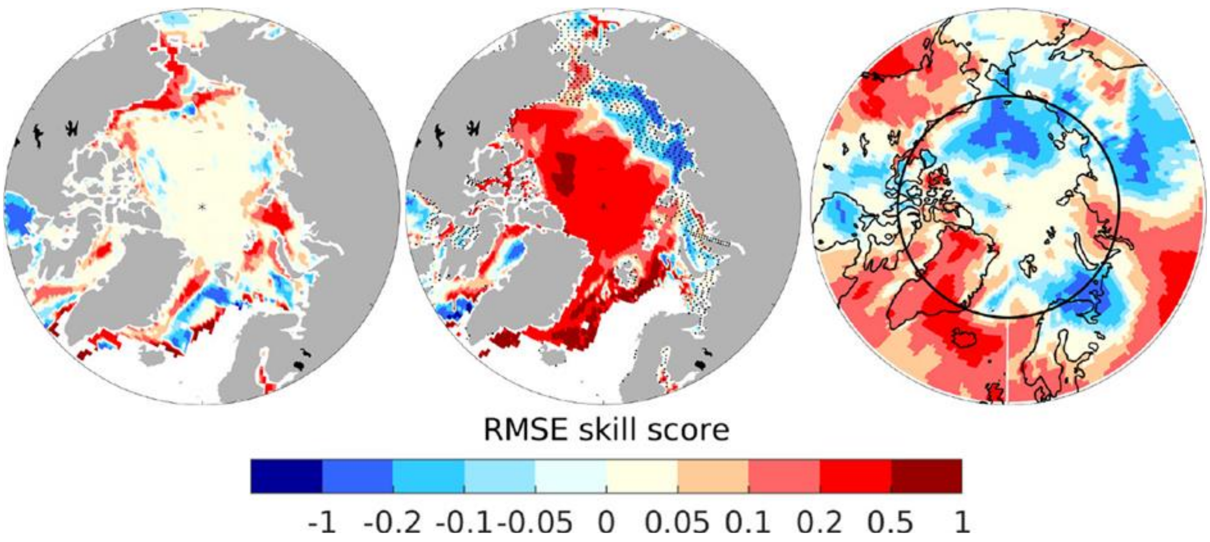


Figure 6.1. *Seasonal prediction skill (measured by the RMSE skill score) gained by the initialization of sea-ice variables for the first winter (DJF) average of sea-ice concentrations (left), sea-ice thickness (center), and 2m-temperature (right). Positive values indicate higher skill (smaller forecast error) than when initializing only ocean temperature and salinity. Figure taken from Tian et al. (2021;* https://doi.org/10.5194/gmd-14-4283-2021, *distributed under the Creative Commons Attribution 4.0 License)*

6.1.2 Hydrological forecasting

The aim of this activity is to demonstrate the added value of an integrated Arctic Observation System for enhancing and make available hydrological model predictions for the major Arctic rivers. The main objective is to combine river discharge data from the Arctic Hydrological Cycle Observing system (Arctic-HYCOS) - assessed and enhanced in INTAROS WP2 – with the pan-arctic hydrological model Arctic-HYPE, provided by SMHI (http://hypeweb.smhi.se), to predict and monitor freshwater inflow to the Arctic Ocean and changes in Arctic hydrological regimes.

The demonstration case consists of an operational application of the Arctic-HYPE model providing daily analyses of the last 60 days, and medium range forecast of the coming 10 days. The Arctic-HYPE analyses and forecasts are stored at SMHI open data repositories and will be made available using OPeNDAP server technology. Arctic-HYCOS observations are accessed by the operational service using the tools and metadata accessible from the INTAROS data catalogue (https://catalog-intaros.nersc.no/dataset/arctic-hycos-hydrological-data/).

For the above-mentioned demonstration case, a sub-set of the Arctic-HYPE model covering the Republic of Sacha (Yakutia) in Far East Russia, was used to develop a spring flood and river ice breakup forecasting service. For the spring flood 2020, the new version of Arctic-HYPE (v4.2) was implemented to run operationally in the SMHI production system, publishing the outputs of the 10-day forecast and 60-day analysis daily in an internal offline version of the OPenDAP server. Results were extracted for selected locations in the Yakutia domain. The forecast points were selected based on availability of in-situ observation as well as stakeholder interest.

A summary of the forecasts providing information on the expected river ice breakup dates, and river water level tendencies, were made every day by collaborators at the Melnikov Permafrost Institute in Yakutsk and communicated with the local stakeholders. For example, the 2020 river ice breakup in the Lena River at Yakutsk took place on the 11th of May and this was correctly predicted by the Arctic-HYPE forecast issued on the 8th of May. A few days after the on-set of ice flow in the river, an ice jam was developed in the Lena River at Kangalassy; downstream of Yakutsk; with flooding of parts of the city. This use-case illustrates how the Arctic-HYPE data may be used in a future application when it is made available on the open OPeNDAP server.

Expected impact, challenges and recommendations

Assimilation of sea-ice concentration is particularly beneficial for predictions along the sea-ice edge, while sea-ice thickness is more important for the central Arctic. Hence, the assimilation of both is complementary and yields the best overall result. A more general way of exploiting sea-ice data is the inclusion into major reanalysis products such as those from ECMWF**.**

Arctic river runoff predictions for regional and/or pan-Arctic applications can be improved by assimilation of observational data, but the access to provisional data needs to be improved for real-time analyses**.** Runoff data should be used for improved runoff predictions, providing river discharge to the climate prediction community, and forecast products for local and regional stakeholder**s.**

6.2 Applying observations and models for environmental and fisheries management

The main aim here is to demonstrate how observational and model data from an Arctic observation system may be used to enhance the environmental and fisheries reporting and management systems of the Barents Sea and Disko Bay, western Greenland. Further, when such systems are established, this is valuable for implementing similar procedures in other parts of the Arctic. Towards these goals, we use a range of state-of-the-art ecosystem models. The work has been carried out in close collaboration with stakeholders, through workshops and one-to-one interaction with representatives from Greenland and Norwegian fisheries and environmental management agencies.

6.2.1 Barents Sea case

The main focus of the Barents Sea case was to evaluate the appropriateness and significance of the indicators applied in the Norwegian Barents Sea ecosystem management plan (BSMP). The data sets used for indicators in the existing management plans consists mainly of a simple time series, here we explore more complex time series, including some with a spatial component and focus on ecosystem-type.

In the MSMP more than 70 indicators have been suggested. The indicators are mainly based upon information from research vessel cruises, the most extensive being the Barents Sea Ecosystem Survey (annually August-October since 2004), run jointly between IMR and VNIRO Arctic, Russia. The extensive spatial and temporal survey collects information on physical and chemical oceanography, meteorology, phyto- and zooplankton, fish, benthos, marine mammals, seabirds, litter and contamination.

We used two end-to-end ecosystem models to evaluate how they respond to changes in climate and fisheries management. NORWECOM.E2E is a coupled physical, chemical, biological NPZD model system (Fig.6.2 left), and NoBa Atlantis is a modular system, which in this case includes 53 functional groups and species, representing key components of the ecosystems in the Nordic and Barents Seas (Fig.6.2 right). Time series of a set of the proposed indicators have been estimated using the methodology suggested in BSMP under a future climate projection. Through an Observing System Simulation Experiment (OSSE) the effect of sampling scheme has been investigated, and the design of a minimum cost monitoring program has been suggested. To reduce the number of indicators without losing to much information, the models have also been used to search for an optimal indicator subset. We found that both the area where the indicators are sampled, and the timing of the observations are important for their performance. The indicators give a good overview of the Barents Sea ecosystem, but the management plans lack socio-economic indicators, which prevents a holistic view of the system. While the concrete outcome is specific for the Barents Sea, the approach and methods developed may be adjusted to be applicable to other regions. By building on models in addition to observations, the approach may also be applicable to data poor regions.

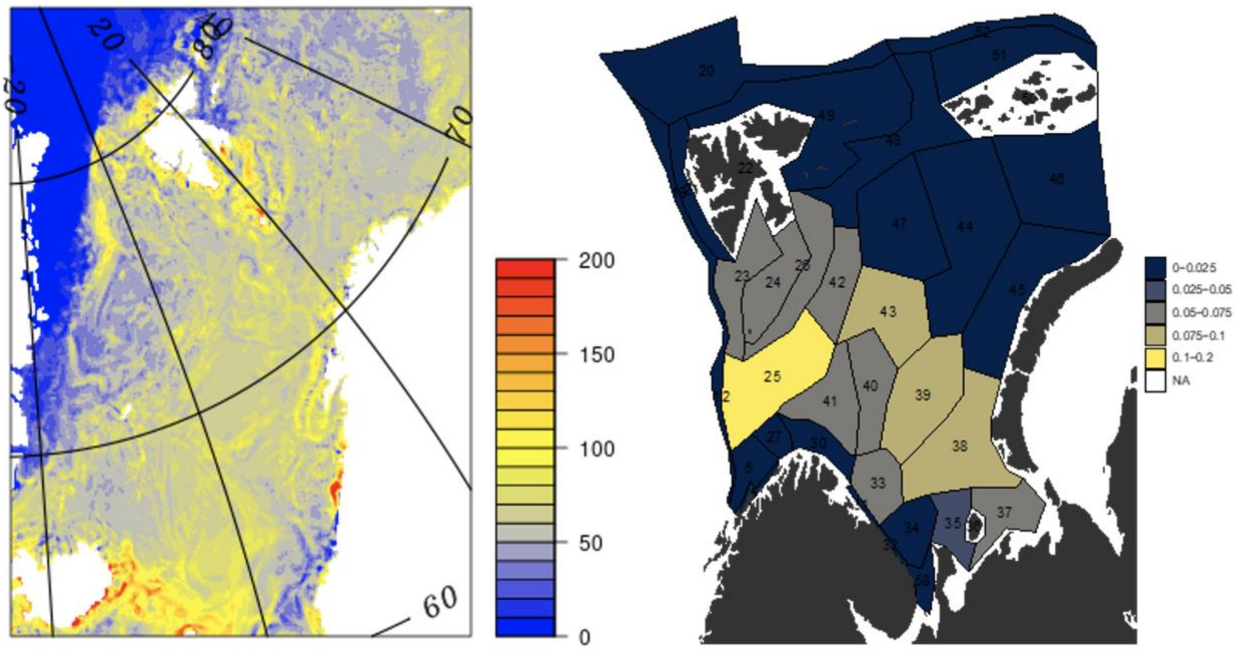


Figure 6.2 *Examples of Barents Sea model products. New primary production from NORWECOM.E2E to the left, cod biomass distribution (winter) per Atlantis polygon to the right.*

6.2.2 West Greenland case

Our work in Greenland were centered around two activities: 1) developing an ecosystem model for Disko Bay and using it for sensitivity studies of the combined impact of sea ice changes and glacial melt water on coastal productivity. 2) a synoptic retro-perspective analysis of the coupling between key ecosystem drivers and the demersal fish community on the western Greenland shelf.

Disko Bay Ecosystem Model
We demonstrate downscaling from large-scale regional models to fine-scale local models of Arctic coastal waters, with focus on the Disko Bay (Fig. 6.3). A coupled hydrodynamic and biogeochemical model was set up using the FlexSem model system. The system contains modules for hydrostatic and non-hydrostatic hydrodynamics, 3D pelagic and 3D benthic models, sediment transport and agent-based models. The biogeochemical model ERGOM was coupled to a 3D hydrodynamic module in the FlexSem framework. Several datasets from INTAROS and other sources were used to set-up and improve the model.

This FlexSem-ERGOM model was used to evaluate impacts of climate and other environmental change on local marine resources to support management decisions and stakeholder involvement. The downscaling approach provides intelligent extrapolation of ocean parameters to un-sampled or under-sampled areas, as well as a platform to conduct OSSE design studies to optimize future observational deployment. We evaluated the relative importance of sea ice cover and freshwater discharge from the ice sheet for primary productivity. Glacier meltwater discharge had a strong local effect near the glacier (Figure 6.3), but when considering the primary productivity at bay scale, sea ice cover was the most important factor. Primary production is a relatively simple indicator that is easy to understand and use in management when considering changes in the system due to environmental change or the link to higher trophic levels.

