Integrated Arctic Observation System

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INTAROS Revised Requirement Report

Requirements for atmospheric, ocean and land environmental in situ observations

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8	AU		**31**	ARMINE	
9	GEUS	***0,2***	**32**	IGPAN	
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16	IFREMER		**39**	SIO	
17	MPG		**40**	UAF	
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19	EUROCEAN		**42**	ONC	
20	UPM		**43**	NMEFC	
21	UB		**44**	RADI	
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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 aim of the INTAROS Revised Requirement Report has been to:

- Capitalise on INTAROS achievements
- Take note of recently articulated user need from the EU and international organisations
- Define more concrete requirements for the identified essential variables
- Address gaps in the present observing system

Requirements for in situ observations address resolution in space and time, quality and timeliness. Users of data generally have clearly articulated needs for time resolution, quality and timeliness, while defining the spatial resolution gives rise to serious considerations because:

- There is a need to find a balance between what ideally would be “nice to have” and what is feasible to achieve from a technical, logistic and especially economic point of view
- There is still a debate among scientists on how to address the spatial resolution:
  - A gridded format with fixed horizontal and vertical distances between observation points
  - Identifying key location with great impact and representativeness

Requirements for atmospheric, ocean and land essential variables has been identified and discussed using the WMO OSCAR and Copernicus Systems – both using a gridded approach – as a baseline for a critical review.

The performed gap analysis points to severe lack of observations in general and in the central Arctic in particular, and lack of sustainability since a majority of observations are based on time-limited campaigns. Additionally, there is a need for investments in developments of observation technology, incl. data communication and data management

The performed requirement and gap analysis results in the following recommendations:

- Ensure work towards a robustly substantiated definition of spatial resolution in an Arctic observing system involving analytic tools such as numerical models (OSE’s and OSSE’s), cost and feasibility studies
- Establish an international coordination and governance structure involving nations, SAON, WMO, IOC, EU Copernicus, , and representatives of Indigenous Peoples and Local Communities to:
  - Ensure a forum for dialogue between users of Arctic information, observation program leaders and sensor and application developers to understand evolving needs and capacities
  - Secure long-term coordination and continuation of measurements
  - Ensure sustained funding to a fit-for-purpose Arctic Observing System
  - Enhance and optimize multidisciplinary observations
  - Ensure open and free real time data exchange following the FAIR principle
  - Increase involvement of Indigenous Peoples and Local Communities in data collection and data integration
  - Promote training and teaching as a key value and fundament for capacity building
- Initiate data rescue activities to ingest existing data presently not freely available incl. Russian data
- Pursue innovative cost-effective technological solutions for Arctic observations securing continuous Near Real Time data flow from this harsh environment also during wintertime

INTAROS experiences suggest that cross-weaving scientist- and community-based monitoring programs can lead to improved information products and enhanced efficiency and sustainability of observing programs. Moreover, it can promote stronger linkages between environmental monitoring programs and government decision-making processes.

LIST OF CONTENT

0. List of Acronyms

AC	Arctic Council
AMAP	Arctic Monitoring and Assessment Programme
AOS	Arctic Observing Summit
AUV	Autonomous Underwater Vehicle
AWS	Automatic Weather Stations
BGC	Bio Geo Chemical
CAFF	Conservation of Arctic Flora and Fauna
C3S	Copernicus Climate Change Service
CAMS	Copernicus Atmosphere Monitoring Service
CBD	Convention on Biological Diversity
CBM	Community Based Monitoring
CBMP	Circumpolar Biodiversity Monitoring Programme
CCI	Climate Change Initiative
CDOM	Cromophoric Dissolved Organic Matter
CIS^2	Copernicus In Situ Coordination Information System
CMEMS	Copernicus Marine Environmental Monitoring System
CON	Committee on Observation and network
COINS	Copernicus Observations In Situ Networking and Sustainability
CS	Citizen Science
CTBTO	Comprehensive Nuclear-Test-Ban Treaty
EAV	Essential Arctic Variables
ECV	Essential Climate variables
EEA	European Environmental Agency
EOV	Essential Ocean Variables
EMODnet	European Marine Observation and Data Network
ESA	European Space Agency
EU	European Union
EUMETNET	European Meteorological Network
EuroGOOS	European Global Ocean Observing System
FAIR	Findable-Accessible-Interoperable- Reusable
GAIA-CLIM	Gap Analysis for Integrated Atmospheric ECV CLImate Monitoring
GCOS	Global Climate Observing System
GEO	Group on Earth Observations
GHG	Greenhouse gases
GlaThiDa	Glacier Thickness Database
GLODAP	Global Ocean Data Analysis Project
GNSS	Global Navigation Satellite System
GOOS	Global Ocean Observing System
GPR	Ground Penetrating Radar
HYCOS	Hydrological Cycle Observing System
IAOAF	International Arctic Observations Assessment Framework
iAOS	Integrated Arctic Observing System
IASC	International Arctic Science Committee
ICES	International Council for Exploration of the Sea
IGSU	International Council of Science
ILK	Indigenous and Local Knowledge
INSTAC	In Situ Thematic Assembly Centre
IOC	Intergovernmental Oceanographic Commission
IPBES	Intergovernmental Platform on Biodiversity and Ecosystem Service
IPCC	Intergovernmental Panel on Climate Change

ITP	Ice-Tethered Platforms
LTER	Long-Term Ecological Research
MEB	Multiple Evidence Base
NAMMCO	North Atlantic Marine Mammal Commission
NDVI	Normalized Difference Vegetation Index
NILU	Norwegian Institute for Air Research
NRT	Near Real Time
NWP	Numerical Weather Prediction
OSCAR	Observing Systems Capability Analysis and Review Tool
OSPAR	Convention for the Protection of the Marine Environment of the North-East Atlantic
OSR	Oil Spill Response
OSSE	Observing System Simulation Experiments
PAR	Photosynthetically Available Radiation
PSMSL	Permanent Service for Mean Sea Level
ROADS	Roadmap for Arctic Observing and Data Systems
ROMP	Roadmap for Optimization of Monitoring and Modelling Programmes for the Polar Region
RRR	Rolling Review of Requirements
QA	Quality assurance
QC	Quality Control
SAV	Shared Arctic Variables
SAON	Sustaining Arctic Observing Networks
SAOS	Sustained Arctic Observing System
SAR	Search and Rescue
SAR	Synthetic Aperture Radar
SIMBA	Sustainable Innovation of Microbiome Applications in Food System
SMB	Surface Mass Balance
SMM	System Maturity Matrix
SOG	Statement of Guidance
SPL	Sound pressure levels
SSH	Sea Surface Height
SSS	Sea Surface Salinity
SST	Sea Surface Temperature
SWE	Snow-water equivalent
TA	Total Alkalinity
TRL	Technical Readiness Level
T/S	Temperature and salinity
UAV	Unmanned Aerial Vehicles
UDASH	Unified Database for Arctic and Subarctic Hydrography
UN	United Nations
UNCLOS	United Nations Convention on the Law of the Sea
UNESCO	United Nations Educational, Scientific and Cultural Organization
WGMS	World Glacier Monitoring Service
WIGOS	WMO Integrated Global Observing System
WMO	World Meteorological Organization
WOD	World Ocean Database

1. Introduction

Changes in the Arctic atmosphere, hydrosphere, biosphere, and cryosphere conditions, of which many have regional and global implications, have been observed over the past decades as well as forecasted to continue in the years ahead. Although the Arctic is not the only region on Earth affected by environmental change, climate related changes are more pronounced there, and the Arctic generally poses special problems and concerns. The Arctic Region is generally undersampled, i.e., huge areas have limited, or no observations and observation campaigns often have been based on time-limited research project funding; but despite these constraints, rapid and systemic changes have clearly been identified.

Society demands multiple products and services but may not connect their needs to the in situ observations required to deliver these products. These societal needs are translated into requirements for observations, data management and flow, as well as synthesis and analysis finally ending up in useful fit-for–purpose products and services for the user. The value chain ranging from observations to products and services delivered to the end user is long and complex and far from transparent to the user, whose involvement is often restricted to a dialogue with the service provider with direct focus on the required products and services. In the justification process for a suitable in situ observing system to meet a downstream user requirement, there is an important task to visualise to the users the entire production chain required to produce the needed information to the required resolution and quality. Thereby this better understanding of the value chain opens up more sophisticated dialogue between user and service provider on the design of product and services.

In situ data is the basis for our understanding of the physical, biogeochemical and biological processes in the Arctic and they are a vital input for product generation, calibration and validation. It is therefore critical to map the requirement (resolution in space and time, quality, timeliness) for in situ data and compare it to the existing observation system to find gaps. At the same time, a tightening fiscal environment requires that the design of a future observation system should be optimised – efficient and cost-effective. This optimisation is made more difficult by the fact that the observing system cannot be designed from scratch but has to be integrated from a collection of disparate observing programs, each with different goals, methods, and governance. As a result, much of the work in designing an integrated observing system addressing societal needs involves ensuring that these existing programs can be integrated coherently into a holistic system that is fit-for-purpose. That is, there needs to be a clear set of standards for components of the observing system, as well as careful consideration of the societal benefits that need to be addressed.

Additionally, it is an important aspect that the environmental observing and data management communities work closely together to align data requirements and observing strategies, but most importantly on a coordinated approach around data formats, standards and best practises to ensure that data can be combined and utilised in a way that is meaningful, authoritative and accessible to users in close to real time.

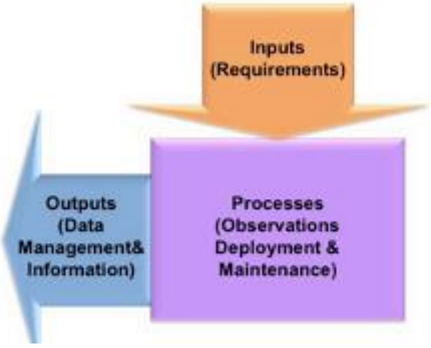
A major deliverable for the INTAROS project is the proposal for a roadmap towards the design and implementation of a future Sustained Arctic Observing System (SAOS). SAOS needs to build on existing observing elements, but also needs to be expanded by new elements aiming to close critical gaps with innovative solutions. A first and important step in this design process therefore is to quantify the requirements for a future SAOS. Having these requirements in place allows a comparison with the existing observing system to identify gaps and addressing these gaps will be the overall challenge in the implementation of SAOS.

Gaps can be divided into four categories:

1. Gaps in the observing Networks
    a. Spatial coverage by in situ observing is insufficient when considering the phenomena
    b. Some elements of the Arctic system lack observations, or the accuracy of the observations is insufficient when considering the phenomena
    c. Gaps in baseline data
    d. There are gaps in observing infrastructure to allow (near) real-time data transmission
    e. Lack of standardization and best practice for certain observing networks or certain variables
2. Gaps in data availability (free and open exchange)
    a. Some data originators have strict data policies that prevent free sharing of data
        i. Data collected by Naval/Military is often not made publicly available
        ii. Data collected in the context of research & development is held back in order to publish results before sharing
        iii. In some institutes data is sold and hence they are not willing to freely share data as that would compromise a part of their income stream
        iv. Data collected in the context of research & development is held back because of concerns about "incorrect” interpretation of environmental data.
3. Sustainability gaps
    a. There is a lack of sustained funding for observations in general
    b. Observing networks lack sustained funding for coordination or management of the network (staff, travel)
    c. In situ observations is based on infrastructures mainly supported by national agencies and the number of observation sites or platforms may decrease due to:
        i. Ageing of instruments/networks
        ii. Changes in scientific goals and priorities
        iii. Funding opportunities decreasing
        iv. Environmental effects (climate change, harsh environment)
4. Gaps in technology
    a. New technology and sensors are required
    b. Technological development is required to close gaps in (near) real-time data transmission (for example surface buoy, automatic system from vessels).

Early in the INTAROS project an “Initial Requirement Report” was prepared. Although the SAOS aim is to design includes atmosphere, land, cryosphere, sea ice and ocean, it used the design philosophy outlined in “*Framework for Ocean Observations”* (UNESCO, 2012), which focuses on a systems approach:

- Delivering a system based on common requirements, coordinated observing elements, and common data and information streams,
- Using "Essential Variables" as a common focus for requirements, defined based on *feasibility* and *impact* on societal and scientific drivers, and
- Evaluation of "readiness levels" for each of these system components.



A simplified representation of the basic system design

After defining the observing objective for a sustained observing system, a set of relevant phenomena and essential variables, but considering the regional context, will emerge. The phenomena assist in determining time and space scales over which the observing is to be executed. The phenomena also narrow down the essential variables that belong to the observing objective. From the combination of phenomena and Essential Variables the set of suitable observing platforms and sensors emerge.

In general, according to the Framework for Ocean Observations (UNESCO, 2012), the readiness of the integrated observing system is measured across three components:

1) an understanding of the requirements of the integrated observing system (i.e., the Essential Variables needed to meet the observing objectives);
2) the ability to make observations with sufficient accuracy on the required time and spatial scales (which depends on technology, funding, and cooperation among observing networks); and
3) data analysis, data management, and the provision of ocean information to users in timely fashion (which includes common standards, as well as free and open access to data).

Along each of these three dimensions, the readiness of the observing system evolves from concept through pilot to mature with rigorous review, vetting, and approval by the community to allow for innovation while protecting against inadequate or duplicative solutions.

The “Initial Requirement Report” gave a comprehensive analysis of phenomena, requirements in general terms, essential variables and observing technology logically split between atmosphere, terrestrial, cryosphere, sea ice and ocean very well knowing that these are strongly interconnected but also have different levels of maturity.

The aim of the present report primarily is to:

- Take note of recently articulated user need from the EU and international organisations
- Capitalise on INTAROS achievements
- Define more concrete requirements (spatio-temporal resolution, quality, timeliness) for the identified Essential Variables
- Address gaps in the present observing system

2. EU and international requirement for Arctic observations

2.1 EU

A safe, stable, sustainable and prosperous Arctic is important not just for the region itself, but for the European Union (EU) and for the world. The EU has therefore a strategic interest in playing a key role in the Arctic region.

2.1.1 EU Polar Strategy

EU released in 2016 an Arctic Policy, which presently is under review and update. The 2016 Policy identified three priority areas:

- Climate Change and Safeguarding the Arctic Environment.
- Sustainable Development in and around the Arctic.
- International Cooperation on Arctic Issues.

The policy stated that the EU should attach particular importance to research, science and innovation which will play a key role across all three priority areas. Actions in the priority areas should contribute to the implementation of Agenda 2030 and be in line with the 17 Sustainable Development Goals adopted by the United Nations in September 2015.

In this context the first priority area – *Climate Change and safeguarding the Arctic Environment* - is the most relevant and the key components will shortly be referenced. The EU highlighted three responses to this priority area:

1 **Research**
To support a better understanding of the processes that rule the Arctic environment, their function and possible responses to various drivers, the EU will continue to invest in Arctic research. Central components are:
  - EU-PolarNet initiative, which supports an EU-wide consortium of expertise and infrastructure for polar research to better assimilate Europe’s scientific and operational capabilities in the Polar regions
  - Support from EU space programmes to research on climate change in the Arctic
  - Operational infrastructure and services of Copernicus providing input to Arctic research activities, including weather monitoring, monitoring of climate variables and ice thickness, and improved ocean modelling.
  - Implementation of the Svalbard Integrated Arctic Earth Observing System — a multidisciplinary and multinational research infrastructure that is geographically distributed across Svalbard
  - Promotion and facilitation of effective international scientific cooperation through supporting transnational access to research infrastructure and open data resources to improve political and economic links and maintain good relations with key countries in the region.
  - Contribution through Horizon 2020 to pan-Arctic observing initiatives such as those promoted by the Arctic Council with SAON or the GEO Cold Region Initiative, with the view of preparing through research the establishment of operational long-standing systems.

2 **Climate mitigation and adaptation strategies**

The EU's ambition is to:

- Be in line with the Paris agreement to limit global average temperature increases to well below 2 °C and make an effort to limit the temperature increase to 1.5 °C. The EU has already committed to reducing its total greenhouse gas emissions by 40% by 2030 and by 80% by 2050 compared with 1990 levels.
- Work with the Arctic states, indigenous peoples and relevant Arctic regional and multilateral fora to share experience, expertise and information on climate change, impacts, adaptation and resilience, with a view to developing an ambitious climate adaptation agenda for the Arctic region.
- Work with regions in the Arctic to draw up appropriate adaptation and mitigation measures that take account of the local circumstances and special nature of the Arctic regions.
- Contribute to international efforts to limit emissions of short-lived climate pollutants such as black carbon and methane that further accelerate climactic changes in the Arctic.

3 Protecting the Environment

The EU aims to

- protect, preserve and improve the environment, including in the wider region, for present and future generations and continue its engagement in multilateral environmental agreements that also have particular relevance to the Arctic, and encourage their implementation. The EU will encourage full respect for the provisions of UNCLOS, which is considered customary international law, including the obligation to protect and preserve the marine environment.
- Work with partners to promote a high level of biodiversity protection with a view to halting the loss of biodiversity and achieving the global biodiversity 2020 targets.
- Promote establishment of marine protected areas in the Arctic, these areas being an important element in the effort to preserve biodiversity.
- Work with Arctic states and other international partners to develop an instrument under UNCLOS for the conservation and sustainable use of marine biodiversity in areas beyond national jurisdiction.
- Continue supporting work at international level to prohibit or phase out the use of persistent organic pollutants in the environment. Effective implementation of the Stockholm Convention by all Arctic states will be important in this regard.
- Encourage a swift ratification of the Minamata Convention with a view to preventing and reducing emissions of mercury.
- Follow guidelines for the Control and Management of Ships' Biofouling proposed by the International Maritime Organisation. Actions could build on the experience gained in the EU and its Member States in managing certain pathways, including measures established through the International Convention for the Control and Management of Ships Ballast Water and Sediments adopted in 2004.
- Work closely with Member States, the OSPAR Convention and other stakeholders on oil and gas activities to promote the adoption of the highest standards of major accident prevention and environmental control.

  - Be ready to share regulatory and technological best practice with international partners to support the safety and preservation of the environment in the region.
  - Welcome the Arctic Council Agreement on Cooperation on Marine Oil Pollution, Preparedness and Response in the Arctic.

The EU launched in July 2020 a public consultation on the Arctic Policy with the aim to gather input on how the EU can contribute to tackling the challenges in the years ahead in an updated EU Arctic Policy. The consultation confirmed that the EU Arctic Policy needs a forward-looking update to allow the EU to contribute in the best way to making the Arctic safe, stable, sustainable and prosperous. The consultation particularly stressed that the EU should:

- Take a long-term view and discourage environmentally unstable practices that undermine Arctic ecosystems, inhabitants, and species
- Make stronger links between climate policy, the European Green Deal, and the updated EU Arctic Policy to achieve sustainable development of the Arctic
- Maintain science and research at the heart of EU policies and actions in the Arctic

2.1.2 EU Polarnet

The EU-PolarNet project (2015-2020) and the follow-up project EU-PolarNet2 (2020-2025) are coordination and support actions to develop strategies to advance European Polar research and its contribution to EU policy-making processes. The project performed a strategic analysis of monitoring and modelling programmes (D2.5)[1] in 2018 and a Roadmap for optimisation of monitoring and modelling programmes (D2.6)[2] in 2019. The requirements for observations are addressed in these documents for all the major research topics and societal benefit areas. The documents have produced extensive inventories of monitoring programmes and presented major gaps in the observing systems.

A common conclusion is that the in-situ observations are very scarce or non-existent for many of the variables needed in all the scientific disciplines. In D2.6 a number of recommendations for observations are identified from more than 40 documents. Many of these documents are developed by the Arctic Council working groups, in particular AMAP and CAFF. The recommendations cover all the prioritized research areas for European polar research, including the human perspective, see Table 2.1 (Table 4 from D2.6).

In Table 2.2 (table 6 from EU-PolarNet D2.6 report) the recommendations are divided into activities: perform monitoring/observations, development of observing systems, basic research, data access and other issues related to the observing systems.

The analyses in D2.5 and D2.6 give an extensive overview of the needs and recommendations for observations, but not how to implement and operate the observing systems. For more quantitative requirements it is necessary to address the services supporting the different societal benefit areas, for example operational sea ice monitoring, fisheries management, permafrost monitoring, etc.

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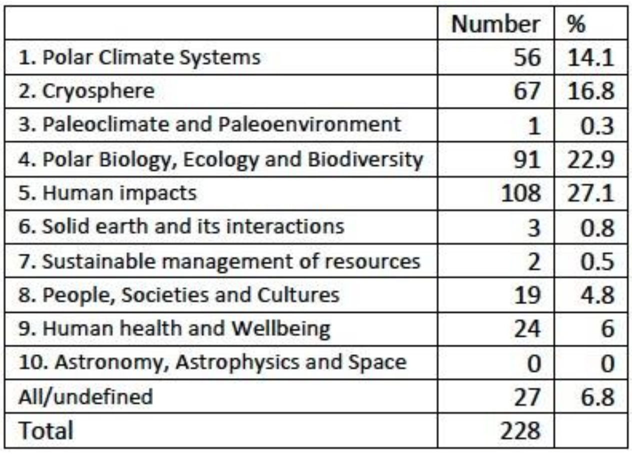
[1] https://eu-polarnet.eu/wp-content/uploads/2020/11/D2.5_Strategic_analysis_of_monitoring_and_modelling_programmes_final.pdf

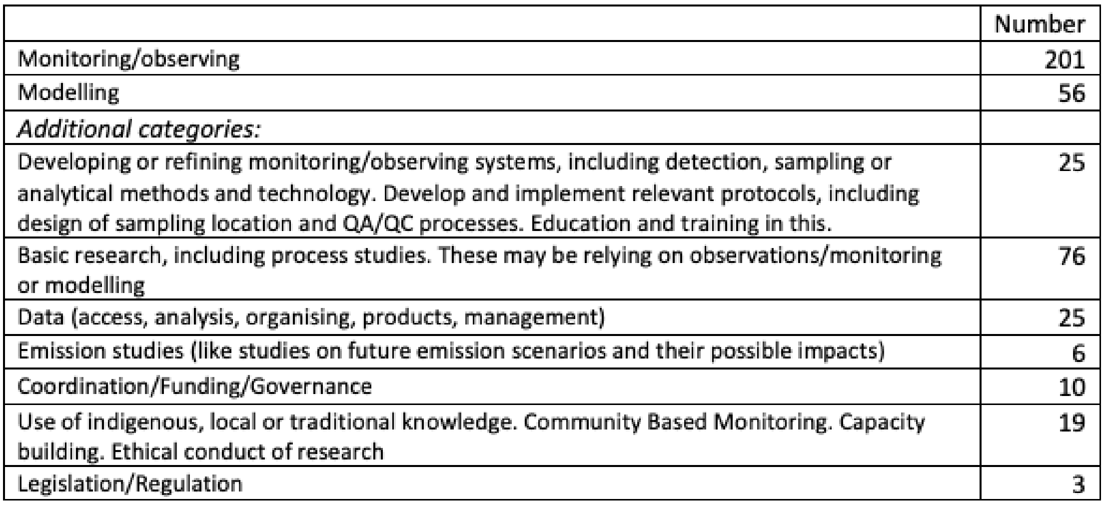
[2] https://1stdirectory.co.uk/_assets/files_comp/47d58953-6f0b-493c-99c7-85cd1b193a7d.pdf

Table 2.1. Documented recommendations on monitoring/observing and their distribution on European Research Priorities. The total number of recommendations is 228, but the number is 398 when distributed among the research areas because some recommendations are registered in more than one category. The percentage is calculated from a total of 398 (from EU-PolarNet D2.6).