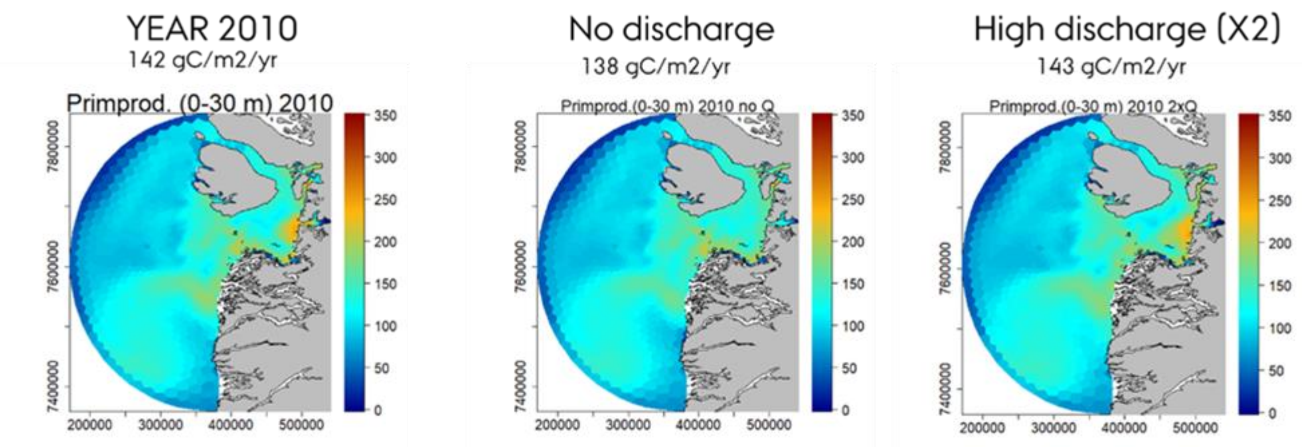


Figure 6.3. *Annual primary production (0-30 m) for Disko Bay and the surrounding area for year 2010 (left), with no freshwater discharge (mid) and double freshwater discharge (right).*

The impact of climate variability on Greenland fish distributions was analysed based on annual fish surveys (1993-2016) conducted by the Greenland Institute of Natural Resources along the West Greenland Shelf (59-73 °N). This data set is one of the most comprehensive biological data sets from the region and is thus ideal to explore links between potential ecosystem drivers and marine resources essential for the Greenland society. Time series of ecosystem drivers were compiled based on open data repositories, remote sensing products and large-scale modelling.

The aim of this study was to characterize biological change and to assess potential drivers of change. We found extensive changes in the fish community, with an increase in biomass, average individual weight and trophic level combined with changes in the composition of the dominant species. Using previous studies as a baseline we found a partial recovery of the fish stock took place in the mid 1980s. Most species showed a range expansion, but a general northern displacement was not observed. The development of all drivers (sea ice cover, water temperature, glacier run-off, shrimp trawling) appears to exert a positive effect on the fish community, hence the apparent recovery is partly facilitated by the climate change driven melt of the sea ice and Greenland ice sheet, which has contributed to increasing the productivity of the coastal ocean off SW Greenland. The documented variability of the marine ecosystem off west Greenland, and the complexity of biotic and abiotic drivers involved, poses a substantial challenge for a society that relies almost exclusively on marine living resources. For the West Greenland coast and shelf, enhanced management should build upon an improved dynamical understanding of food-web changes in response to multiple stressors.

Expected impact, challenges and recommendations

Observing System Simulation Experiment (OSSE) for Barents Sea monitoring program has been carried out successfully. Models used to evaluate impacts of climate and environmental change on local marine resources have been used to support management decisions and stakeholder involvement. These has been good involvement and interaction with stakeholders from fisheries, maritime, and petroleum management and industry, and especially environmental management, both in Norway and Greenland.

Recommendations are:

- OSSEs should be made integrated part of management plan work
- Evaluation of indicators should be expanded to an Arctic international setting
- Indicators based on more complex set of time series should be used to better monitor a broader range of human pressures
- Support, contribute to and use results from new Greenland GIOS program
- Establish new NAFO/ICES working group on the west Greenland-Canadian system

6.3 Ice-ocean statistics for research and environmental assessment

Ice-ocean statistics in the Arctic can be estimated in many ways depending on what data and models are used. In this chapter the work performed by the INTAROS partners is summarized.

6.3.1 Observing system simulation experiments and reanalysis

Two Ocean system simulation experiments (OSSE) have been conducted for a period 10 year. In order to assess impacts of assimilating (1) near-real-time ocean and sea ice observations, (2) delayed-mode oceanographic and sea ice data, and (3) monthly sea level data on from altimetry. Results show that both ice concentration and ice thickness estimates are significantly improved after data assimilation. A 10 year reanalysis has been produced to evaluate the capacity of the existing Arctic Ocean observing system. The reanalysis was produced by assimilating all available observations between 2007-2016 (Fig. 6.4).

Results suggest that the mooring systems needs to be enhanced since temperature and salinity are only observed at a couple of levels. Although the numbers of in-situ profiles in the central Arctic have increased significantly over the past decades, it is still too sparse, and its effects are not apparent in the data assimilation experiments.

Expected impact, challenges and recommendations

The Arctic reanalysis must be viewed as a tool that can now be further improved and further developed. Including new observations and prescribing more realistic errors both will lead to more accurate estimates of the Arctic circulation and its impact. Resulting fields will form the basis for developing information for users and stakeholders, such as transports and their changes, sea level change, freshwater or heat content change. Respective fields in the future will be used especially also for analyses of carbon budgets in the Arctic; they will likewise serve to initialize climate prediction efforts. It is recommended to continue development and validation of OSSEs and reanalysis products for the whole Arctic Ocean benefiting from new satellite products and enhanced in situ observations. Use the systems to analyse the benefit of adding new data to support the development of the arctic ocean observing system, and to provide validated synthesized 4 D fields with uncertainty estimates into risk assessment systems.

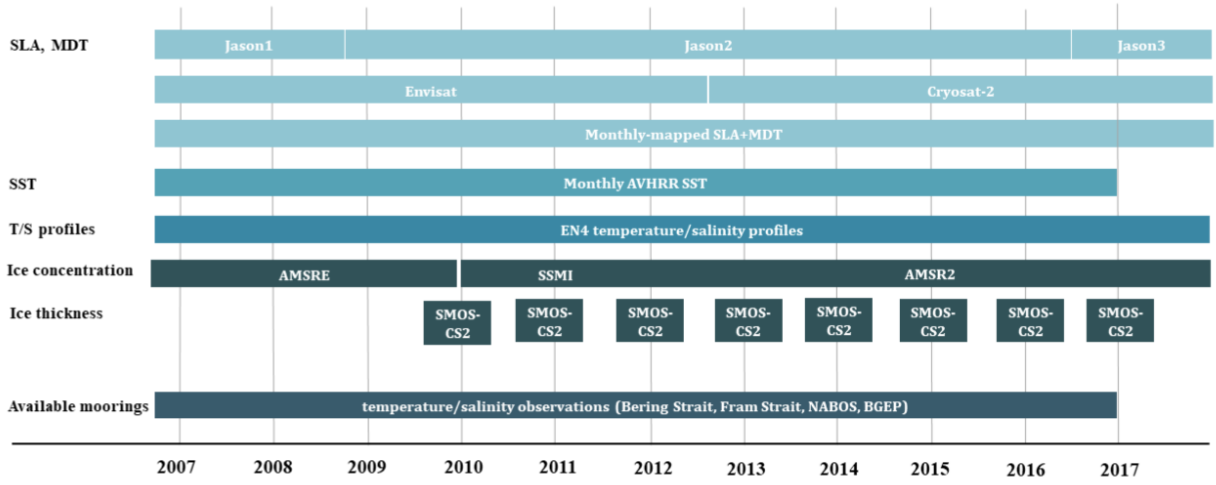


Figure 6.4. *Data used for the reanalysis 2007-2017.*

6.3.2 Risk assessment system

A risk assessment system with a user-friendly interface has been developed to support different stakeholder groups in planning of safe operations in ice-infested areas. The 10-year reanalysis and sea ice extent data from satellites were used as data sources in the risk assessment system. The structure of the integration of gridded data are shown in Figure 6.5. The workflow in the assessment system is the following:

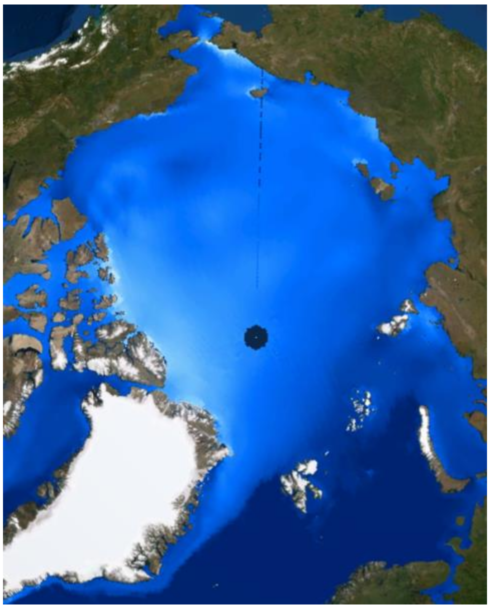
1. Determine relevant data sources to the analysis (i.e., the use cases)
2. Qualify data with respect to quality, consistency, and reliability
3. Assemble and integrate data in ArcGIS
4. Spatial analysis to derive statistics on phenomena and their co-variation
   a. Capture spatial and temporal variation
   b. Location specific risk analysis

The link to the reanalysis opens for a wider application of the environmental risk assessment including the impact of ocean climate change on the eco system and impact of increased shipping on the 'ocean sound'.

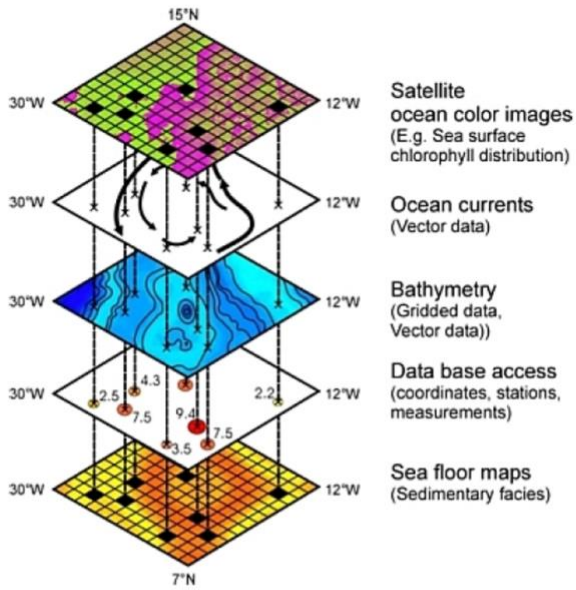
Expected impact, challenges and recommendations

The risk assessment system developed by DNV has focused on providing statistical information on sea ice concentration and ice edge position mainly for ship traffic in the Arctic. The system has ingested oceanographic and sea ice field from reanalyses, which makes it possible to include oceanographical conditions in the risk assessment. To have more impact it is important that risk assessment systems are extended to include 3D fields from re-analyses from both physical and ecosystem models as well as in situ observations from monitoring programs. It is a challenge that large areas of the Arctic have no in situ data, and in aeras where such data have been collected there is significant delay in the delivery chain. This implies that reanalyses are not using the most recent in situ observations.

The impact of better environmental risk assessments in the Arctic will support a sustainable development of the Arctic regions and the implementation of the SDG11 (sustainable communities in the Arctic), SDG12 (adaptation to climate change in the Arctic), SDG14 (assess risks and provide mitigation plans to protect and manage life under water).



a



b

Figure 6.5. *(a) Map of sea ice thickness generated from the UHAM reanalysis for April 2016; (b) the main layers of data in the GIS system of the risk assessment system.*

Recommendations are:

- *Develop holistic risk assessment systems seamlessly integrating and exploiting reanalysis products, in situ observations in support to a wide range of actors (e.g. public and private sector) in the Arctic.* In particular, the assessments should cover the full ice-water column (physics, biogeochemistry, and ecosystem). A particular focus should be to detect regions with environmental risk, and eventually suggest improved new observing sites.
- *To include 'ocean sound' into risk assessment and co-develop environmental risk assessments with actors in the Arctic.* A holistic assessment should involve a wide range of experts within underwater acoustic, ocean climate and processes, biology, and bioacoustics. A particular focus should be to detect areas which are particularly vulnerable and provide recommendation for required long term or short-term observing sites.

6.3.3 Ocean Sound in the Arctic

Ocean Sound includes natural sound (e.g. ice cracking, waves in ice, melting ice, communicating marine mammals) and sounds coming from human activities (e.g. shipping, research, helicopters, ice breakers). Due to climate change and increased knowledge about the potential impact of man-made sound on marine life there is a growing awareness of the human impact on the ocean acoustic environment in all world oceans. The acoustic environments are in general pristine in the Arctic, but it is also assumed to be vulnerable to changes in human generated sound. In INTAROS we have focused the acoustic work on the Fram Strait (Fig. 6.6 and 6.7).

Acoustic modelling and ice-ocean reanalysis have been used to improve the design of future acoustic observation systems in the Fram Strait. Analysis of passive acoustic observations from moorings showed that data from moorings in areas with strong currents are strongly influenced by strumming and care must be made when using the data to assess levels. The data from a two-year long experiment shows that the open ocean environment is significantly more disturbed by seismic exploration (e.g. Barents Sea and North Sea) than the environment inside the ice edge (Figure 6.4). This is because the mid frequency sound is rapidly damped down by the presence of sea ice, and bottom interaction in the shelf regions are dampening the low frequency component. Seasonal and spatial variability in the acoustic environment is large in the Fram Strait and compared to other regions.