	Number	%
1. Polar Climate Systems	56	14.1
2. Cryosphere	67	16.8
3. Paleoclimate and Paleoenvironment	1	0.3
4. Polar Biology, Ecology and Biodiversity	91	22.9
5. Human impacts	108	27.1
6. Solid earth and its interactions	3	0.8
7. Sustainable management of resources	2	0.5
8. People, Societies and Cultures	19	4.8
9. Human health and Wellbeing	24	6
10. Astronomy, Astrophysics and Space	0	0
All/undefined	27	6.8
Total	228	

Table2.2 Document recommendation and their distribution on activity Priorities (from EU-PolarNet D2.6).



	Number
Monitoring/observing	201
Modelling	56
Additional categories:	
Developing or refining monitoring/observing systems, including detection, sampling or analytical methods and technology. Develop and implement relevant protocols, including design of sampling location and QA/QC processes. Education and training in this.	25
Basic research, including process studies. These may be relying on observations/monitoring or modelling	76
Data (access, analysis, organising, products, management)	25
Emission studies (like studies on future emission scenarios and their possible impacts)	6
Coordination/Funding/Governance	10
Use of indigenous, local or traditional knowledge. Community Based Monitoring. Capacity building. Ethical conduct of research	19
Legislation/Regulation	3

The D2.6 document concludes with recommendation for a *Roadmap for Optimisation of Monitoring and Modelling Programmes for the Polar Regions* (ROMP). It should proceed under the following principles and assumptions:

1. ROMP should complement and integrate, without duplication, the current planning approaches used by existing networks (national, regional or global), activities and projects.
2. ROMP should support stepwise development through a flexible, federated and evolving structure that allows “bottom-up” identification of themes and foci. It recommends the definition of Essential Variables for the Polar Regions.

3. Indigenous Peoples and Local Community participation is critical to ROMP from its inception through its implementation (see Chapter 3.4).

White papers from EU-PolarNet
A set of five white papers have been developed to identify polar research priorities for EU and support EU's strategies for Arctic and Antarctica.

1. The coupled polar climate system
2. Footprints on changing polar ecosystems
3. Managing human impacts, resource use and conservation of the Polar regions
4. The road to the desired states of ecological systems in the Polar regions
5. Advancing operational informatics[3] for Polar regions

The documents describe the needs and recommendations for observing systems to support the research. Their focus is on process-oriented research to understand the coupling of physical processes and facilitate coupled modelling. General description of requirements for satellite data and in situ data (involving research stations, research vessels, icebreakers) and data services are provided. Observing infrastructure should be strengthened and measurements should be standardized to provide comparable data in the circumpolar regions. It is a severe challenge that several in situ observing systems are declining because they are not funded to be adequately maintained and developed. In addition, to improve the existing long-term observation sites, new sites should be established in remote areas where no observing systems are present today. The sparseness of the observing sites inhibits the assimilation of data into Earth System models, weather and climate prediction. New and improved technologies need to be developed regarding sensors, platforms and data communication which can operate autonomously in the polar regions. New observing and data transmission technologies can facilitate more data collection through community-based observing systems. There is also a need to coordinate existing data into common databases to enable integration of data between scientific disciplines. Data management should be standardised to ensure interoperability between data repositories and facilitate best use of existing and accumulating data sets.

2.1.3 Copernicus

Copernicus is the European Union's Earth Observation and Monitoring Programme. It transforms information from multiple sources, including satellites, into operational services for keeping watch over the planet Earth's land, ocean and atmosphere, monitoring climate change, supporting European emergency management and safeguarding civil security supporting a wide range of applications, including environment protection, management of urban areas, regional and local planning, agriculture, forestry, fisheries, health, transport, climate change, sustainable development, civil protection, and tourism. The Copernicus Services rely on many environmental measurements from ground-based, sea-borne or air-borne monitoring systems, as well as geospatial reference or ancillary data.

The user community for polar data is an important one and is provided with products generated from several Copernicus services. In the regulations for the EU Space Programme, entering into force in 2021, Polar monitoring is spelled out as a priority. This follows the line of the EU

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[3] Definition: "informatics studies of the representation, processing and communication of information in natural and engineered systems. It has computational, cognitive and social aspects" (University of Edinburgh, School of Informatics, 2017)

Arctic Policy from 2016 that describes the importance of space assets and Earth Observation to collect an evidence base for monitoring the rapid changes in the Arctic due to a changing climate. Given the remote and challenging conditions in the Arctic, evidence of change from Earth Observation is fundamental to the development, implementation and monitoring impact of the EU Arctic Policy.

The European Environment Agency (EEA) has been entrusted with the coordination of the Copernicus In Situ Component, under a Delegation Agreement with the European Commission. The EEA maps the landscape of in situ data availability, identifies data access gaps or bottlenecks, supports the provision of cross-cutting data and manages partnerships with data providers to improve access and use conditions.

The Arctic activities listed below have been managed by the EEA and carried out by the COINS (Copernicus Observations In Situ Networking and Sustainability) consortium composed by EUMETNET (European Meteorological Network), EuroGOOS (European component of the Global Ocean Observing System) and NILU (Norwegian Institute for Air Research). The work was done in close cooperation with the relevant Copernicus Services.

Arctic Data Report

The Copernicus Services and Space Component raised on different occasions in 2018 a strong concern on the timely availability of enough and relevant in situ data from the Arctic region.

Consequently, the EEA and the COINS consortium initiated a project focusing on clarifying to which extent the necessary in situ data (near real-time as well as delayed quality controlled) are available to:

- Maximize the exploration of present and future Copernicus Sentinels
- Produce and validate products from the Copernicus Services – CMEMS, C3S, and CAMS

The analysis was performed and reported by Buch et al, 2019[4]. The Copernicus community's requirements for environmental in situ data from Arctic region were collected together with information on the existence of such data – freely available or restricted. Comparing the two sets of information reveals severe gaps in:

- The present Arctic Observing System – especially the central Arctic is under-sampled
- Timely availability and quality of existing observations
- Availability of data from non-European countries
- Fit-for-purpose of observation technology
- Sufficient data management structures at data producer level
- Sustainability of existing observing system – many rely on time limited research funds

Arctic Project Catalogue

Much of our present knowledge and understanding of the Arctic Region environment has been built via national, regional and international funded research projects. Many of these projects included an in situ observation component, but unfortunately not all the collected observations have been made publicly available.

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[4] https://insitu.copernicus.eu/library/reports/CopernicusArcticDataReportFinalVersion2.1.pdf

The EEA and the COINS consortium therefore initiated a survey to prepare a catalogue over relevant time-limited projects with an Arctic focus within the domains of atmospheric chemistry, cryosphere, ocean, and meteorology. The focus was on:

- EU-funded projects - FP7 and H2020 (2007-now),
- regional and national projects
- For each project, to identify:
    - If and which in situ data have been collected?
    - Where are data stored?
    - Is data freely available, e.g., available to Copernicus?
    - For data not available to Copernicus identify the limitations for a free data exchange

The survey identified in total 205 projects with an Arctic component – 73 EU-funded, 119 nationally funded and 13 regionally funded. Not all of them included an in situ observing component and for some projects it has, at the time of reporting, not been possible to retrieve relevant information on data repository and data policy.

Key findings from the survey:

- 22 projects did not reply to the survey.
- 24 projects did not contain an in situ observing component.
- Of the 159 projects reporting in situ observing activity 50 projects (31,4%) have open and free data availability
- The remaining 109 projects have some kind of restriction on the data availability

Arctic Marine Data Portal

At the Polar Data Forum III (PDF III) in November 2019 the Copernicus In Situ Coordination Group, EMODnet Physics, CMEMS INSTAC and EuroGOOS organised a workshop on marine data from the Arctic Ocean. Recent surveys performed by the EEA and the COINS Consortium and the INTAROS project have revealed severe gaps in the present Arctic Observing System – especially the central Arctic, but also gaps in timely availability and quality of existing observations and in the availability of data from both European and non-European countries. A major part of the marine observations in the Arctic are funded via time-limited research projects with limited capacity for data management. The workshop recommended to establish a "Marine Arctic Data Portal".

The abovementioned organisations subsequently took the initiative to establish such a Data Portal with the purpose:

- To be a one-stop- shop for Arctic Marine in situ data easily accessible and freely available for any users
- Support European data integrator infrastructures (CMEMS, EMODnet and SeaDataNet) with relevant data
- Unlock existing data from a variety of projects not yet freely exchanged
- Display performance of Arctic Ocean Observing System

It was agreed to use the EMODnet Physics platform for the purpose since it can provide straightforward access to centrally curated circumpolar datasets and metadata records and a cooperative agreement between CMEMS INSTAC and EMODnet ensures data ingested into the Arctic Data Portal are fully available to the Copernicus community.

The portal was implemented during 2020 and launched via a virtual kick-off meeting for invited participants on 20 November 2020 and open webinar on 27 November 2020.

The portal is available on**: https://arctic.emodnet-physics.eu/**

The portal aims at

- helping scientists find the data they need to answer key questions,
- allowing research planners and program coordinators to explore the spatial and temporal distribution of observing platforms using the map interface. This knowledge will help them to identify gaps that need to be filled in the observing system.
- allowing researchers to easily and rapidly explore the data to test its suitability for their needs using the plotting tools for the datasets

Requirements

The Copernicus Services rely on the availability of a wide variety of in situ data. These data are used for the production, integration and validation of service products as well as to directly provide users with precise basic information collected by different and heterogeneous data collectors and producers.