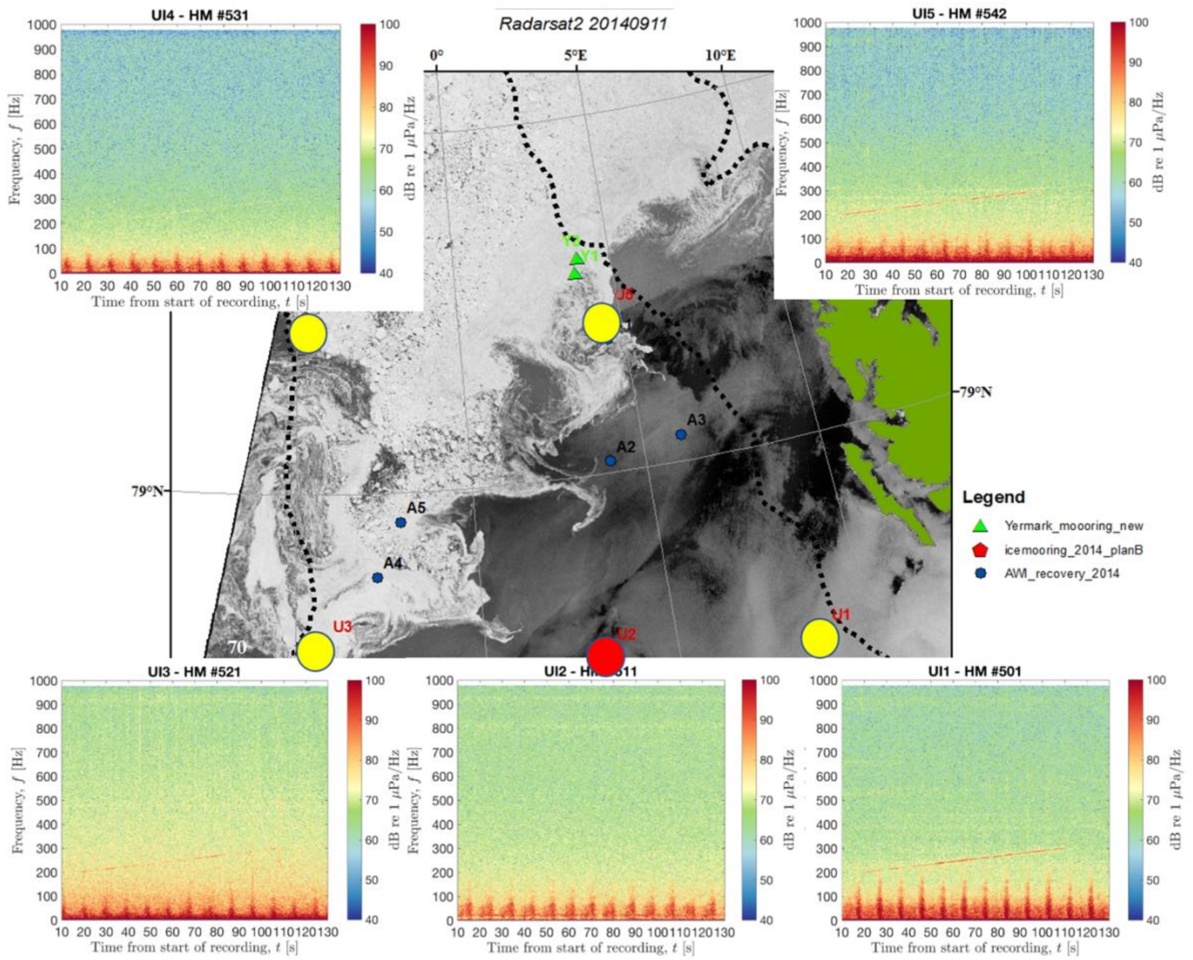


Figure 6.6. *Passive acoustic measurements from five moorings (shown in yellow) in the Fram Strait from the UNDER-ICE experiment 2014-2016. The data show strong impact of seismic between 20-200 Hz. The signature is strongest at the location nearest the Barents Sea, and weakest at the moorings inside the ice edge. The tomographic signal sent from the mooring in red is barely seen, but the signal is detected through advanced signal processing.*

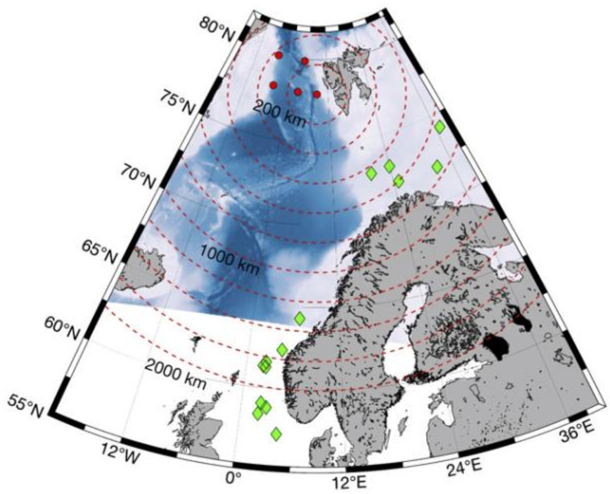


Figure 6.7*. The map shows seismic exploration activities (shown in green) taking place on the same day as the passive acoustic recordings were made (12 Sept 2014).*

Expected impact, challenges and recommendations

The following recommendations are given:

- *Gain more knowledge through research programs about long-term effect on the acoustic environment caused by environmental changes due to climate change and increased human activities in different arctic regions.* In understanding and assessing the evolution of 'ocean sound' it is crucial to consider the effect of topography, geo-acoustic conditions, and sea ice. This can be done by analysing passive acoustic observations from different locations over time, and through 3D+T acoustic modelling using reanalysis fields as input to the model systems.
- *'Ocean sound' observations should be standard observations in existing mooring networks or in drifting ice observatories.* Such observations will provide data on how seasonality, climate change, and human activities impacts the acoustic environment in different regions. Furthermore, work should be done to detect and identify the sounds produced by marine life to understand the extension and migration of species with respect to changes in the acoustic environment.
- *Make knowledge about the acoustic environment (e.g. ambient noise and propagation conditions) available for useful for technology developers to tailor and improve acoustic technologies for the Arctic.* Ambient noise stems either from natural sources or human activities, and together with acoustic propagation conditions (e.g. ocean stratification and sea ice roughness) it influences capabilities in underwater acoustic communication, navigations, and observation technology.
- *Implement and sustain a multipurpose ice-ocean observing network in integration with moored and drifting acoustic network for observing (passive acoustic and thermometry), geo-positioning for floats and navigation of gliders.* An acoustic network will foster innovation within autonomous underwater observing platforms (e.g. improved geo-positioning of gliders and subsurface floats operating under ice) and technology for search and rescue operations (e.g. localization and tracking of objects). This will reduce the environmental footprint of increased observing and operations in the Arctic.

6.3.4 Oceanographic and sea ice time series

Ice-Ocean statistics have been derived from oceanographic in situ measurements collected in the in the Nordic Seas and Arctic Ocean over the last two decades. Data from several ice buoys have been analysed to better parameterize the melting processes in ice-ocean models. These fields can be used for further ocean reanalysis and for validation of climate modelling/synthesis. Several satellite remote sensing products of sea ice have been improved and the time series have been extended. These include sea ice concentration, drift, multiyear fraction and thickness of thin ice. Ice concentration time series have been used on climate model studies reported in section 6.1.

6.3.5 Sea level from altimeter and tide gauge data

Sea level is an important measure of multiple ongoing processes related to the changing climate in the Arctic. Observing sea level is therefore important for monitoring the Arctic climate system. The main data source is satellite radar altimetry data which has been collected for more that 30 years and provides a unique data set to estimate mean surface topography and sea level anomalies. In INTAROS work has been done to improve the retrieval methods from altimeter data in the Arctic. Furthermore, the steric sea level change has been calculated from all available temperature-salinity profiles in the oceanographical database UDASH. The altimeter sea level records have been compared with tide gauge measurements (Fig. 6.8). These data have been used in a combination with a model to estimate the vertical land motion in the Arctic.

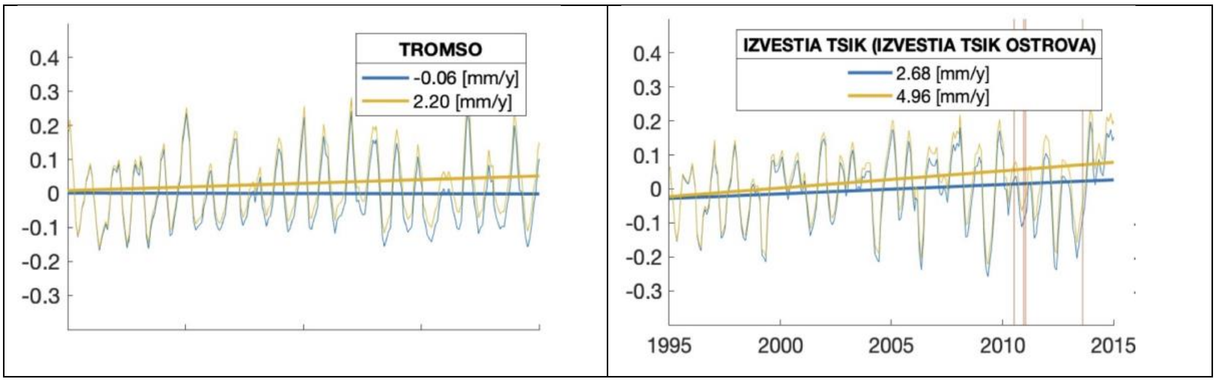


***Figure 6.8**. Tide gauge observed relative sea level (blue) and vertical land motion (VLM) corrected sea level (yellow) at 2 selected stations (in meter). Red bars indicate missing data.*

Expected impact, challenges and recommendations

The largest challenge in the Arctic is the limited number of observations of sea level tide gauges. The number of operational tide gauge stations has been severely reduced since the 1980s. It is therefore of high priority to maintain and develop the tide gauge data sets in the Arctic, including use of new technology such as GNSS reflectometry. In situ sea level data are essential for validating the satellite altimetry data, which will continue to be collected as the main source of data for sea level observations.

6.3.6 Sea ice mass balance buoys

The objective of the drifting sea ice mass balance buoys is to measures high-resolution (2cm) vertical temperature profiles through the air-snow-sea ice-ocean column. The temperature profiles are used to derive snow depth and ice thickness. In INTAROS a network of 44 of these buoys were deployed and provided valuable thickness data for estimating the total volume of sea ice and the ocean heat flux in the Arctic (Fig. 6.9). The data are also important for validation satellite retrievals of snow and ice thickness from altimeter data. The temperature data from the buoys are transmitted via Iridium. The algorithms for calculating snow and ice thickness from the temperature profiles are improving, but manual analysis is required to provide good quality thickness data.

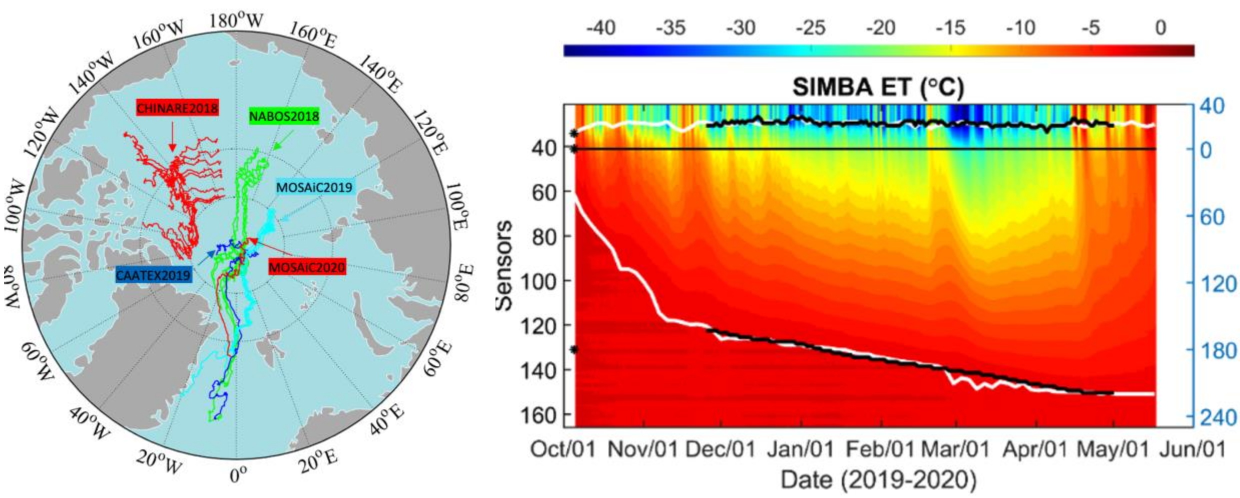


***Figure 6.9.** (a) Trajectories of SIMBA buoys deployed 2018-2020; (b) Temperature data from one SIMBA buoy indicating the snow thickness on top and the ice thickness at the bottom.*

Expected impact, challenges and recommendations

SIMBA data will be valuable for future scientific research as well as development of operational marine weather forecasting system for the Arctic Ocean. Snow and ice thickness along Arctic Northeast Passage (ANP) is of great important for the commercial shipping industry. It is recommended to deploy a long-term sustainable SIMBA network. Collaboration with shipping industry (tourist industry) is very useful to support deployment of SIMBAS in a larger part of the Arctic.

6.3.7 Sea ice products from remote sensing

The work has focused on further development of sea ice products from satellite passive microwave (PMW) and scatterometer sensors (Fig. 6.10). These sensors have been used over many years to retrieve sea ice variables, in particular sea ice concentration (SIC)/extent, sea ice type and sea ice displacement. Daily SIC data are used for (1) initialisation of and assimilation into global climate models (GCM) and numerical weather prediction (NWP), (2) for shipping in polar seas, and (3) various climate and environment studies. The SIC data were used in the ice-ocean reanalysis described in section 6.3.1. The sea ice products are produced and delivered under the Copernicus Marine Services and are updated daily with new data. Use of drones for sea ice observation was tested during the cruise with KV Svalbard in 2019. Drones can provide very high-resolution optical images of sea ice floes, leads, ridges, cracks and other small-scale features. The drone data can mainly be obtained over smaller areas in connection with icebreaker cruises and can be useful for mapping the details of the sea ice which is useful for ice navigation. The drone images can also be useful for validation satellite remote sensing data of sea ice.

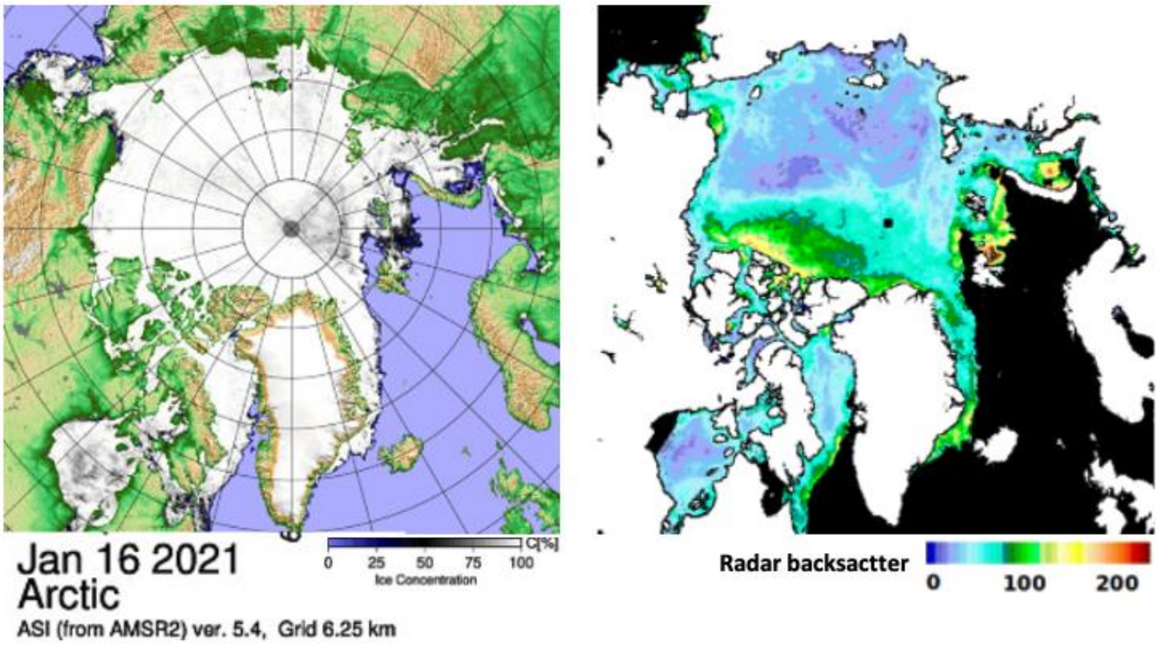


Figure 6.10. *Left: University of Bremen's ice concentration map produced from AMSR2 passive microwave data. Right: Ifremer's radar backscatter map from ASCAT scatterometer, where different ice types can be distinguished. Both products are obtained on the same day, 16 January 2021*

6.4 Natural hazards in the Arctic

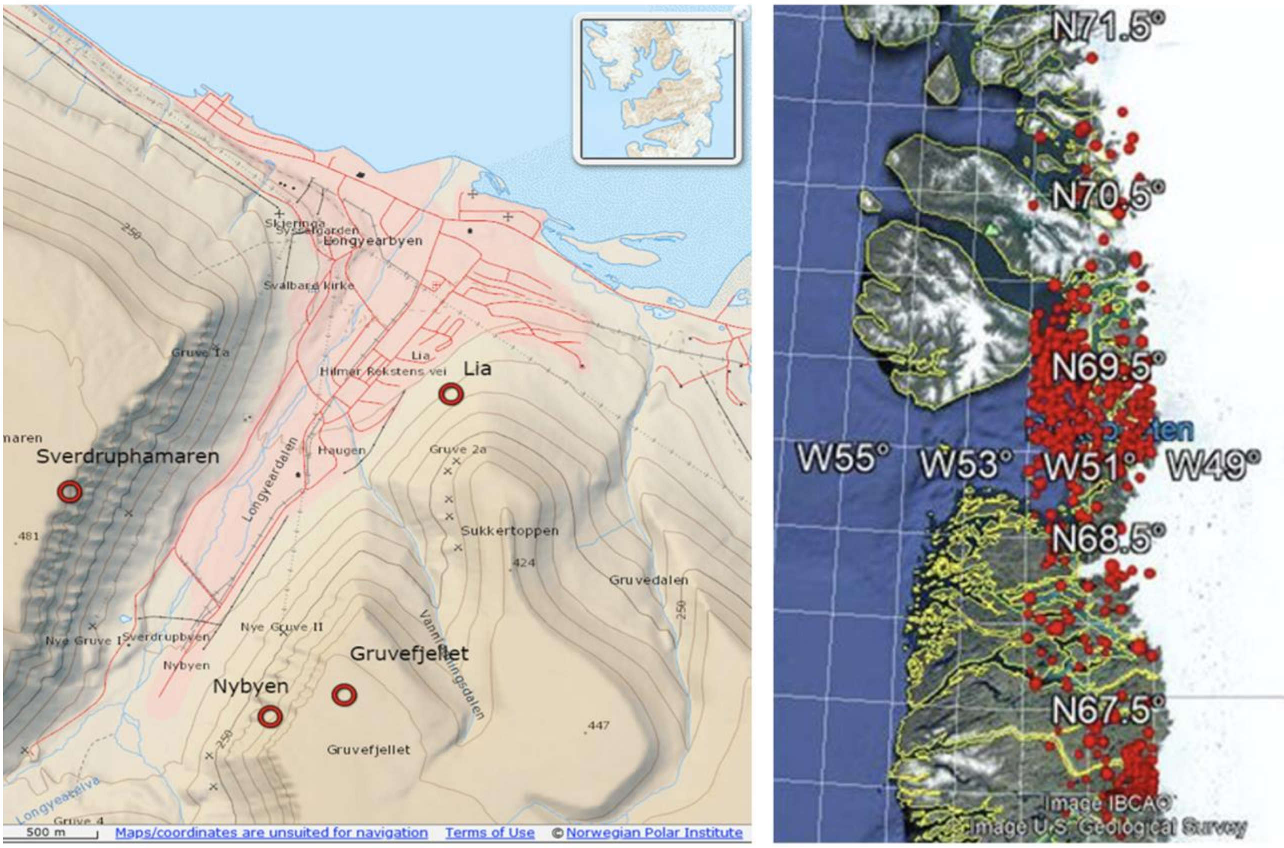
The studies of natural hazards in the Arctic have focused on three selected types of hazards:

- Snow avalanches
- Earthquakes, landslides, and tsunamis
- Mass loss from ice sheets and glaciers: Sea level rise and freshwater discharge

The chapter summarizes how data and methods available from Arctic observation systems are used to increases our understanding of the hazards. The chapter also identifies gaps in the observations and suggests improvement to better fulfil stakeholder needs.

Snow avalanches

The snow avalanche work has focused on Longyearbyen, Svalbard (Figure 6.11) where a disastrous event occurred in 2015. Heavy precipitation, in the form of snow or rain, generally occurs during these extreme events, challenging infrastructures and local communities because of the high risks of avalanches and landslides. Snow avalanche forecasting models rely on output from numerical weather prediction models of snow precipitation and snow accumulation as input. However, numerical weather prediction models cannot resolve the complex Svalbard topography and therefore cannot provide accurate snow precipitation and snow accumulation on the mountain slopes where avalanches take place. Studies were conducted to find statistical relationships between the in-situ measurements of snow depth at a few observing stations (Fig. 6.11a) and the meteorological parameters that affect the distribution of snow accumulation on the mountain slopes surrounding Longyearbyen.



b

Figure 6.11. *(a) Map of Longyearbyen the snow stations (Lia, Nybyen, and Sverdruphamaren) and of the closest automatic weather station (AWS) Gruvefiellet; (b) Map of Western Greenland with earthquake epicenters registered between January 2016 and February 2020, shown as red circles.*

Weather forecast models still have too coarse spatial resolution to produce near surface wind and precipitation that would be precise enough for snow avalanche prediction models. Forecasted snow accumulation can be empirically corrected based on in-situ observations, but the main challenge is lack of observation in the critical areas for avalanches. This is now being improved by efforts by the local community in Longyearbyen to improve snow observations. A new project at the Arctic Safety Centre at UNIS starting in 2021: *Risk governance of climate-related systemic risk in the Arctic* (Arct-Risk) will focus on how to manage snow avalanche risks and othe climate related risks. .

Recommendations: Longer time series of collocated snow and meteorological observations from the snow release areas around Longyearbyen need to be established. Terrestrial laser scanner (TLS) would provide invaluable data of the snow thickness distribution at the slopes surrounding Longyearbyen. Meteorological, snow depth, and TLS data should be delivered in real time.

Earthquakes, landslides, and tsunamis

Seismometers can provide information on earthquakes, but also on landslides, snow avalanches and, to some extent, tsunamis. Local communities need clear information that can be implemented in decision-making. This includes information on previous events, the potential for future events with associated uncertainties, and the potential impact of events on societies and the environment. Good detection requires a dense network of stations, also covering the ocean areas, at locations with a low noise level. Permanent seismic stations are currently restricted to land areas, leading to large monitoring gaps in the ocean areas (Fig. 6.11b).

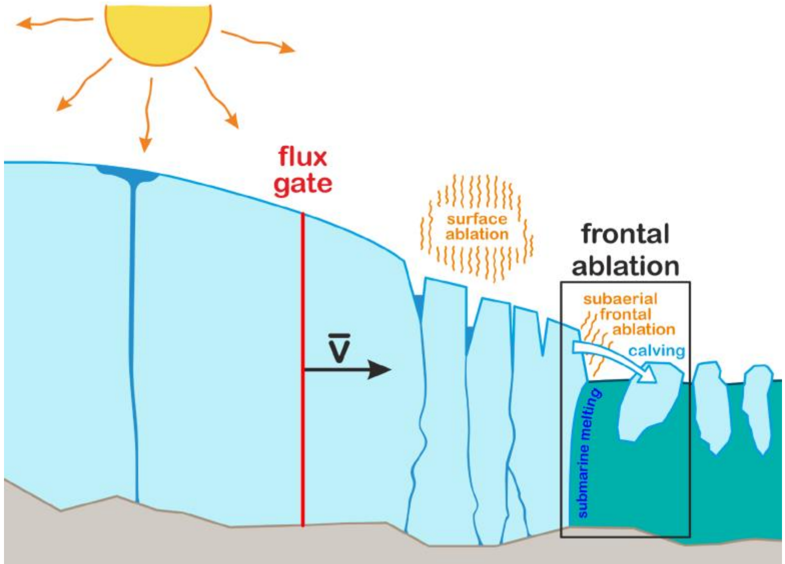
In INTAROS three ocean bottom seismometers (OBS) were deployed to fill the observational gap in the oceans. In addition, community-based seismometers were deployed in West Greenland. The results show that observations from the OBS improve our understanding of the ridge seismicity and demonstrate how even very few stations can significantly improve earthquake detection and locations. Community based seismometers have contributed to better earthquake location detection and to raise awareness among community members where they are deployed.

Data from the seismic stations have been used together with remote sensing study of landslides in West Greenland. The combination provided accurate location in time and space of landslide events, since the seismic data have high time resolution, but low spatial resolution whereas the satellite data have a low time resolution but a high spatial resolution. This method showed very promising results and should be used in the evaluation of future landslide risk. **Recommendations:** For smaller earthquakes and other seismic events that can have severe impact in local communities, a long-term monitoring is needed. In coastal regions, this can be obtained using existing technology, but power supply and internet access is challenging at remote locations, especially in the ocean. In addition to cabled OBS deployment, long-term seismic monitoring on the sea bottom can be achieved with other types of cabled systems, allowing for continuous power supply and real time data transfer. Fiber-optic cables have been demonstrated as potential seismic sensors, also in remote/inaccessible areas. Floating seismometers (Mermaid systems) may be another solution for seismic monitoring, potentially also under the sea ice, if the technology is further developed. Effort should be put into multi-hazard and -risk assessment in the arctic region, considering the effects of climate change and also the potential for cascading events.