The EEA with the support of the COINS consortium has implemented the Copernicus In Situ Component Information System (CIS[2]). This is a database which is intended to provide a detailed overview of requirements for and availability of in situ datasets used by the Copernicus Services and to identify possible gaps. It relates the in-situ requirements expressed by the Copernicus Services and Satellite Component to in situ datasets and their providers, in order to provide a clear picture of what data is already available and what would be needed to deliver improved and more reliable products and monitoring services.

Sustainability

Concern on the sustainability of environmental in situ observations has been raise on several occasions over the past years. Therefore, in 2018 the EEA and the COINS consortium conducted a sustainability survey and analysis of environmental in situ observing networks in Europe. The work was based on a questionnaire that was circulated to observation system operators to monitor any known funding risks to the platforms they operate. The platforms within the scope of the survey included ocean, meteorology, and atmospheric composition in situ networks. Based on a total of 233 replies – 91 for ocean, 122 for meteorology and 20 for atmospheric composition an analysis of the funding source and sustainability was performed (Buch et al, 2019), see Chapter 5.3 for details.

2.1.4 CORE-CLIMAX and GAIA-CLIM

In the framework of the EU CORE-CLIMAX FP7 project, an assessment of Europe's capacity to provide climate data records for Essential Climate Variables (ECV) as defined by the Global

Climate Observing System (GCOS) was conducted (EUMETSAT, 2014). One of the scopes of the assessment was to support the establishment of the Copernicus Climate Change Service.

The assessment addressed satellite and in situ climate data records (mostly gridded products) as well as weather prediction model-based reanalysis output and was based on the System Maturity Matrix (SMM) method. In SMM there are 6 major categories where assessments are made:

1. Software readiness
2. Metadata
3. User documentation
4. Uncertainty characterization
5. Public access, feedback, and update
6. Usage

For each of these categories, the assessment assigned a range of score (1 – 6) that reflected the maturity of the data with respect to a specific category. The major categories of the SMM are subdivided into several minor categories and assessment scores are assigned based on scores in these minor categories. The best score (6) is given when the data fulfil the best practices in that category. This score system made the assessment semi-quantitative and enabled a comprehensive overview of the addressed data records. In the H2020 GAIA-CLIM project the SMM approach developed in CORE-CLIMAX was adapted to in situ data series: software readiness became optional, and the category "sustainability" was added (Thorne et al., 2017).

The SMM was designed to principally be used without considering specific applications e.g., SMM does not depend on user requirements for specific applications and their change over time. However, the semi-quantitative nature of SMM enables an evaluation of the data with respect to the best practices, which are the goal requirement for most applications.

The applicability of the SMM for observational capacity assessment was well demonstrated by the 37 climate data records assessed in CORE-CLIMAX and the 43 ground-based atmospheric reference networks assessed in GAIA-CLIM. Moreover, SMM has served as the objective tool to quantitatively assess the data characteristics that are not listed among the WMO OSCAR requirements in many more applications:

- SMM is used in H2020 EUSTACE project to assess the maturity of data set development.
- SMM was included in the Quality Assurance concept of FP7 QA4ECV project.
- CEOS-CGMS WG Climate uses SMM to assess status of data records in GCOS ECV inventory, which will be periodically repeated.
- The WMO initiative for Sustained and Coordinated Processing of Environmental Satellite Data for Climate Monitoring (SCOPE-CM, http://www.scope-cm.org/) uses the SMM as a progress monitoring tool in each of its dedicated internationally coordinated Climate Data Record projects.

Planned systematic applications include:

- Implementation in the Quality Assurance and Enhancement (QC&E) pillar of Copernicus Climate Change Service (C3S).

2.2 SAON

The Sustaining Arctic Observing Networks (SAON) is a joint initiative of the Arctic Council and the International Arctic Science Committee (IASC) that aims to strengthen multinational engagement in pan-Arctic observing. The SAON process was established in 2011 at the Seventh Ministerial Meeting of the Arctic Council (AC) via the Nuuk Declaration. This declaration recognizes the *"Importance of the Sustaining Arctic Observing Networks process as a major legacy of the International Polar Year for enhancing scientific observations and data-sharing"*.

In 2012, the SAON established two committees:

- The Arctic Data Committee (ADC) aiming to promote and facilitate international collaboration to establish free, ethically open, sustained, and timely access to Arctic data through easily accessible and interoperable systems
- The Committee on Observations and Networks (CON) aiming to promote and facilitate international collaboration towards a pan-Arctic Observing System, which is defined as a sustained, integrated and multi-disciplinary system for observing this region of rapid change.

In 2018, the SAON Strategy 2018-2028 document was developed to provide a 10-year strategy to address current and future Arctic observing needs. It describes SAON's vision, mission, guiding principle and goals, and outlines the way the goals will be achieved. In support of the new SAON Strategy, the new SAON Implementation Plan approved in 2018 provides detailed information about the objectives of SAON, as well as descriptions of timelines, cooperation with external organizations and resource/funding requirements.

Roadmap for Arctic Observing and Data Systems (ROADS)
SAON's vision is for a connected, collaborative, and comprehensive long-term Pan-Arctic Observing System that serves societal needs. This vision requires a way for the existing patchwork of observing activities to work jointly towards more coordinated observations. The organizational framework that is meant to move such collaboration forward is referred to as the Roadmap for Arctic Observing and Data Systems (ROADS). The 2020 Arctic Observing Summit was the first opportunity for community input into the development of ROADS.

SAON has identified three key principles for the ROADS process:

- ROADS should complement and integrate the current planning approaches used by existing observing networks (regional to global), activities and projects.
- ROADS should support stepwise development through a flexible, collaborative, and evolving structure that allows "bottom-up" identification of themes and focus regions.
- Indigenous Peoples' equitable partnership and funding for their active participation are critical to ROADS from its inception through its implementation.

The plan for ROADS is centred around the identification of Essential Arctic Variables (EAVs) that serve societal benefits and that can provide guidance as to how and what observations should be made. Clustering observations by EAV would then facilitate both the sharing of best practices and optimizing the use of resources within an observational community that spans disciplines, applications, and national funding systems. Coordinating observations within and between these EAV clusters could then facilitate the information infrastructure and data products to make observations as useful as possible for the communities they benefit.

Essential Arctic Variables (EAV*)*

The essential variable strategy clearly emerged as a main requirement and best practice for supporting network development in SAON. The approach is conceptually holistic; yet it can proceed stepwise as each variable's implementation strategy achieves readiness, and ROADS will be organized around Essential Arctic Variables (EAVs). These are conceptually broad observable phenomena (e.g., "sea ice") identified for their criticality to supporting Arctic societal benefit, as defined through International Arctic Observations Assessment Framework (IAOAF) assessment. A useful EAV will cut across multiple SBAs and fulfil at least a portion of the observing requirements of many *Key Objectives*.

EAVs shall be specified by their observing system (e.g., spatial resolution, frequency, latency, uncertainty) and data management requirements, which should transcend specific observing strategies (i.e., technology neutral), programs or regions. They shall be implemented through specific recommendations based on Arctic-viable technology and practices. A holistic and collaborative Observing and Data System organized around EAVs is achieved through employing consistent strategies in assessing, linking and developing requirements for sampling. The EAV approach allows for progress on implementation, under an expectation of continuous innovation in the underlying technologies. Importantly, EAVs provide a structured interface for coordination and collaboration in support of societal benefit as well as a data management framework for integrating independently sponsored observations into interoperable data streams.

In keeping with the ROADS principle of complementing current efforts in a non-duplicative approach, a rational starting point for identifying priority EAVs begins with a recognition of the considerable work that has already been done, as reflected in existing catalogues of essential variables associated with global networks (e.g. Essential Ocean Variables, Essential Climate Variables, Essential Biodiversity Variables), regional programs (e.g. Arctic Monitoring and Assessment Programme (AMAP) and Circumpolar Biodiversity Monitoring Programme, (CBMP)) and with reference to gaps analyses like the European Space Agency's Polar View assessment. ROADS EAVs should extend the requirements (e.g., adding requirements for fast ice observations to global variables for sea ice) and implementation strategies of the global networks, where necessary, to account for Arctic conditions (e.g., polar night) and opportunities (e.g., community observers). A global variable should only be an EAV if the global definition inadequately serves Arctic needs. The ROADS process for each EAV should fully specify *the observing and data systems requirements* from acquisition through high impact information dissemination. It is recognized that new EAVs - unique to the Arctic - could also be identified through IAOAF assessment. Both the adoption of existing and creation of unique EAVs should be based on practices of co-design.

Many global networks have defined procedures, templates and principles for essential variable maintenance. It is envisioned that the ROADS process will evolve stepwise through a series of funded pilot efforts that will lead towards a unified model for structuring documentation about ROADS EAVs.

The SAON's Road Mapping Task Force (RMTF) outlined a multi-phase process for the initiation and progression of Expert Panel work under ROADS for identifying, defining and implementing EAVs. Its main steps include:

- *Initiating* – Each proposing Expert Panel is invited to write a brief proposal to the ROADS Advisory Panel outlining a proposed scope of EAV development activities and participants.
- *Phase I* – Convene relevant participants in one or more community meetings to identify critical EAVs for the Expert Panel's scope of interest. Criticality should be systematically assessed using IAOAF principally, through *Value Tree Analyses*, as well as using ethical guidelines.
- *Phase II* – Convene relevant participants in one or more community meetings to specify the requirements for each relevant EAV for the scope. Requirements should be comprehensive of data collection, data management (in keeping with the IASC *Statement of Principles and Practices for Arctic Data Management*), analysis, system management, and dissemination. Systematic approaches to requirements development, such as Observing System Experiments, are highly encouraged where viable.
- *Phase III* – Convene relevant participants, in collaboration with relevant funding agencies and partner organizations, to outline strategies for implementation and engage commitments for sustainment. This process should describe which infrastructures (physical and cyber) are essential for current implementation. These include satellite earth observation programs, terrestrial stations, vessels, aircrafts and various autonomous platforms providing observing systems. Implementation should also describe how these infrastructures will be integrated into value-added services and products and the strategy for their dissemination, such as ArcticGEOSS. This phase of work should also identify technology development needs to improve readiness of future generations of the observing system.
- The collection of approved EAVs and their underlying descriptions should be evaluated every five years as the requirements and strategies for observing will be subject to change. The pace of Arctic change suggests as much, but also the recognition that our scientific and societal needs from an observing system will change over time.

The SAON Strategy covers a ten-year timeline from 2018 to 2028, but progress on ROADS is expected to advance more swiftly. ROADS will not measure its success by the number of Essential Arctic Variables defined, but rather by the extent to which the Key Objectives have been translated through EAVs into a system of observing requirements and resource-estimated implementation plans. A successful ROADS process could generate 20 or more EAVs by 2028. Collaboration with Arctic Observing Summit Working Groups and funded proposals working on ROADS will facilitate this progress. The following timeline is thus tied to the AOS schedule.

By the 2022 Arctic Observing Summit, ROADS should accomplish:

- Completed value-tree assessment of 2 to 4 Societal Benefit Areas and their underlying *Key Objectives*.
- Development of 3-6 Essential Arctic Variables through at least Phase II of the ROADS process, ideally at least one EAV will have gone through all 3 Phases of development.