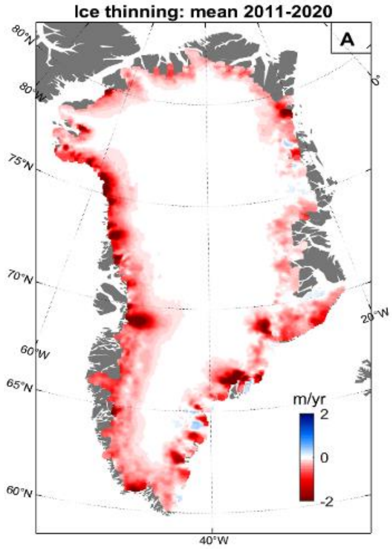
Mass loss from ice sheets and glaciers: Sea level rise and freshwater discharge

Mass loss from glaciers and ice sheets from either melt or calving eventually ends up as a freshwater input to the local fjords and ultimately the oceans, contributing to sea level rise. It therefore potentially constitutes a hazard important to both local and global stakeholders, who require an estimate as accurate as possible of the projected sea-level rise under various emission scenarios.

Monitoring and understanding the mass loss from the ice sheet is essential in order to project its future contribution (Fig. 6.12). However, separating the mass loss between the main processes of surface mass balance (snowfall and melt) and marine mass loss (iceberg calving and glacier front melting in the ocean) remains elusive. Continued observations of ice-sheet-wide mass change and an improved understanding of the processes leading to this change are needed to improve the projections. In INTAROS multiple data products have been developed quantifying the total mass loss, solid mass loss, liquid mass loss, and freshwater runoff from the Greenland Ice Sheet. Also, tools have been developed to improve the error estimates of the solid ice discharge and a model-based approach to separate the frontal ablation of tidewater glaciers into its two main components iceberg calving and submarine melting.



a



b

***Figure 6.12** (a) Illustration of iceberg calving, and (b) map of the thinning of Greenland ice sheet from 2011 to 2020.*

Solid ice discharge A tool delivering highly resolved spatially (glacier scale) and temporally (bi-weekly) estimates of where and when solid ice and submarine melt discharges into the surrounding fjords and seas exists. It is an "operational" product from 1986 until last month, updating approximately every 12 days with a one-month lag. The ice discharge uncertainty is primarily due to uncertainties in the ice thickness at the flux gates. As the ice thickness dataset is updated, the uncertainty will decrease. This solid ice discharge is either submarine melt, which impacts ecosystems, or icebergs, which are both an important part of the Greenlandic tourism economy, a navigation hazard for boats and ships, and a potential tsunami-source hazard for coastal towns.

Freshwater runoff This product includes melted ice (a mass loss term), but also rainfall which is mass neutral. We have created a high spatial (outlet scale) and temporal (daily) estimate of where and when liquid freshwater (i.e. rainfall, melted ice, and melted snow) discharges into the surrounding fjords and seas from 1958 through 2019. With this product quantifying liquid water runoff, stakeholders now have access to a dataset that can be used for a variety of ecosystem model studies related to the regional fishery economy or safety and hazards.

Quantifying ice discharge errors Within INTAROS we have developed tools based on statistical error propagation techniques, to estimate the error in ice discharge as a function of the errors in the variables and parameters involved in the discharge computation. This fills a significant gap in the uncertainty estimates associated with ice discharge computations, by narrowing their error ranges.

Expected impact, challenges and recommendations

The studies of natural hazards have shown how the data and tools available through INTAROS can be used to better understand snow avalanches, earthquakes and mass loss from ice sheets and glaciers in the Arctic. Snow avalanche forecast models rely on accurate data on snow depth and accumulation, and such date has been lacking in the Longyearbyen region. Now there are efforts to improve the data collection needed for better snow avalanche forecasting. Seismometers can provide information on earthquake, landslides, snow avalanches and, to some extent, tsunamis. Analysis of data from the Ocean Bottom Seismometers deployed in INTAROS show that these observations can improve understanding of the ridge seismicity and demonstrate how even very few stations can significantly improve earthquake detection and locations. Community-based seismometers have been demonstrated to be a useful low-cost supplement to permanent seismic stations on land. They contribute to better earthquake locations and to raise awareness among community members where they are deployed. Mass loss from ice sheets and glaciers constitute both a local and global hazard. Multiple datasets on total mass loss, solid mass loss, liquid mass loss, and freshwater runoff from the Greenland Ice Sheet have been produced and published. These datasets can be applied in studies of local conditions in a fjord or help inform global scale studies. Several process studies using numerical modelling were developed and published to separate the marine mass loss from glaciers into iceberg calving and submarine melting.

Recommendations: Long time series of observations with adequate temporal and spatial resolution are the backbone for quantifying the hazard and risk of natural hazards, for increased process understanding and improved predictions. The data need to be freely available through various platforms in order to be useful for scientists and available for the public. This will facilitate interdisciplinary studies e.g. the landslide study combining seismic observation and remote sensing products. It is recommended to establish super sites where multi-disciplinary data can be acquired. This will help to overcome the lack of observations co-located in time and space. To deliver data in real time is important for operational services to allow authorities to respond in case of geohazard events.

6.5 Case studies of greenhouse gas exchange in the Arctic

6.5.1 Atmospheric case studies of GHG budgets

Studies of methane emissions over the East Siberian Arctic Shelf has been done using a data assimilation scheme based on a geostatistical inverse modelling framework. The environmental conditions that explain spatio-temporal patterns in surface-atmosphere emissions has been explored with links to biogeochemical and biogeophysical processes. A reference model framework was set up and used for model sensitivity studies and process investigation. The data assimilation used new data layers from INTAROS showing that sea ice concentration and surface heat fluxes from the reanalysis gave improved results compared to previous data. The basic requirement for the new auxiliary data layers from INTAROS was a continuous spatial grid of data that covered the entire model area. Therefore, the products used in the assimilation consisted of Total Water Vapor over ice and open and ice-ocean reanalysis fields for the period 2007-2016.

The results of the study showed that the annual methane emissions from the East Siberian Arctic Shelf to the atmosphere at varied from 0 – 1.4 Tg CH_4 yr^{-1}, which is at the low end of the estimates in existing literature. The highest emissions were attributed to shallow waters, while no emission spike was observed during sea ice retreat, indicating low accumulation of methane under the ice in winter. We also found potentially substantial emissions in fall and sustained emissions during winter, but these findings were sensitive to filters applied to atmospheric observation data, thus we have lower confidence in them. All results could be explained by two underlying processes: first, trapping of methane below the pycnocline could be responsible for a dominance of emissions from shallow waters, the potential emissions in fall (sea-ice growth, storms) and the missing emission spike during sea ice retreat (meltwater barrier). Second, significant emissions through cracks in sea ice could explain winter emission estimates and the missing methane spike during sea ice retreat (low accumulation). Examples of the results are shown in Fig. 6.13.

Recommendations: There is a general need for expanding the atmospheric greenhouse gas observation network in the Arctic, with a particular for the ocean. The data assimilation approach presented in this study can be a powerful tool for exploiting additional data sources to generate new information on carbon budgets and underlying processes in understudied regions with few observations. Future research should focus on assimilating additional datasets (e.g., oceanographic and biogeochemistry data) in order to provide better understanding of the role of ocean shelves in the Arctic carbon cycle.

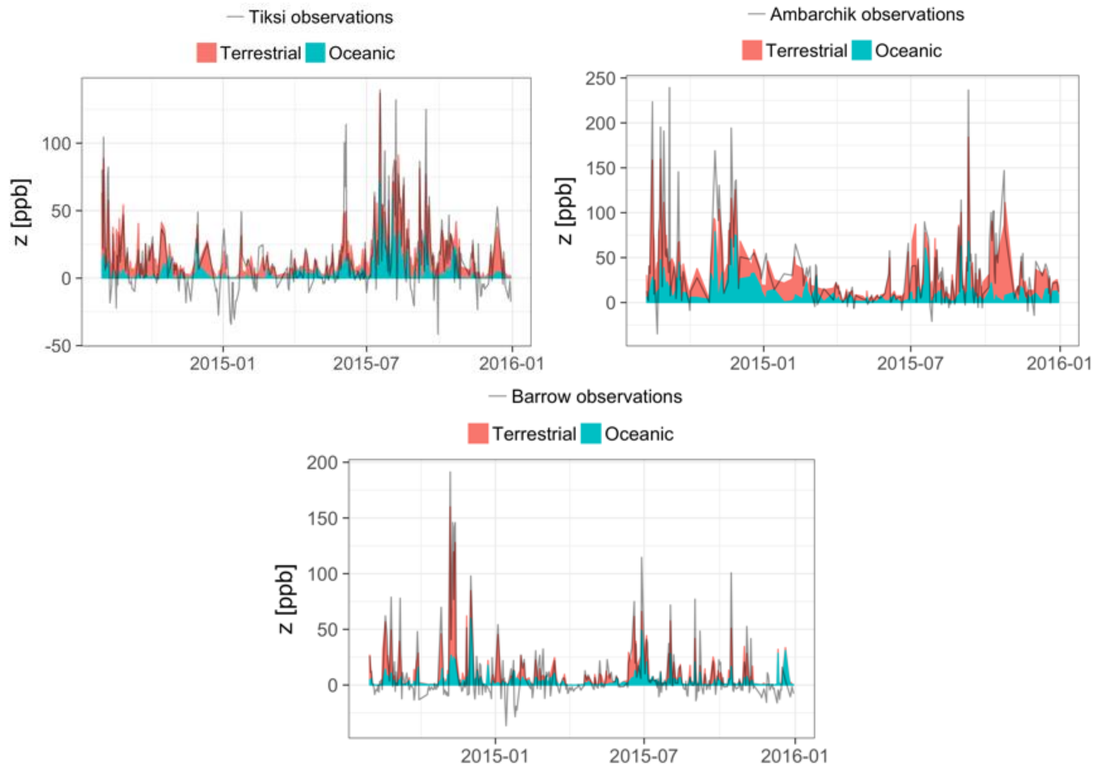


Figure 6.13. *Example of modeled atmospheric CH_4 mole fractions at three Arctic stations (Tiksi, Ambarchik and Barrow) based on posteriori emission estimates of a single inversion scenario ("Coastal flux + Sea ice growth", with relaxed atmospheric data selection).*

6.5.2 Ocean case studies of GHG budgets

The carbonate system chemistry in the Arctic and Subarctic oceans is very dynamic due to strong/seasonal variability in biological activity (production/respiration), wind and other physical mixing mechanisms, and sea surface temperature. Precise estimates of the oceans uptake and release of CO_2 is essential to predict the rate of climate change in earth system models. It is also equally important to observe present day carbonate system chemistry as a baseline and to understand the impact/role of major drivers in carbonate system dynamics.

A self-organising map technique and data synthesis

The main result here is a self-organising map technique. This artificial neural network that uses machine learning was implemented to estimate surface water pCO_2 values for the Barents Sea opening (Fig. 6.14). Initially, the network was trained using satellite observations of chl-*a*, sea ice concentration, sea surface temperature and salinity, as well as bathymetry and estimates of mixed layer depth. The training data was labelled with pCO_2 observations from the SOCAT database, which enabled preliminary maps of monthly sea surface pCO_2 for the year 2018 to be created. The network is now ready to include the training and labelling data sets from INTAROS partners and atmospheric inverse modelling.

Norwegian coastal data from a FerryBox

The FerryBox system on M/S Norbjørn, collects ocean surface data during 25-30 roundtrips per year between Tromsø and Svalbard. The FerryBox system includes a number of physical, chemical, and biological sensors: a inlet temperature sensor, a conductivity-temperature sensor, a membrane equilibrator pCO_2 sensor, a NIVA spectrophotometric pH sensor, and a microFlu *chl a* fluorometer. Measurements of pCO_2 started in 2020, see example of data in Fig. 6.15.

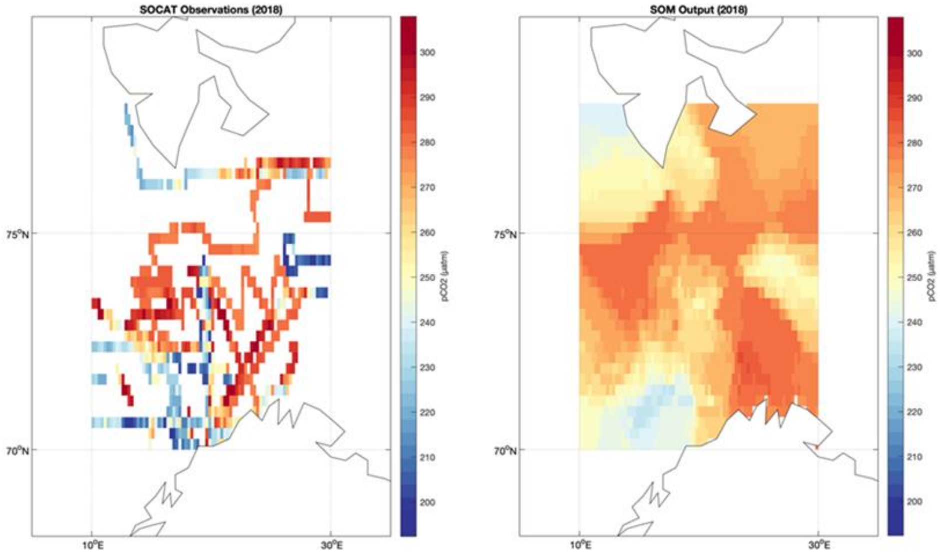


Figure 6.14. *Data extracted from the SOCAT-database for the area 10°E-30°E; 70°N-77.5°N and year 2018 (left panel) and an example of corresponding output in the form of a self-organization map (right panel).*

Greenland Ecosystem Monitoring Programme

In Greenland, measuring ocean CO_2 and carbonate chemistry is included in the Greenland Ecosystem Monitoring (GEM) Programme. About 750 individual CO_2 measurements were made across 11 different fjord transects. In spite of the considerable variation within local fjords primarily related to the amount of glacial meltwater, clear differences between summer surface (0-50 m) conditions in pCO_2 where found. Most notable the variation between sites and with depth was notably smaller along the East Greenland coast compared to West Greenland. This result in lower undersaturation (on average) in west Greenland, but also over-saturation at depth.