By the 2024 Arctic Observing Summit, ROADS should accomplish:

- Completed value-tree assessment of 5 to 8 Societal Benefit Areas and their underlying *Key Objectives*.
- Development of further Essential Arctic Variables, as relevant, through all 3 Phases of development.
- Development of cyberinfrastructure to support EAVs.

By the 2028 Arctic Observing Summit, ROADS should accomplish:

- Completed value-tree assessment of all Societal Benefit Areas and their underlying Key Objectives.
- Development of further EAVs as relevant to the above though all 3 phases of development.
- Development of cyberinfrastructure to support EAVs.

Recommendations on requirements from AOS 2020

Conference Statement and Call to Action from Arctic Observing Summit 2020 (AOS) convened as part of SAON recommend that in identifying Essential Arctic Variables (EAVs) they be prioritized as *Shared Arctic Variables (SAVs), identified by their importance to multiple information user groups and applications*.

Expert panels, comprising observation data providers and users – Indigenous People and Arctic communities being prominent among these - coordinated through SAON are called on to define these variables. The Expert Panels should use processes established by global observing systems for identifying and defining EAVs and SAVs wherever possible and should be broadly inclusive and draw on rounds of user community input to best reflect a range of perspectives.

International networks are invited to develop formal engagement mechanisms or to help lead the process where appropriate. To guide identification of SAVs, AOS2020 recommend launching regional studies. Regions such as the Bering Sea, the Beaufort/Mackenzie Delta area, Baffin Bay and surrounding coasts, and the Barents Sea, with strong regional networks of Indigenous observers, broadly international scientific activity, large-scale commercial fisheries, and major impacts from rapid environmental change are particular suited as locales for regional efforts.

Regional and pan-Arctic efforts under ROADS need to be complemented by continued, and expanded, funding and infrastructure support of in situ observations and field measurements. Improved understanding of system components, essential variables and processes gives the ability to project the longer-term trajectory of the system and plan for the future. Near real-time data is vital to decision-makers and informs operational and tactical decision making, as well as longer-term adaptation and mitigation. AOS2020 recommended continued development of easily understood graphical data drawn from multiple observing/monitoring programs, networks, and systems to project long-term trajectories and information flow on short time scales.

Planning for, adapting to, and mitigating change in the Arctic, as elsewhere, requires sustained and iterative design and implementation of a pan-Arctic, internationally supported network of observing systems. Many elements of the system are already in place but there are gaps to be identified and filled to maximize benefits. AOS2020 recommend quickly identifying essential variables most useful for observing in support of disaster management and risk reduction, improving resilience and co-management of terrestrial and marine ecosystems, including wildlife, and ensuring the resilience of Arctic communities and people.

Indigenous and science-based observing together should inform decision making across time, space, people and organizations. Information from such observing approaches should support development of policy, real-world solutions to existing and emerging problems, and the implementation of adaptation initiatives and mitigation efforts.

2.3 WMO – operational, climate

WMO has defined requirements for in situ and satellite geophysical variables for their most important application areas:

- Aeronautical meteorology,
- Agricultural meteorology,
- Climate monitoring,
- Global NWP,
- High Resolution NWP,
- Hydrology,
- Nowcasting,
- Ocean Applications,
- Sub-seasonal to longer predictions,
- Space Weather.

These application areas focus primarily on meteorological, hydrological, and climatological services; hence the requirements fulfil the needs of the weather, climate, and hydrological models. Recently other application areas have been included to reflect the need of climate scientists and the atmospheric composition community: Climate Science, forecasting atmospheric composition (Variable: CH_3OH Mole Fraction), monitoring atmospheric composition (Variable: CO_2), providing Atmospheric Composition information to support services in urban and populated areas. However, there are still no requirements defined for these application areas.

The requirements are defined in terms of 6 criteria: uncertainty, horizontal resolution, vertical resolution, observing cycle, timeliness, and stability (where appropriate). For each of these criteria 3 values have been determined by experts: the threshold is the minimum requirement to be met to ensure that data are useful, the goal is an ideal requirement beyond which further improvements are not necessary, and breakthrough is an intermediate level between threshold and goal which, if achieved, would result in a significant improvement for the targeted application.

Observation requirements are collated in a comprehensive, systematic and quantitative way in the OSCAR database, and are regularly reviewed by groups of experts. Using the Rolling Review of Requirements (RRR) process, defined by the Manual on the Global Observing System (WMO-No. 544) (Part II, Requirements for observational data), requirements for observations are compared with the capabilities of present and planned observing systems. The output of this is reviewed by experts in the relevant application and used to prepare a Statement of Guidance (SOG), one per application area, the main aim of which is to highlight gaps between requirements and observing system capabilities. More information on RRR process and the SoG document for each application area are available at: https://community.wmo.int/rolling-review-requirements-process (WMO, last access August 18, 2021). The addressed observing systems are both in situ (OSCAR/Surface database) and satellite (OSCAR/Space database).

For each of the application areas considered, the SOG provides an assessment of the adequacy of observations to fulfil requirements and suggests areas of progress towards improved use of space-based and surface-based observing systems. Only the most significant variables have been analysed in the SOGs, and the provided gap analysis is only qualitative.

In Table 2.3 the key variables assessed in the SOGs are listed for 3 groups of application areas on meteorology and forecasting services, and the main gaps in term of critical variables that are not adequately measured are listed on the right column. Many of the listed gaps refer to variables that are observed in the Arctic (highlighted in red). Severe gaps are detected in data temporal and spatial coverage, quality, and data reporting of several surface observation parameters.

*Table 2.**3** Groups of applications areas as defined by WMO and related relevant variables assessed in the corresponding Statements of Guidance (see: https://community.wmo.int/rolling-review-requirements-process (WMO, last access August 18, 2021). The critical variables that are not adequately measured by the in situ observing systems are listed in the right column. Red text refers to in situ variables observed in the Arctic.*

Application area	Variables assessed in the SOGs	Critical variables that are not adequately measured
• **Global NWP** • **High Resolution NWP** • **Nowcasting and very short range forecasting** • **Agricultural meteorology**	• 3D wind field (horizontal component) • 3D wind (vertical component) • Surface pressure and surface wind • 3D temperature field • 3D humidity field • Sea surface temperature • Sea-ice • Ocean sub-surface variables, Sea Level and Surface Salinity • Snow • Soil moisture • Surface air temperature and humidity • Land and lake-sea-ice surface skin temperature • Vegetation type and cover • Clouds and Precipitation, lightning • Visibility • Short-wave irradiance • Ozone • Wave height, direction and period • 3D aerosol (inc. dust/volcanic ash)	• Temperature and humidity profiles of adequate vertical resolution in cloudy areas, particularly over the poles and sparsely populated land areas; • Satellite based rainfall estimates; • Wind gust • Wind profiler data over oceanic, sparsely populated and polar regions is nearly absent. • Surface air temperature and humidity are are marginal or missing over Polar regions • Solid precipitation is not measured adequately. • Snow equivalent water content • Soil moisture • Non-professional cooperative observers have a vital role in providing supplemental reports of accumulated precipitation on an event-driven basis • The horizontal resolution of observations of most surface variables and phenomena needed for nowcasting and VSRF is acceptable in some populated area but marginal to absent in sparsely populated areas and above seas. Only a subset of all available surface observations

• **Sub-seasonal to longer predictions** • **Ocean applications** • **Climate monitoring**	• Ocean and ocean-related variables • Sea surface temperature • Ocean wind stress • Sub-surface temperature • Salinity • Ocean topography • Surface heat, radiative and freshwater fluxes • Ocean current data • Sea ice • Deep sea • Land variables • Snow • Soil moisture • Aerosol and greenhouse gases • Solar irradiance	arrive in useful time to the weather centres, particularly for nowcasting applications. Interpolation techniques can provide real-time high-resolution fields for many surface variables, but the measurement frequency should be increased (i.e. automated), the data transmission accelerated and where possible some automatic QC introduced. Many automatic stations belong to networks external to NMSs and the data are not integrated in the NMS database (their number is increasing in the last years); • Current in situ wave measurements are not standardized resulting in impaired utility. Differences in measured waves from different platforms, sensors, processing and moorings have been identified. In situ measurements are currently too sparse in the open ocean (poor coverage) to be of particular value. • Coverage in sea surface temperature and salinity is marginal or poor over the Polar seas. • Ships and buoys provide chlorophyll, nitrate, silicate and phosphate concentration data of poor spatial-temporal resolution over many regions. These products are poor in terms of timeliness required for marine services applications • 3D ocean currents: moored buoys are good in temporal resolution and accuracy, but marginal or poor otherwise.
• **Aeronautical meteorology**	• 3D Wind and Temperature Fields and Profiles • Surface and near-surface wind • Surface pressure • Humidity fields • Cloud and liquid / ice water content • Visibility and cloud amount / cloud base height Surface heat, radiative and freshwater fluxes • Gravity waves • Volcanic Ash • Sand-and Dust Storms • Space Weather • Snow • Soil moisture • Aerosol • Solar irradiance	

A synthesis of recommendations from SOGs to close existing gaps in meteorology, ocean and hydrology in situ observations is presented below.

Meteorology

- Beneficial for NWP models are:
    - more timely availability and wider distribution of some observations would be beneficial, in particular several types of in situ measurement and radar that are made but not currently disseminated globally, such as soil wetness, snow depth, wind gusts, precipitation from rain gauges and radar and ground-based GPS; over marine areas, more ice thickness data and surface salinity.
    - increased coverage of data in the boundary layer, which is characterized by high vertical resolutions in the models, would be beneficial.
    - increased coverage of aircraft data in all the regions of the globe, particularly from ascent and descent profiles.
    - high resolution observations over sea areas upstream of populated areas, or of high-impact weather areas.

    - more Doppler radar data (including precipitation types deduced from polarimetric measurements) and ground-based GPS stations (which are relatively new observations in terms of assimilation).
- The critical atmospheric variables that are not adequately measured by current or planned systems are (in order of priority): wind profiles at all levels outside the main populated areas, particularly in the tropics and in the stratosphere; temperature and humidity profiles of adequate vertical resolution in cloudy areas, particularly over the poles and sparsely populated land areas; snow equivalent water content.

Other recommendations include:

- Improve the use of QC/QA techniques and recording of metadata (with reference to the WMO WIGOS and RRR tables: www.wmo-sat.info/oscar/)
- Recommend “opening” of third-party data through cooperation with private companies, at least in case of “significant events”.
- Make more use of data from specific observation networks (all power plants, electrical grid operators, mining industries, pipeline operators, TV stations, pollution, military, forest, etc.).
- Obtain rapid transmission of all real time observations both from surface stations and from remote sensing systems.
- Develop non-professional alternative observations networks like trained spotters’ network, meteorological observations performed in schools, cell phones, web cameras, etc.