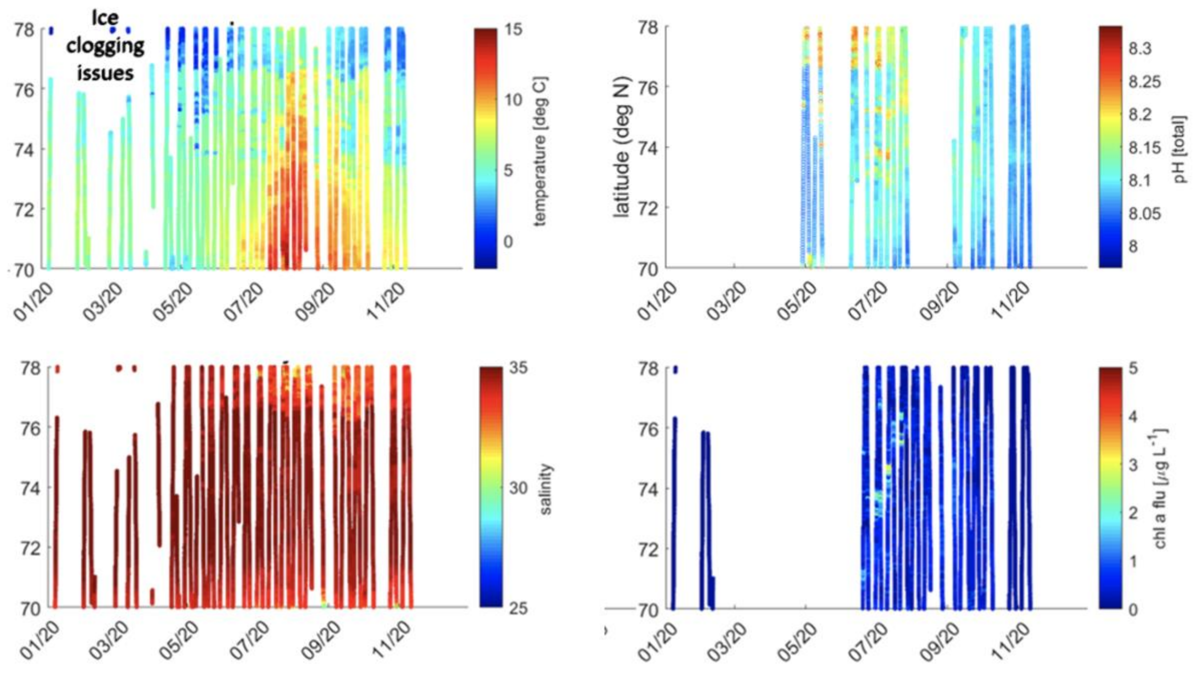


Figure 6.15. *Data from the Ferrybox system onboard Norbjørn obtained from January to November 2020: temperature, salinity, pH and chl-a.*

Recommendations: Production of carbonate system data for the ocean can be strengthened by using moorings, ships of opportunity and other automated observing platforms in addition to conventional research cruise-based observations. It is necessary to collect more observations to obtain better seasonal, annual, interannual and decadal coverage of the carbonate system and ocean acidification.

There are some challenges that need to be addressed before the automated platforms can produce reliable data of sufficient high quality and spatial/temporal coverage. There is also the need to improve observations related to phytoplankton blooms and biological production to fully characterize and understand carbon system dynamics. However, the developments in ocean acidification-related sensors in addition to other biological and biogeochemical sensors (e.g., nitrate and oxygen) are on track and can be used for more data collection, especially in the Arctic.

6.6 Community-based observing systems

Through dialogue with civil society organizations, research institutions, and the local authorities in Greenland and Svalbard, three topics of high priority have been identified in INTAROS where community-based observing and citizen science observations are important:

- Local and scientific observations for improving fisheries and hunting in Greenland
- Natural disasters in Disko Bay, Greenland and Longyearbyen, Svalbard
- Monitoring Svalbard's environment and cultural heritage by expedition cruises

The data from these observations are directly relevant for better planning and better-informed decisions by the authorities. The project initiated cooperation with key players in these sectors and facilitated the preparation of four jointly-developed policy briefs, thereby securing broad ownership to the recommended actions (D6.6). The results of the work are presented in more detail in WP4.

6.6.1 Local and scientific observations for improving fisheries in Greenland

The project co-developed a policy brief on the use of local observations for improving fisheries in Greenland together with Greenland Association of Fishermen and Hunters (KNAPK), Oceans North Greenland, Ilisimatusarfik, University of Greenland and University of Alberta (https://old.uarctic.org/media/1601946/policybrieflokalvidenfiskeriforvaltning_final_8june2021.pdf). The policy brief is summarized below. A new Fisheries Act is being developed in Greenland. Fisheries are of great importance in the country but there is uncertainty as to future sustainability and stock dynamics. Fisheries management advice is currently based mainly on catch statistics and researchers' surveys although there is growing international recognition that user knowledge is of great value and importance. The new agreement on the future of fisheries in the Central Arctic Ocean gives user knowledge from coastal communities a central role in the future management of fishery resources (Fig. 6.16).

The Greenland government and civil society organizations have been testing ways of incorporating user knowledge in the management of fisheries and other living resources, e.g. through the PISUNA program (see Section 4). Experienced fishermen have been discussing and reporting systematically on the status of several fish species. They have also provided possible explanations for changes in stocks and have proposed specific management measures. The methods tested have provided valuable knowledge on the development of several stocks. Using these tested methods, users have come up with management proposals that both expand and limit fishing activity (Figures 6.16 and section 4.2).

In addition to bringing important knowledge into play on the various fish stocks, the inclusion of user knowledge in fisheries management offers better opportunities for: 1) Obtaining knowledge from wider geographical areas; 2) Early detection of stock changes; 3) Establishing user and site-specific knowledge for management plans in specific management areas; 4) Promoting realistic local regulations e.g. of trawling; and 5) Strengthening the use of regulatory tools such as quotas, legal gear, zoning and seasons. Increased incorporation of user knowledge helps to create a meaningful dialogue between users, researchers, and managers. This can lead to fewer conflicts and greater co-ownership in relation to the management decisions that are made. The policy brief therefore recommends that the inclusion of user knowledge be written into the aims of the new Fisheries Act.

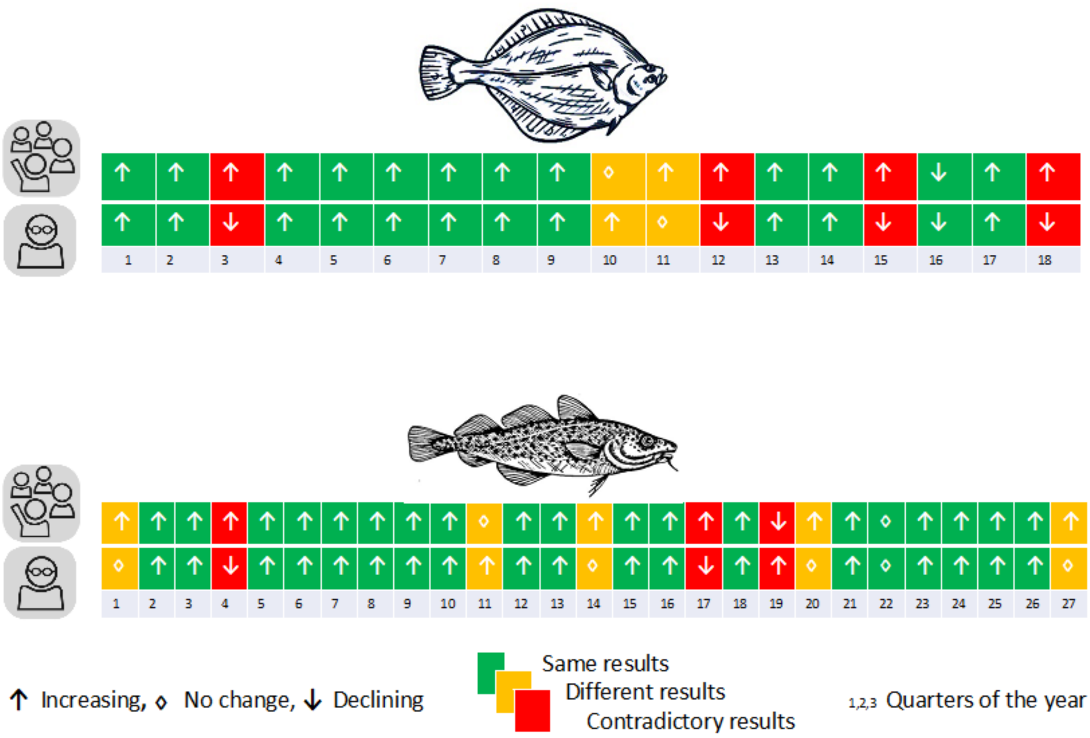


Figure 6.16. *Incorporating user knowledge in the management of fish and other living resources in Disko Bay. Degree of agreement between established management results and reports from experienced fishers for Greenland halibut (upper panel) and Atlantic cod (extract from the Policy Brief, see D6.6 and D4.3).*

6.6.2 Natural disasters in Disko Bay and Longyearbyen

Both Greenland and Svalbard have been exposed to several natural hazard events in recent years. With climate change, more landslides, earthquakes and other natural disasters are to be expected in the Arctic (see section 6.4). In two policy briefs we used our findings from citizen seismology (Section 4; D4.3) and previous and current knowledge from scientists' monitoring and research and presented a summary of the current knowledge about landslides and earthquakes in Disko Bay and Longyearbyen with recommendations (D6.6).

In Disko Bay the policy brief describes the risk for natural hazards and the importance of collecting more data, inc. from citizen seismology. In order to reduce the effects of landslides and earthquakes, including possible abrupt changes in topography (land uplift), it is recommended that: 1) The municipal councils look at whether the critical infrastructure is secured against strong earthquakes, landslides and tidal waves. Moreover, it is suggested that they assess the potential consequences of such natural disasters and have action plans ready when they occur; 2) The Ministry of Housing and Infrastructure should develop guidelines for protection from natural disasters; 3) The contractors in Disko Bay should look at the strength of vibrations that all planned installations can withstand and whether precautions should be taken against strong tremors in the planning phase.

In Longyearbyen, the policy brief describes that it is of great importance for urban planning to know how about the risks for natural hazards, and how the risk will be affected by climate change. It is recommended that the local council and contractors ensure that critical infrastructure and buildings are built outside the runways of potential landslide events and adequately secured against earthquakes. In addition, the consequences of major natural disasters should be studied, and action plans should be developed. A new project, ARCT-RISK, has been established to build up expertise in risk governance (https://www.ntnu.edu/iot/arct-risk).

6.6.3 Monitoring Svalbard's environment by expedition cruises

One policy brief focused at expedition cruises that travel around Svalbard waters with guides and tourists who are observing and contributing to ongoing citizen science programs (D4.3; D6.6). INTAROS has promoted and supported increased use of tourists in collecting data on environmental topics (D7.14). These observations need to follow guidelines and regulation from environmental management authorities (the Governor's Office). In the policy brief the potential for expedition cruises for contributing to environmental monitoring is described. The policy brief recommends that cruise expedition vessels are equipped with tablets containing apps for citizen science programs to enable easy uploading of records. The selected programs should be popular among users, gather information that can improve the basis for environmental management, and present results in a form that can be used by environmental management planners and decision-makers. Work must be done to understand how the right type of data can be gathered and be made available to those responsible for environmental management.

Recommendations. As highlighted above, the four policy briefs recommend severalactions. For Greenland, inclusion of user knowledge should be written into the aims of the new Greenland Fisheries Act. Municipal councils should get better overview of whether critical infrastructure is secured against strong earthquakes, landslides, and tidal waves. In Longyearbyen, local council and contractors are recommended to ensure that critical infrastructure and buildings are built outside the runways of potential landslide events and adequately secured against earthquakes. Cruise expedition vessels should support programs where tourists will gather data that can improve the basis for environmental management, and present results in a form that can be used by environmental management planners and decision-makers

6.7 Benefits of ocean observing for Blue Growth in the Arctic

The value and benefits of an upgraded Arctic Observing System in support of Blue Growth is briefly described. It is a policy object of EU's Arctic strategy to support inclusive and sustainable development of the Arctic regions. The potential for growth of the Arctic Blue Economy is increasing due to climate change, fast technological development, and strong demands from the global economy. Such development will however put severe stress on the vulnerable Arctic environment and there is a growing consciousness among nations surrounding the Arctic to ensure a responsible and sustainable development of Arctic Blue economy, which calls for a science-based management approach.

In INTAROS the future business development perspectives for three important components of the Arctic Blue Economy – maritime transport via the Arctic Ocean, cruise industry in the Svalbard area and fishery in the Barents Sea has been analysed. The maritime transport and cruise industry will potentially increase substantially over the coming years due to retreat of Arctic sea ice. Barents Sea fishery will have to address changes in the pursuit of their profession due to changes in fish stock composition and distribution originating from climate change and other human pressures.

Entering into operations in the harsh Arctic environment requires good knowledge and understanding of the physical environmental conditions to ensure a sound decision process on economy, efficiency, safety of ship, crew and cargo and protection of the vulnerable Arctic environment. Therefore, examples of basic statistical analysis of relevant parameters like sea ice, wind, waves, temperature, and salinity has been performed to outline the trends in change of environmental condition of importance for maritime operations in the Arctic. Additionally, operational meteorological and oceanographic near real time products and services are important when actually operating in the area.

It is therefore crucial to design and implement a fit-for-purpose Arctic Observation System to ensure the availability of high-quality in situ data needed for model assimilation as well as validation of the quality of model and remote sensing products used both for statistical trend analysis and particularly operational purposes.

A science-based management approach is mandatory for ensuring a responsible and sustainable development of Arctic Blue economy. This calls for good knowledge and understanding of the Arctic Ocean environment and ecosystem, which again demands a well-coordinated, integrated, sustained fit-for-purpose Arctic Ocean Observation System. We recommend that the design of a proper Arctic Ocean Observation System follows the concept outlined in the UNESCO “Framework for Ocean Observations”. This will require a strong international coordination and governance structure responsible for dialog with users and stakeholders, sustained funding, maintenance of observation requirements, technology development, and free and open access to data.

General recommendations for improving and extending Arctic observing systems:

- *Support research and innovation to develop technologies for platforms and sensors collecting data required by the different user groups and improve logistical solutions for deployment and recovery of the platforms.* This is in particular important for use in ice covered regions to reduce the environmental impact of complex and time-consuming operations in the Arctic.
- *Improve the data delivery chain by operationalizing of processing and dissemination, particularly for sub-surface systems (e.g., moorings, tide gauges, and bottom installation) into interoperable data systems fulfilling the FAIR principles.* Standardisation of the data delivery chain for ice-ocean products for environmental assessments are strongly recommended. This would make these data accessible for reanalysis activities, validation of climate model products and risk assessment systems.

7. WP7: Dissemination and outreach

In WP7 the consortium has conducted various communication activities to inform projects, programmes, user and stakeholder groups, agencies, and policy makers about INTAROS. The consortium members have promoted the project through several hundred meetings, workshops, conferences, publications, and other dissemination activities. Much of this communication and dissemination work has been done in collaboration with WP1. Various online tools were employed to maximize the visibility and communicate the project activities including: a public project website, social media, videos on YouTube, blogs, printed materials (brochures, factsheets, posters, policy briefs, photos), project identity toolkit (graphical image, logos, lettering, templates and branded materials). Furthermore, several training and education activities have been organized, including training workshops with local communities.

7.1 Summary of main achievements

Informing decision-makers in European agencies and businesses. Specific communication and dissemination material has been prepared for decision-makers and businesses in Europe, some of this has been done in collaboration with EU Polarnet (www.eu-polarnet.eu) and the EU Polar Cluster. INTAROS has organized presentations at key events for these stakeholders, e.g. European Maritime Day and Arctic Ministerial in 2018 and 2020. Decision-makers and policy developers were engaged in various stakeholder workshops. INTAROS was an active member of several EU Polar Cluster working groups.

Informing Arctic and international bodies. INTAROS was active participant in key events such as Arctic Frontiers, Arctic Circle, Arctic Observing Summits and Arctic Science Summit Week, which are the most important Arctic events, attracting policy makers, industries, Indigenous people and scientists from all disciplines of importance for the circumpolar Arctic. A key output from the project was a set of 1-page Info Sheets compiled into a booklet showcasing the substantial work carried out in INTAROS.

Interdisciplinary science dissemination. INTAROS promoted cross-disciplinary dissemination of high -profile scientific topics through conferences and workshops, including sessions at EGU conferences, AGU conferences and during Arctic Science Summit Week. More than 10 videos from INTAROS field work and educational activities have been produced and are available on Youtube (https://www.youtube.com/channel/UCoegF3QSQe17mmGvj8oNs_g) (Fig. 7.1). The number of scientific publications which have been published or submitted exceeds 100. Two special issue publications are in progress in EGU Ocean Science journal (https://os.copernicus.org/articles/special_issue1157.html) and in Environmental Research Letters ('Trans-disciplinary aspects of researching Arctic change').

Figure 7.1 *Example of dissemination material from INTAROS. Cover page of a video from Greenland ice sheet work (left). This and other videos are available at https://intaros.nersc.no/content/video-material-and-presentations-intaros-work . A popular science booklet was prepared, giving an overview of the range of activities in the project (right).*

Capacity building for early-career scientists. INTAROS has co-organized three dedicated research schools together with the Useful Arctic Knowledge project at UNIS in Svalbard and onboard the Norwegian Coast Guard icebreaker KV Svalbard. Furthermore, INTAROS has contributed to 12 courses organized by consortium members. Incentives were offered to early-career researchers to participate in special sessions of international conferences such as EGU and AGU conferences. These comprised travel grants (or monetary prizes during the COVID-19 pandemic) that were awarded to three early-career scientists on the basis on excellent science through the evaluation of the submitted abstracts. Further, a series of e-learning modules were developed on four chief INTAROS themes, to facilitate and encourage independent learning among the early-career researcher community. These modules are available via the INTAROS public website.

Capacity building for high-school and general public. INTAROS contributed to development and implementation of e-learning modules designed for high school students and the wider public. Two packages of educational materials for teachers and students of lower and upper secondary schools were prepared to enhance literacy of Arctic Observations among teachers and students. Each package consisted of methodological material for teachers, and multimedia material and worksheets with tasks for students. Teachers were prepared for using packages during workshops conducted within cooperation with other European projects, in particular Scientix (community for science education in Europe). Schools were encouraged to use packages via different activities (sending invitation to 3500+ STEM teachers from Europe with the use of Scientix Digest, including materials in Scientix repository. Toolkits prepared by INTAROS were uploaded in the Golabz.eu repository (Fig. 7.2). The material was presented to teachers from 60 countries taking part in the EDU-ARCTIC project).

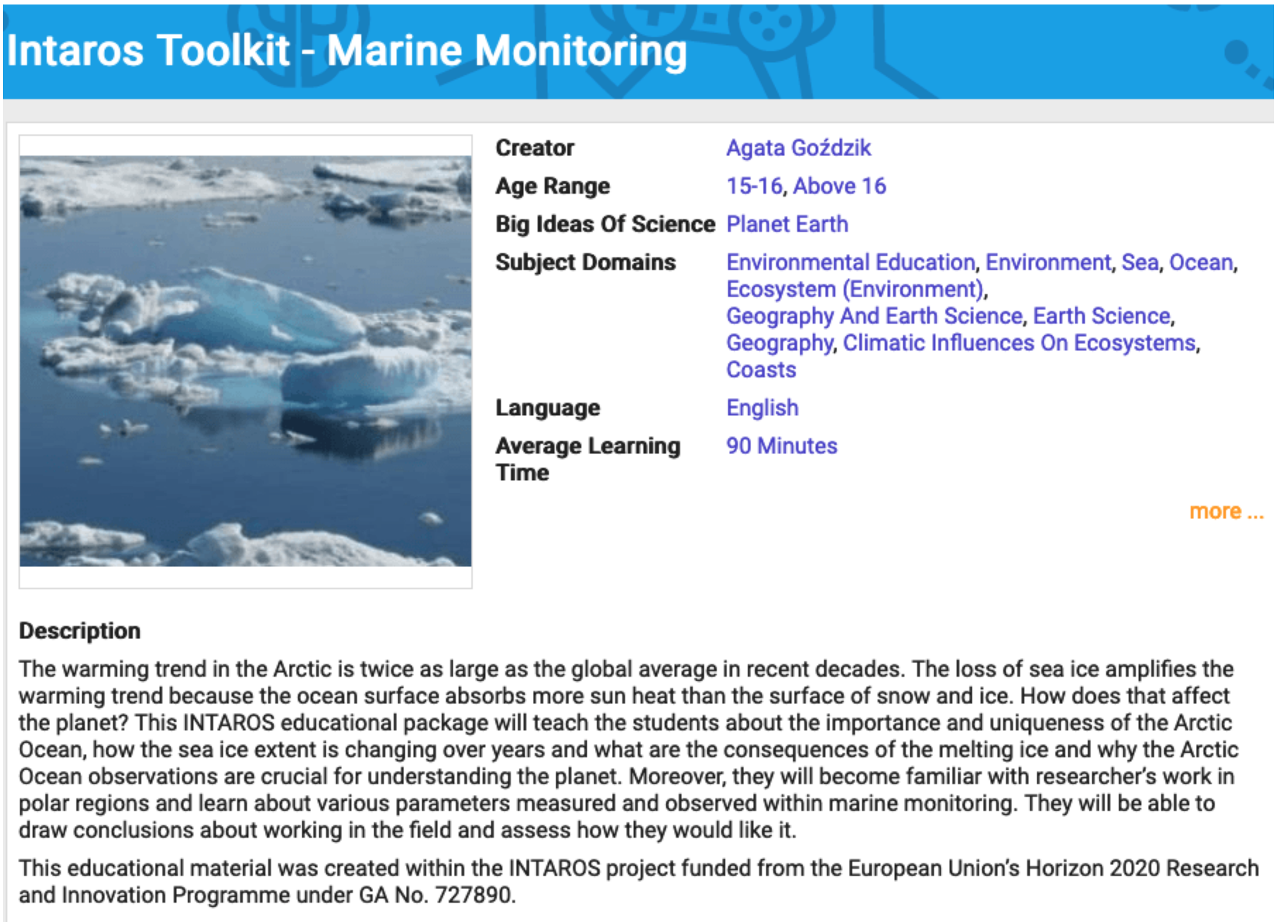


Figure 7.2. *Screenshot of toolkit for marine monitoring prepared by IGPAN as part of the Scientix repository (https://www.golabz.eu/ils/intaros-toolkit-marine-monitoring)*

Capacity building for local communities and civil society organizations. INTAROS has supported community-based observing efforts, and e.g. co-organized 40 workshops with many partners inc. ELOKA, Yukon River Inter Tribal Watershed Council (North America), and Center for Support of Indigenous Peoples of the North (Europe). Their purpose was to facilitate experience exchange and to build further capacity in community-based observing, with particular focus on professional and cross-disciplinary skills and competences of the youth to help ensure the sustainability of community-based observing into the future (see D7.14). In collaboration with many partners and CBM programs, the project has also produced a book on Community-Based Monitoring in the Arctic, where state-of the-art is described based on a number of examples from the pan-Arctic region. Furthermore, the project has established the UArctic Thematic Network on Collaborative Resource Management. The network has prepared a course on the subject Collaborative Resource Management and CBM tools. The course material is available at https://www.uarctic.org/organization/thematic-networks/collaborative-resource-management/. It is envisaged that through this network a number of dissemination and training activities will continue to be organized for capacity-building among local communities, Arctic-based students, public resource managers and scientists in the coming years.

7.2 Expected impact, challenges and recommendations

Impact

INTAROS has built up a strong international collaboration, shown visibility in the Arctic research community and presented a wide range of results which contribute to developing Arctic observing systems. Expected impact has been shown in relation to:

Science - contributions to conferences such as EGU, AGU, ASSW, OceanObs19; many scientific publications and special issues of peer-reviewed journals.

Governance - Arctic Ministerial letter to ministers, contributing to AOS joint statement, contributing to COP meetings and their side events, contribution to Arctic Circle, and ongoing participation in SAON and other influential Arctic organisations.

Youth - through a series of learning tools and materials targeted towards non-experts (high school and general public) as well as emerging experts (graduates and post-graduates). Incentives for participation in conferences (grants and prizes).

Communities and public resource managers – capacity enhanced with training, experience exchange workshops, connections and tools to support ongoing CBM beyond the lifetime of the INTAROS project

Challenges

Visibility of individual projects. The Arctic research community is growing larger and diverse with many projects, organisations, stakeholders, and other actors. In such a landscape, it can be difficult for an individual project to be visible. It is helpful when several projects work together to create impact towards the stakeholders. In specific areas, such as in local communities in Greenland, Alaska, Svalbard and Russia, INTAROS has had strong impact on supporting community-based observing and collaboration between scientists and the local population. INTAROS has collaborated with other Arctic projects on dissemination, promotion, and communication with stakeholders. The Polar Cluster has been useful, where INTAROS worked with other projects and organisations to produce mutual, high impact recommendations to decision makers and policy makers.