Ocean Applications (Liui, G., 2016)

The assessed variables for Ocean applications include surface water discharge, surface water storage fluxes, groundwater fluxes, precipitation, evaporation, soil moisture/soil wetness, snow cover, depth, and water equivalent and glaciers, land surface temperature, vegetation type and NDVI, and water use. The key points from the SoG are:

- A large part of marine and ocean observing systems is currently maintained by research funding with limited duration. This has the potential of leaving observational gaps unless ongoing funding for sustained observing networks is guaranteed.
- The uneven geographical coverage of the in-situ ocean observing network is also an ongoing issue for ocean applications. Considering the regional variability in requirements as well as to ensure optimized planning for observing networks with limited resources, geographical variability in spatial/temporal resolution for ocean observations should be emphasised.
- Ocean observing communities should also improve geographical coverage of ocean observing systems, particularly for measuring SST, SSHA, SSS and visibility, along with higher resolution geometry and extend open-ocean and coastal wind-wave observing networks (e.g., 400 time-series reporting in open ocean), possibly developing other existing observing sites (e.g., global sea level and tsunami monitoring network) into multi-purpose stations.
- The critical met-ocean variables that are not adequately measured (more accurate and frequent observations and better spatial/temporal resolution are required) by current or planned systems are: sea-surface height anomaly, wave parameters, sea level, surface pressure, visibility.

Hydrology and Water Resources

The SOG for Hydrology (WMO 2014, available at https://community.wmo.int/rolling-review-requirements-process: Hydrology) assessed variables: Surface water discharge, Surface water storage fluxes, Groundwater fluxes, Precipitation, Evaporation, Soil moisture/Soil wetness, Snow cover, depth, and water equivalent and glaciers, Land surface temperature, Vegetation type and NDVI, and Water Use. The main conclusion is that in despite of better availability and applicability of satellite-borne observations, there are significant gaps in sustainability, regional coverage, and data quality. Similarly, all available data and sources are not yet routinely used by national hydrological services. Focus needs to be placed on the integration of in-situ and space-based observations for hydrological applications in a comparable space and time domain and of acceptable accuracy. The latter would require increased efforts to assess observation quality through intercomparison and (re)-calibration projects and include estimates of uncertainty. In general, access to hydrological data and observations of all variables mentioned is insufficient for many research and development purposes and for practical applications by national Hydrological Services.

Climate system monitoring

The WMO SoG for climate monitoring is based on document: The Global Observing System for Climate: Implementation Needs (GCOS, 2016). The implementation plan discusses the requirements and actions needed for each selected Essential Climate Variable (ECV) to enable a holistic global climate monitoring that includes the atmospheric (surface, upper-air, composition), oceanic (physics, biogeochemistry, biology) and terrestrial (hydrology, cryosphere, biosphere, natural resources) domains. Each measurement domain was assessed by an expert GCOS science panel. Several gaps related with essential and supporting climate variables' coverage, quality, sustainability, and data access were identified and corresponding actions, in total 40 for Atmosphere, 57 for Ocean and 72 for Terrestrial, were proposed.

In conclusion, the gap analysis performed in the SOGs was done not only using the main 5 criteria that quantitatively define requirements (uncertainty, horizontal resolution, vertical resolution, observing cycle, timeliness) but considering also other important aspects of the data such as sustainability and data management. These last aspects, however, were addressed in a purely qualitative way.

One outcome of the gap analysis led to a design of a Global Basic Observing Network (GBON). The gaps in global surface and upper atmospheric observations data are critical for global NWP thereby impacting several weather and climate application areas. WMO raised this concern by launching GBON, which aims at facilitating an improved global access to surface and upper atmospheric data. Sustainability of this network is considered.

It should also be noted that the WMO analysis of observational gaps largely comes from a global NWP perspective and all conclusions may not be of high priority, or even valid, in an Arctic context. For example, while accurate measurements of winds aloft are of course important everywhere, they are in a global context of particular importance in the tropics; this even initiated special space-borne observation assets such as the space borne AEOLUS Doppler lidar. The reasons is that the impact of Earth's rotation on the winds is weaker in the tropics, partially severing the so-called geostrophic relationship between the atmospheric motion and mass fields, while the vertical thermodynamic structure is dominated by convection keeping the atmosphere well mixed. Instead taking an Arctic perspective, wind is to larger degree determined by the atmospheric mass distribution - the thermodynamics - which here has a complex vertical structure depending on many factors such as clouds, weather systems and advection. This makes observations of the thermodynamic vertical structure relatively more important in the Arctic.

2.4 IOC - Ocean Decade

The marine realm is the largest component of the Earth's system that stabilizes climate and supports life on Earth and human well-being. However, the First World Ocean Assessment released in 2016 found that much of the ocean is now seriously degraded, with changes and losses in the structure, function and benefits from marine systems. In addition, the impact of multiple stressors on the ocean is projected to increase as the human population grows towards the expected 9 billion by 2050. Adaptation strategies and science-informed policy responses to global change are therefore urgently needed.

Scientific understanding of the ocean's responses to pressures and management action is fundamental for sustainable development. Ocean observations and research are also essential to predict the consequences of change, design mitigation and guide adaptation.

The United Nations has consequently proclaimed a Decade of Ocean Science for Sustainable Development (2021-2030) to support efforts to reverse the cycle of decline in ocean health and gather ocean stakeholders worldwide behind a common framework that will ensure ocean science can fully support countries in creating improved conditions for sustainable development of the Ocean. Mandated by the UN General Assembly, the Intergovernmental Oceanographic Commission (IOC) of UNESCO will coordinate the Decade's preparatory process, inviting the global ocean community to plan for the next ten years in ocean science and technology to deliver, together, the ocean we need for the future we want.

In response to this invitation the Arctic marine science community produced a number of key insights, particularly related to the presence of cross-cutting barriers for progress. These spanned broadly from purely scientific gaps in understanding and data availability, to organizational issues concerning efficient international coordination and the lack of tools and services to make new knowledge products accessible for industry, governance and the public. To mirror this an Arctic Action Plan has been formulated structured around three types of challenges and their suggested solutions.

1 Research challenges – to achieve transformative ocean science solutions
The Ocean Decade's call for transformative ocean science can be synthesized into four overarching themes for the Arctic region:

- Transformative Solution 1: Provide the entire Arctic region with a detailed open-access inventory of spatial and temporal information on bathymetry, oceanographic conditions, documenting geodiversity and biodiversity, disaster and pollution risks, provisioning of ecosystem services and their value to support evidence-based decision making.

- Transformative Solution 2: Understand the core Arctic climate and ecosystem dynamics; the impacts of anthropogenic pressures on the environment and ecosystem; and the mechanisms which threaten human health and safety in the region.
- Transformative Solution 3: Observe the state of Arctic environments and development trends in near-real time supported by information services tailored to the needs of science, management and industry. This includes sustained observation programmes to establish baselines and trends in: ice distribution; weather and sea state; ecosystem structure and dynamics; distribution of natural resources; carbon cycling; anthropogenic pressures; ocean circulation; and spatial and temporal distribution of contaminants.
- Transformative Solution 4: Predict and forecast Arctic climate and ecosystem dynamics on scales from hours to millennia, to enable climate adaptation and ecosystem-based management of human activities.

2 Organisational challenges – for achieving high impact science in the region

There is a strong community awareness of pivotal importance of international collaboration and organizational support to deliver high impact solutions in the region. This relates in particular to efficient international coordination, adequate funding, infrastructure and equipment availability, data management and political support. To emphasize this and catalyse progress a dedicated agenda to advance these priorities is proposed:

- Connecting the Arctic
- Establishing large-scale sustained internationally co-funded programmes
- Collaborating and coordinating ongoing and future Arctic research, management and observation programmes
- Collaborating on creating and maintaining joint open data sharing platforms.
- Co-designing and producing actions linking across local, national and regional communities
- Collaborating with key stakeholders throughout the Arctic on increasing global awareness of Arctic issues and ocean literacy in the region
- Developing technology to improve temporal and geographical coverage of multidisciplinary observation programs in the region

3 Uptake challenges - to enhance societal benefit of ocean science in the Arctic

While ocean science is at the foundation of the Arctic Action Plan, the benefits arising from it require dedicated actions to realise its full potential across management, industry and society. To accelerate progress, the plan presents an agenda which highlights particular challenges which should be addressed. These relate to the end of the ‘knowledge value chain’ where scientific progress is translated into tangible services and products and ultimately brings society closer to the desired societal outcomes of the decade:

- Developing the information services necessary for safe navigation.
- Developing Search And Rescue (SAR) and Oil Spill Response (OSR) capacity.
- Coordinated management and response to risks and disasters.
- Managing the marine and coastal environments through an integrated framework.
- Managing vulnerable habitats or threatened species through designation of marine protected areas.
- Managing the marine and coastal areas with adequate enforcement measures.
- Collaborating with key industry stakeholders and governments to create an Arctic-Specific Corporate Social Responsibility (CSR) program

2.5 Arctic Fisheries Management

Different parts of the Arctic and sub-arctic seas have highly different fisheries management regimes. Some areas are managed by one nation, others by two or more. However, they have in common that they rely on scientific advice, largely dependent on observation-based data. For instance, the Barents Sea, with the world's largest stock of Atlantic cod and a well-developed fishing industry, is managed by the Joint Norwegian–Russian Fisheries Commission. The commission, and underlying working groups, build heavily upon scientific advice, mainly channelled through the International Council for the Exploration of the Sea (ICES).

The high seas areas of the central Arctic Ocean are a special case. With retreating ice, these areas that until recently have been unavailable for fishing, are now of increasing interest. To avoid the start of unregulated fisheries, with potentially negative impacts on the affected stocks and the ecosystem as a whole, *the International Agreement to Prevent Unregulated Fishing in the High Seas of the Central Arctic Ocean* was signed in 2018 by Canada, Iceland, Denmark, Norway, the United States, the Russian Federation, China, Japan, South Korea and the European Union. This Agreement will remain in force for an initial period of 16 years following ratification by all parties.

Part of the Agreement is a Joint Program of Scientific Research and Monitoring with the aim of improving the understanding the ecosystems of the Agreement Area and, in particular, of determining whether fish stocks might exist in the Agreement Area now or in the future that could be harvested on a sustainable basis and the possible impacts of such fisheries on the ecosystems of the Agreement Area. Further, *as part of the Joint Program of Scientific Research and Monitoring, the Parties shall adopt, within two years of the entry into force of this Agreement, a data sharing protocol and shall share relevant data, directly or through relevant scientific and technical organizations, bodies and programs, in accordance with that protocol*. Consequently, the Agreement raises clear requirements for enhanced and coordinated observation of the high seas of the Arctic, including open and efficient data sharing. The Agreement also requires that decisions on living resource management in the region take into consideration *both Indigenous/local knowledge and scientific knowledge*. This is further discussed in Chapter 2.6 and 3.4.

For harvested fish, Essential Ocean Variables (EOVs) include abundance (number) and biomass. For well-monitored fish stocks, minimum information also includes weight and numbers per age group and biomass of the mature part of the population (spawning stock biomass). Observations of fish abundance and biomass still depends heavily on access by vessels. For areas and times of year with ice, specialized ice-certified vessels are necessary, but with smaller areas with ice for shorter periods, research surveys with normal vessels can safely expand their coverage given sufficient priority. For instance, it is important that the Barents Sea coverage is extended further northwards, also beyond the shelf edge and into the Arctic Ocean proper. While a one-off explorative research cruise is interesting, to expand or establish new measurement series it is a requirement that sufficient sustained funding is allocated. There are a few cases where fish in Arctic areas are monitored by autonomous observations. For instance, in the Eastern Bering Sea the seasonal movements of walleye pollock across the US/Russia boundary are quantified by means of an innovative seafloor-mounted upward-looking echosounder (SME). This relatively inexpensive technology could be applied in other Arctic areas. Further requirements for common biological/ecological measurements are described in numerous publications by the ICES community.

However, commercially harvested fish don’t live in isolation and fishing is not the only factor affecting them. Fish feed on lower trophic level organisms, including plankton and other fish, and are consumed by marine mammals, seabirds, and other fish. In addition, physical constraints are important; especially sea temperature affects the fish directly through physiology and indirectly through the ecosystem. Also ice coverage and quality (seasonal, multi-year…) is important: many fish species do not enter ice-covered waters. While measurements of zooplankton and fodder fish to a large degree requires ship-based measurements, a wide range of other platforms have potential for observing physical and biogeochemical EOVs and primary production. For ecosystem-based Arctic fisheries management, enhanced understanding of these ecosystem components is required, and this further requires routine measurements. Autonomous platforms that should be considered include profiling floats (Argo), drifters, gliders, fixed moorings, and Ice-Tethered Platforms (ITP). These platforms may to varying degree be equipped with a range of sensors for measuring physical and biogeochemical propertied of the ocean (in some cases also sea surface level atmosphere or cryosphere).

2.6 Strategies regarding engaging indigenous and local communities

Key international environmental agreements stress the importance of engaging the knowledge and observations of indigenous and local communities. The three most important environmental agreements will be presented in the following.

1. The Convention on Biological Diversity

Countries that have ratified the Convention on Biological Diversity (CBD) are obliged to respect, preserve and maintain knowledge of Indigenous and local communities as expressed in:

- Article 8(j): Each contracting Party shall, as far as possible and as appropriate: Subject to national legislation, respect, preserve and maintain knowledge, innovations and practices of indigenous and local communities embodying indigenous lifestyles relevant for the conservation and sustainable use of biological diversity and promote their wider application with the approval and involvement of the holders of such knowledge, innovations and practices and encourage the equitable sharing of the benefits arising from the utilization of such knowledge innovations and practices.
- Article 10(c) and 10(d): Each Contracting Party shall, as far as possible and as appropriate: (…) (c) Protect and encourage customary use of biological resources in accordance with indigenous cultural practices that are compatible with conservation or sustainable use requirements. (d) Support local populations to develop and implement remedial action in degraded areas where biological diversity has been reduced.
  (Source: http://www.cbd.int; see also http://norden.diva-portal.org/smash/get/diva2:791816/FULLTEXT03.pdf)

Among the Arctic States, Canada, Iceland, Norway, Denmark, Sweden and Russia have ratified the CBD. Finland has accepted the CBD but not ratified it. USA has neither accepted nor ratified.

The CBD is the most important international agreement when it comes to d sustainable use of living resources and achievement of the CBD is guided by several indicators called the Aichi Targets. One of the Aichi Targets states that "traditional knowledge" (Folke 2004) should be integrated into the implementation of the Convention. Specifically, the target says:

> "*By 2020, the traditional knowledge, innovations and practices of indigenous and local communities relevant for the conservation and sustainable use of biodiversity, and their customary use of biological resources, are respected, subject to national legislation and relevant international obligations, and fully integrated and reflected in the implementation of the Convention with the full and effective participation of indigenous and local communities, at all relevant levels*." (Aichi Target 18; https://www.cbd.int/aichi-targets/target/18).

A new global strategy for the CBD is under development. The strategy is expected to be discussed and approved at the Conference of the Parties of the CBD in the autumn of 2021 and sprin 2022. The most recent draft of the strategy highlights the importance of the knowledge and observations of Indigenous and local communities:

- Among the proposed 2030 Action Targets are "*By 2030, ensure that quality information, including traditional knowledge, is available to decision makers and public for the effective management of biodiversity through promoting awareness, education and research*" (Target 19).
- The draft strategy also emphasizes "*greater protection of traditional knowledge and recognition of its contributions to the conservation and sustainable use of biodiversity*".
- The draft strategy also lists a number of enabling conditions required for implementation of the strategy. These include "*The participation of indigenous peoples and local communities and a recognition of their rights in the implementation of the framework*", and "*Recognition of intergenerational equity, including the transmission of knowledge, language and cultural values associated with biodiversity, especially by indigenous peoples and local communities*".
- Finally, the draft strategy states that "*Outreach, awareness and uptake of the post-2020 global biodiversity framework by all stakeholders is essential to effective implementation, including by: (a) Increasing understanding, awareness and appreciation of the values of biodiversity including the associated knowledge, values and approaches used by indigenous peoples and local communities"* (ref: CBD 2020. The Zero Draft of the Post-2020 Global Biodiversity Framework. CBD/WG2020/2/3).

2. The Intergovernmental Platform for Biodiversity and Ecosystem Services

One of the functions of the Intergovernmental Platform for Biodiversity and Ecosystem Services is to bring the different knowledge systems, including Indigenous and Local Knowledge (ILK), into the science-policy interface:

> *While one of the functions of the Intergovernmental Platform on Biodiversity and Ecosystem Services (IPBES) is to produce synthetic global, regional and thematic assessments of the state of the planet's environment, it also plays three other roles: promoting knowledge generation; delivering policy support tools and methodologies;*

> *and capacity building. IPBES therefore has a potentially strong role to play in promoting the use of new approaches that allow the improved capture of data and information, in promoting the means for bringing together data and information from different knowledge systems, including ILK and scientific knowledge, and in building capacity to do both. (*Source: http://ipbes.net/)

Except for Iceland, all eight Arctic states are members of the IPBES.

3. Central Arctic Ocean Fisheries Agreement

An agreement was recently reached on managing fisheries in the Central Arctic Ocean ("*The Agreement to Prevent Unregulated High Seas Fisheries in the Central Arctic Ocean*"). Among the signatories of the agreement is the European Union (Section 2.5).

The agreement requires that decisions on living resources in this region take into consideration both ILK and scientific knowledge, yet operational approaches for cross-weaving people-based and scientific observations for managing the Central Arctic region have yet to be developed.

Recommendations on requirements from the European Polar Science Week 2020

During the First European Polar Science Week in October 2020, one of the sessions on Grand Challenges in Polar Science had the title "Cross-weaving Citizen Science, Local Knowledge and Scientific Research in the Arctic" (Anon. 2021). The session discussed key barriers and opportunities for moving further from theory to practice with cross-weaving of knowledge approaches in the Arctic.

It was concluded that mobilizing all relevant knowledge, observations and data from on the Arctic environment will be *transformational*. It will bring about a better understanding that will 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.

The key barriers were identified to be:

- Insufficient respect among scientists for the knowledge and observations of community members.
- 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 policy in support of cross-weaving knowledge;
- Asymmetric power relationships (and financial resources).
- The digital divide.

Key research needs – and opportunities are:

- 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 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 (link to YouTube video from the session: https://youtu.be/ljUTNlw4slM).

2.7 Monitoring natural hazards

Arctic areas are prone to a range of natural hazards, many of which are expected to be amplified in the future due to climate change. The focus will mainly be on the hazards that have been addressed in the INTAROS project. It is, however, worth noting that several hazards, which may have significant impact in the Arctic, are not considered. Such hazards include weather-related hazards, sea ice, ice-dammed lakes and associated outburst floods, and icebergs.

Collection of data from past earthquakes and information on recent earthquakes is vital to provide information on recent earthquakes to the public, authorities and decision makers, as well as to estimate future earthquake hazard. Long records describing earthquake frequency, hypocentre locations and earthquake magnitudes are needed to assess future earthquake hazard. Historical records of pre-instrumental earthquakes are included in hazard assessments through macro-seismic intensity observations for significant earthquakes. The hazard assessments feed as hazards maps into building regulations (e.g., Eurocode 8, Bisch et al. 2012). The accuracy of the hazard maps depends on availability of long time series, high seismic network sensor density and recordings with high signal to noise ratio. High seismic network sensor density, real-time data transfer, international data sharing, recordings with high signal to noise ratio and experienced staff are the main elements required to provide fast and accurate information on recent earthquakes to the public, authorities and decision makers.

The forecast of snow avalanche hazards is based on in situ observations from manual observers and automated snow and weather station networks, as well as forecasts from meteorological and snowpack models. Although there has recently been strong development in snowpack modelling, the use of modelled snow products by snow avalanche forecasters is very limited, hampered by the large errors in model outputs (especially snow depth), insufficient assessment of uncertainty and representativeness in in situ observations and, consequently, also in model products, and the too complex visualization of the post-processed model outputs (Morin et al., 2020). Requirements to improve the usefulness and usability of snow model outputs for snow avalanche forecasting include a better assessment of the uncertainty and spatial representativeness of in situ observations, as well as improvement in the modelling of the snow physics, in the data assimilation, and in the post-processing of model output. One of the largest error sources in the snow model output is the error in the input atmospheric variables, in particular snow precipitation: in mountain environments it is very difficult to automatically monitor it with ground-based instruments (Nitu et al., 2018) and the precipitation forecast by weather prediction models has too coarse a resolution. The ability of statistical downscaling to improve the atmospheric variables used as input to snow models employed in avalanche forecasts in the Longyeardalen valley of Svalbard has been investigated in INTAROS. Moreover, snow depth maps of the valley at high spatial resolution utilizing a geo-statistical tool were developed combining atmospheric model outputs and in situ observations. This product can be generated operationally in real time and is intended to improve the input to snow models used for avalanche forecasting.

Rock avalanches can in most cases be forecast based on data from intensive monitoring systems (e.g., Åkneset, Norway; Roth et al., 2006). Such systems monitor movements in the slope, as well as cracking/seismicity and other parameters. Early warning systems are based on observed accelerations of the slope (e.g., Roth et al. 2006). Other types of landslides, such as earth slides or debris flows, can be forecasted based on meteorological and snow-melt data (e.g., varsom.no). In remote areas, field-based landslide identification and mapping of recent landslides can be supplemented by joint utilization of seismic and satellite data (e.g., Svennevig et al. 2020).

For tsunamis (earthquake or landslide generated), national and international cooperation on early warning systems is required. Such systems require extensive and interdisciplinary monitoring systems, real-time data, coordination from local (fjord system) to ocean-wide scale, communication systems and response plans, including extensive training of local populations. Detection of and warning about tsunamis in fjord systems rely on nearby monitoring networks. For tsunamis in the oceans, the CTBTO (2015) global seismic network and national seismic networks play a key role. To mitigate the risk of tsunamis and develop evacuation plans, hazard models are a vital element both for fjord systems and oceans (e.g., Basili et al. 2020).