Integration of different fields of expertise. The breath of the INTAROS project makes it unique but adds to the challenges of providing an integrated summary of the project's results. An attempt to provide an interdisciplinary view of Arctic observing is the organization of an EGU Special issue. Results from INTAROS are presently published in different disciplinary EGU journals, but as a joint Special Issue.

COVID-19 - Dissemination and outreach relies on taking part in events, conferences, meetings and other in-person activities, for the project to maintain a presence in the community. This challenge was overcome, as far as possible, by participation in and organization of online events, e.g. UN Ocean Decade workshop in collaboration with other Arctic projects. There are also plans to continue to promote and disseminate INTAROS and its results following the close of the project, e.g. through a special session at ASSW 2022.

Recommendations

- Continued support for networks of Arctic projects, with sufficient funding for communication and dissemination.
- Continued support for community engagement and citizen science.
- Greater efforts towards engagement with non-scientific audiences on the micro- rather than macro-scale for long term impacts.
- Continue supporting interdisciplinary projects, and the development of better integration across different fields. Tackle a science question by integrating different field is a key to understanding the complex arctic systems

  Investment in a long-term Arctic educational hub, extending the educational programs by universities and research centers related to Arctic topics.

8. Conclusions

The requirements for Arctic observations are identified for a wide range of climate and environmental variables, which require a complex system of remote sensing and in situ observations. The requirements are formulated by user groups from science communities, public services, private sector, global observing programmes, as well as from Indigenous and local communities. The baseline requirements for long-term climate observations are fairly constant, while new requirements arise in response to societal needs and improvements in observing technologies. It is therefore necessary to update the requirement documents at regular intervals through dialogue with the user groups.

The in situ component of the observing systems has large gaps in the Arctic. Especially in the ice-covered Arctic Ocean there is very little data because access to area is limited and the cost of deploying observing systems is high. This is in strong contrast to remote sensing on polar orbiting satellites which produce large amounts of data over the whole Arctic every day. To assess the status of the in situ observing systems, a survey was conducted among the partners showing that most of the observations are provided by research projects with short-term funding. Only a few systems have long-term funding and can operate sustainably over many years. The ARCMAP online survey system was established to update the status of the existing systems and register new observing systems in the future. The INTAROS data catalogue was set up for registration of metadata for the data sets from the observing systems and providing access to the data stores in distributed repositories.

A major effort in the project was to enhance the in situ observing systems for atmosphere, ocean and terrestrial variables, using well-proven and robust technologies. Extensive field work was conducted on ocean, sea ice, land ice and terrestrial sites in the circumpolar region. These systems were deployed for up to several years and produced data that was used to extend climate data sets and study processes as part of the climate change in the Arctic. In addition, work was devoted to develop and test new solutions and novel technologies to improve the in situ observations. Data processing, analysis and uploading to data repositories followed after the field work. The INTAROS data catalogue was populated with metadata for all the data coming from the observing systems and it will be maintained after the end project.

Community-based observing programs (CBM) have been supported in several regions, a tool for sustainable resource use as well as a means for protecting Indigenous Peoples' rights to land and resources. Many experience-exchange workshops were organized, and the status of several ongoing community-based observing programs and their capabilities, "good" practice and challenges have been analysed. Furthermore, a set of tools to cross-fertilize local knowledge with scientific knowledge have been developed. New CBM and citizen science initiatives have been initiated, and several existing CBM programs have been strengthened to inform local and national decision-making.

A number of case studies were performed to demonstrate use of in situ observing systems in combination with remote sensing data and modelling systems. The cases studies involved various stakeholder groups and comprised (1) climate modelling in the Arctic, with examples from sea ice prediction and hydrological forecasting; (2) combining observations and models for environmental and fisheries management, with case studies in the Barents Sea and west Greenland; (3) ice-ocean statistics using examples from Observing System Simulation Experiments (OSSE), preparation of a 10 year reanalysis, development of a risk assessment system, studies of ocean sound, oceanographic and sea ice time series, sea level studies from altimeter and tide gauge data, sea ice data from ice mass balance buoys, and sea ice remote sensing applications. Furthermore, studies were conducted on (4) natural hazards, (5) greenhouse gas fluxes, (6) community-based observing systems in Greenland and Svalbard, and (7) a review of ocean observing benefit for blue growth in the Arctic.

Finally, extensive efforts were made to plan and conduct various communication and outreach activities to inform other projects, programmes, users, rightsholder and stakeholder groups, agencies, and policy makers about INTAROS. More information about the results at http://intaros.eu.

9. Appendix: List of deliverables

All public deliverables are available at https://intaros.nersc.no/list-of-open-deliverables

		Delivered	Public	Lead
WP1	**Requirements and strategy for pan-Arctic observing syst.**			
D1.1	Initial requirement report	May 2017	P	EuroGOOS
D1.2	Data Management Plan V1	Jan 2019	P	NERSC
D1.3	Engagement Strategy	Nov 2017	P	EurOcean
D1.4	Collaboration establishment	May 2019	P	NERSC
D1.5	Report on second stakeholder workshop	Dec 2019	P	EuroGOOS
D1.6	Data Governance Framework	Jan 2020	P	NERSC
D1.7	Report on third stakeholder workshop	May 2021	P	EuroGOOS
D1.8	Data Management Plan V2	May 2021	P	NERSC
D1.9	Revised requirement report:	Sept 2021	P	EuroGOOS
D1.10	Roadmap for sustainable Arctic Observing Systsm	Apr 2022	P	NERSC
D1.11	Synthesis report of the project	Apr 2022	P	NERSC
D1.12	Collaboration with Arctic shipping	Apr 2022	P	NERSC
WP2	**Exploitation of existing observing systems**			
D2.1	Ocean and sea ice: Report on present observing capacity & gaps	May 2018	P	DTU
D2.2	Ocean and sea ice: Report on exploitation of existing data	May 218	P	NERSC
D2.3	Ocean and sea ice: Catalogue of products-services	Nov 2018	P	AWI
D2.4	Atmosphere: Report on present observing capacity and gaps	May 2018	P	MISU
D2.5	Atmosphere: Report on exploitation of existing data	May 2018	P	FMI
D2.6	Atmosphere: Catalogue of products and services	Nov 2018	P	SMHI
D2.7	Land: Report on present observing capacity and gaps	May 2018	P	USFD
D2.8	Land: Report on exploitation of existing data	Nov 2018	P	GEUS
D2.9	Land: Catalogue of products-services	Nov 2018	P	GFZ
D2.10	Report on synthesis and recommendation from WP2	Nov 2019	P	MISU
D2.11	Report on the maturity scores of existing observing systems	Nov 2019	P	NUIM
D2.12	Observational gaps revealed by model sensitivity studies	Dec 2018	P	FMI

WP3	**Enhancement of multidiscipinary in situ observing systems**			
D3.1	Greenland: Technology development and system design	May 2018	C	GEUS
D3.6	Greenland: First implementation of the observing systems	Nov 2019	P	GEUS
D3.10	Greenland: Final implementation of the observing systems	June 2021	P	GEUS
D3.2	North Svalbard: Technology development and system design	May 2018	C	UIB
D3.7	North Svalbard: First implementation of the observing systems	Nov 2019	P	UIB
D3.11	North Svalbard: Final implementation of the observing syst.	Oct 2021	P	UIB
D3.3	Fram Strait: Technology development and system design:	May 2018	C	AWI
D3.8	Fram Strait: First implementation of the observing systems	Nov 2019	P	AWI
D3.12	Fram Strait: Final implementation of the observing systems	June 2021	P	AWI
D3.4	Ocean and sea ice: Technology development & system design	May 2018	C	IOPAN
D3.9	Ocean and sea ice: First implementation of the observing syst.	Nov 2019	P	IOPAN
D3.13	Ocean and sea ice: Final implementation of the observing syst.	Oct 2021	P	IOPAN
D3.5	Atmosphere-land: Technology development and system design	May 2018	C	MPG
D3.14	Atmosphere-land: First implementation of the observing syst.	Nov 2019	P	MPG
D3.15	Atmosphere-land: Final implementation of the observing syst.	July 2021	P	MPG
D3.16	Synthesis and technical recommendation	Feb 2022	P	IOPAN

WP4	**Community-based observing programs**			
D4.1	Report on survey of existing community-based obs. programs	Dec 2018	P	NORDECO
D4.2	Library with tools on local and scien. knowledge	May 2018	P	NORDECO
D4.3	Lessons learned on CBM observing in Svalbard and Greenland	May 2020	P	NORDECO
D4.4	Community-based observations from two focal communities	Nov 2020	P	NORDECO

WP5	Data integration and management			
D5.1	IAOS requirements and architectural design V1	Nov 2017	C	TDUE
D5.2	IAOS cloud platform and tools V1	Nov 2018	P	TDUE
D5.3	Data integrated from existing repositories V1	Dec 2018	P	AWI
D5.4	iAOS portal with user manual V1	Dec 2018	P	NERSC
D5.5	IAOS requirements and architectural consolidation V2	June 2020	C	TDUE
D5.6	Geo-statistical library for iAOS V1	June 2020	P	ARMINES
D5.7	Processing services for iAOS V1	June 2020	P	TDUE
D5.8	IAOS cloud platform and tools V2	June 2020	P	TDUE
D5.9	Data integrated from existing repositories V2	Dec 2021	P	AWI
D5.10	Geo-statistical library for iAOS V2	July 2021	P	ARMINES
D5.11	Processing services for iAOS V2	Nov 2021	P	TDUE
D5.12	iAOS portal with user manual V2	July 2021	P	NERSC
D5.13	Synthesis of the IAOS cloud infrastructure	Dec 2021	P	TDUE

WP6	Applications towards stakeholders			
D6.1	Climate model initialization: first report	May 2020	P	BSC
D6.2	Impact of climate change on Greenland ecosystems, first report	July 2020	P	AU
D6.3	Extension of ecosystem management systems, first report	May2020	P	IMR
D6.4	Report and model fields on ice-ocean state estimation	Feb 2020	P	UHAM
D6.5	Risk assessment system. First results	May 2020	P	DNV
D6.6	Policy briefs from local community studies	Nov 2020	P	NORDECO
D6.7	GHG studies - atmosphere	Oct 2021	P	MPG
D6.8	GHG studies - ocean	Nov 2021	P	UIB
D6.9	Support to Business Planning and Development	May 2021	P	EuroGOOS
D6.10	Report on ecosystem management for managers	July 2021	P	IMR
D6.11	Climate model initialization: final report	Nov 2021	P	SMHI
D6.12	Impact of climate change on Greenland ecosystems, final report	Nov 2021	P	AU
D6.13	Extension of ecosystem management systems, final report	Nov 2021	P	IMR
D6.14	Fram Strait Ocean and Acoustic Environments	Nov 2021	P	NERSC
D6.15	Risk assessment system. Final results	Sept 2021	P	DNV
D6.16	Natural hazard assessment in the Arctic.	July 2021	P	GEUS
D6.17	Ice discharge from glaciers to the ocean	Sept 2021	P	UPM
D6.18	Report on economic benefits in the Arctic	Nov 2021	P	EuroGOOS
D6.19	Synthesis report from WP6	Mar 2022	P	IMR
D6.20	Observing systems for sea level in the Arctic	Nov 2021	P	DTU
D6.21	Sea ice and snow thickness from SIMBA buoy experiments	Nov 2021	P	FMI
D6.22	Sea ice products from satellite scatterometers and PMW instr.	Nov 2021	P	Ifremer
D6.23	Sea ice and water vapour products from satellites	Nov 2021	P	P UB
D6.24	Use of drones for sea ice observations	Nov 2021	P	NORCE

WP7	Dissemination and outreach			
D7.1	Project Website, social media accounts and branding materials	Feb 2017	P	EurOcean
D7.2	Print material – brochures, fact sheets	May 2017	P	EurOcean
D7.3	Dissemination Plan V1.0	June 2017	P	NERSC
D7.4	Dissemination material for use towards stakeholders, etc.	Nov 2017	P	NERSC
D7.5	Dissemination Plan V2.0	Jan 2020	P	NERSC
D7.6	Contribution to OceanObs 2019	Nov 2019	P	NERSC
D7.7	Report on existing teaching and public outreach products	Nov 2019	P	GINR
D7.8	Updated dissemination material for use towards stakeholders	Dec 2020	P	NERSC
D7.9	Educational materials for teachers and students	Dec 2020	P	IGPAN
D7.10	Special issue in EGU journals	Nov 2021	P	USFD
D7.11	Scientific Capacity Building report on Svalbard summer schools	Sept 2021	P	EurOcean
D7.12	Educational packages for early career scientists and students:	Nov 2021	P	EurOcean
D7.13	Contribution to the ERL Special Issue	Nov 2021	P	USFD
D7.14	Proceedings from CBM and CS workshops 2017-2021	May 2021	P	NORDECO
D7.15	Summary for policy makers	Apr 2022	P	EurOcean
D7.17	Booklet and info sheets	Jan 2022	P	NERSC

----------- END of DOCUMENT-----------

INTAROS

This report is made under the project
Integrated Arctic Observation System (INTAROS)
funded by the European Commission Horizon 2020 program
Grant Agreement no. 727890.

Project partners:

s