Within INTAROS, mass loss from glaciers and ice caps is treated as a natural hazard. It occurs at a much slower pace than earthquake, landslide, and avalanche hazards, but it has world-wide implications and constitutes a major hazard to all. Mass loss from ice sheets includes both calving of icebergs at the fronts of marine terminating glaciers and liquid water run-off from both the surface and base of the ice sheet. The mass loss is a direct freshwater source to the oceans and constitutes global hazards in the form of sea level rise and changes to the large-scale ocean circulation. Locally, changes in the freshwater flux into fjords affect the marine ecosystem altering food webs. (Meredith et al., 2019: Chap. 3, IPCC Special Report on the Ocean and Cryosphere in a Changing Climate).

Currently, existing international and EU requirements related to ice sheet mass loss and changes are those relating to Essential Climate Variable's (ECV's) specified by GCOS. For ice sheets and ice shelves the ECVs include surface elevation change, ice velocity, ice mass change, Grounding Line Location and Thickness. As part of ESA's Greenland Ice Sheet CCI project a user requirement survey was carried out including the same ECVs asking users to provide both minimum and optimum spatial and temporal resolution and accuracy. The values are provided in the "User Requirements Document", which is updated regularly throughout the project (Hvidberg et al., 2021). The optimum requirements are similar to the GCOS requirements, but the minimum requirements provide insights to the resolutions users can employ as a bare minimum.

2.8 Research infrastructures

The INTAROS stakeholder consultation included in 2021 dialog meetings with representatives from European Research Infrastructures to discuss possible involvement, contribution and cooperation on the implementation of a Sustained Arctic Observing system, Buch et al, 2021 (INTAROS D1.7).

Research Infrastructures are organisations that enable the research community to use specific facilities, resources and services in order to accelerate scientific achievements and promote sustainable research.

The dialog meetings included participation of the following Research Infrastructures:

Hydrosphere: DANUBIUS, EuroARGO, JERICO, EUROFLEETS+ and ARICE
Atmosphere: ACTRIS and IAGOS
Geosphere: INTERACT and Arctic HYCOS
Biosphere: LifeWatch Eric, EMBRC Eric and eLTER

Highlights from the meetings are:

- Out of the 12 Infrastructures 3 have full focus on the Arctic, 6 have some or few activities and 3 do not presently have any engagement in the Arctic
- The dialog meetings clearly reveal the need for a more sustained and coordinated observing system within all thematic areas (atmosphere, hydrosphere, geosphere and biosphere) and especially the central Arctic is severally undersampled.
- Most of the Infrastructures are or in the process of becoming a legal entity – registered either as an ERIC or AISBL. This provides some sustained funding via member fees from member countries, but most importantly being a legal entity allows them to become partners in externally funded projects.
- All Infrastructures were engaged in discussion and formulation of observational requirements:
  - Generally, they have clear and ambitious policies on data quality, resolution in time and timelines of data delivery
  - Requirements for spatial resolution are however more uncertain where discussions often end in a conflict between scientific requirements and what is feasible from a logistic and financial point of view. In this context it was stressed that biological observations presently are very expensive since they require human resources for sampling, analysis and data handling resulting in compromising the spatial resolution. The ARGO community constitute an exception by formulating ambitious goals for spatial resolution several years ago.
- The Infrastructures generally have an open and free data policy compliant with the FAIR principle, although a few members may have a more restrictive data policy but that is being worked on. All face problems in data exchange with Russian partners.
- There is great focus on formulation and implementation of “Best practices” on observation procedures, quality control, data management etc.
- Sensor and instrument development is high on the agenda for some but not all Infrastructures. Automated measuring technology and stations is in focus in particular for biogeochemical observations
- There is established close cooperation between the Infrastructure primarily via the ESFRI and ENVRI systems. The three Infrastructures with full focus on the Arctic are engaged in Arctic cooperative bodies like SAON.

- Many of the INTERACT research stations are manned year-round and constitute thereby potential platforms that can be incorporated in an Arctic Observing System e.g., for meteorological observations in real-time

3. INTAROS achievements

The INTAROS project has in its five-year lifetime had a strong focus on mapping and understanding the existing Arctic in situ scientist-executed and community-based observing systems and identifying gaps. Highlights from the work on scientist-executed systems will be presented in chapter 3.1-3.3 and on community-based systems in chapter 3.4.

3.1 Existing observations (WP2)

In the INTAROS WP2 the existing Arctic atmospheric, ice-ocean and terrestrial observing systems were assessed based on the extensive information collected from INTAROS partners through a set of questionnaires. To perform the gap analysis, it was first necessary to identify the requirements for each of the criteria addressed in the assessment.

3.1.1 Requirements for Arctic in situ observing systems

Most requirements presented for in situ atmospheric, terrestrial and ice ocean data collections are defined based on needs of the modelling community. The WMO requirements (Sect. 2.3) and the Copernicus CIS[2] requirements (Sect. 2.1.3) given for uncertainty, horizontal resolution, vertical resolution, observing cycle and timeliness refer to key, global variables observed in the Integrated Global Observing System (WIGOS) from in situ and satellite platforms, and mainly reflect the needs of models that require gridded input on global scale. These variables correspond to the processing levels 3-4 as defined by the National Ecological Observatory Network (NEON) terminology (http://www.neonscience.org/data/data-processing), i.e. they are spatially interpolated and result from the integration of in situ and satellite data.

The INTAROS WP2 assessment, however, did not address the globally integrated observing system. It focused on individual in situ Arctic observing assets, including regional networks, field campaigns and the Arctic section of global systems, and separately addressed the satellite products. Information and requirements on spatial coverage and temporal duration of the observations, irrelevant for the WMO WIGOS integrated approach, become crucial to assess the in-situ Arctic observing assets and to integrate them in an optimized and sustained observing system. Moreover, in situ observing systems provide data collection from Level 0 to 2, e.g., point measurements or sections in a variety of time windows and heterogeneous spatial distribution. Hence, the requirements from WMO and Copernicus are not directly applicable for assessing in situ observation system at level 1 and 2.

Requirements for the in situ observing systems were therefore defined in INTAROS WP2 for the spatial and temporal coverage of the systems and were identified on the basis of the scientific and/or monitoring purposes of the systems (Tjernström et al., 2018; Zona et al., 2018). For instance, the requirement on spatial coverage of a network established to monitor a specific area (e.g., Greenland) is defined on the basis of the spatial extension and representativeness needed to the network for the fulfilment of its goal. As a matter of fact, each observing system has constraints due to technical, practical, economical, and political reasons, which will affect the degree in which they can achieve their goals (this “gap” between goal and actual achievement is evaluated in Sect. 5). The spatial and temporal coverage requirements for the Arctic in situ atmospheric systems and terrestrial systems are shown in Tables 3.1 and 3.2, respectively. The requirements are defined for the specified application areas.

Table 3.1. INTAROS spatial and temporal coverage requirements for the in situ Arctic atmospheric observing systems.

Observing system	App. Area	Spatial coverage	Temporal coverage (length of the record, breaks)	Conf Level (1)	Source (name of the person defining the requirement)	Comment
Stable water isotopes	Climate research and monitoring, process studies	Pan-Arctic	> 20y time series for climate studies	Firm	Harald Sodemann	
IMR-PINRO Ecosystem Survey	Climate research and monitoring	Barents Sea (roughly from 68-82 N, 5-60 E)	> 20y time series for climate studies	Tentative	Geir Ottersen	
IMR Barents Sea Winter Survey	Climate research and monitoring	Barents Sea (roughly from 68-80 N,7-56 E)	> 20y time series for climate studies	Tentative	Geir Ottersen	
ASCOS/ ACSE	Scientific understanding: Central Arctic climate processes, boundary-layer processes & clouds	Entire Arctic Ocean	Continuous annual, multi-year	Firm	Michael Tjernström (MISU)	Set of comprehensive intensive observations during research cruise, including extensive cloud observations. Similar to land-based so-called “super-sites”.
NICE/ SeaState	Scientific understanding: Surface energy budget and atmospheric structure:	Entire Arctic Ocean	Continuous annual, multi-year	Firm	Michael Tjernström (MISU)	Set of intensive limited observations during research cruise, excluding extensive cloud observations. Similar to land-based observatories (e.g. IASOA etc.)
Polarstern	Atmospheric structure	Transect cruises; local within open ocean and sea ice	Monthly duration field campaigns during summer	Firm	Joseph Sedlar (MISU)	Complementary observations, taken on research cruises, regardless of science mission
Greenland Ecosystem Monitoring	Ecosystem monitoring and research	Greenland	> 20y time series for climate studies	Firm	Mikael Sejr (AU)	Quantifying ecosystem change in Greenland
PROMICE	Climate research and monitoring	Greenland ice sheet ablation zone	> 20y time series for climate studies	Tentative	GEUS	Determining the atmospheric near-surface climatology of the Greenland ice sheet ablation area
PROMICE	Global and regional NWP	Greenland ice sheet ablation zone	Continuous	Tentative	GEUS	Providing atmospheric near-surface parameters (e.g. atm pressure, air temp, relative humidity)

PROMICE	Research	Greenland ice sheet ablation zone	Continuous	Tentative	GEUS	Process understanding of the surface mass balance of the ice sheet ablation zone
GC-Net	Climate research and monitoring	Greenland ice sheet accumulation zone	>20y time series for climate studies.	Tentative	Konrad Steffen	Determining the atmospheric near-surface climatology of the Greenland ice sheet accumulation area
GC-Net	Global and regional NWP	Greenland ice sheet accumulation zone	Continuous	Tentative	Konrad Steffen	Providing atmospheric near-surface parameters (e.g. atm pressure, air temp, relative humidity)
GC-Net	Research	Greenland ice sheet accumulation zone	Continuous	Tentative	Konrad Steffen	Process understanding of the surface mass balance of the ice sheet accumulation zone
Radiosonde soundings	Global and regional NWP; Climate monitoring	Horizontal: Global (whole Arctic); Vertical: Through Troposphere and lower stratosphere	> 20y time series for climate studies, continuous	Firm	OSCAR	Most important user of radiosonde sounding data is numerical weather prediction. Sounding data can be found in the IGRA archive, and at most national weather services.
GAW programme	Climate research and monitoring	Gobal	> 20y time series for climate studies	Firm – tentative	Eija Asmi	Following WMO guidelines for different programs and parameters (confidence level depending on variable); include many data series older than establishment of official programme.
ICOS	Climate research and monitoring, Atmospheric composition for inverse modelling	Europe	> 20y time series for climate studies.	Firm	ICOS	Following WMO recommendation for compatibility of measurements of greenhouse gases and related tracers (GAW Report N°213), although this is now deprecated in the OSCAR database.
ACTRIS	Climate research and monitoring	Europe	> 20y time series for climate studies.	Firm	Eija Asmi	Aerosols, clouds, trace gases in situ ground-based and tower measurements infrastructure in Europe
FMI AWS	Meteorology	Finland	Continuous	Firm	Anna Kontu	Following WMO guidelines for meteorological measurements
FMI Snow depth stations	Meteorology/climate research	Cover the land types typical of the Arctic boreal forest, in an area of ~25 km^2	> 20y time series for climate studies.	Firm	Anna Kontu	Providing reference data for satellite cal/val purposes
GRUAN	Climate monitoring, satellite validation, process understanding	Global sparse	> 20y time series for climate studies.	Firm	DWD (GRUAN Lead Centre)	GRUAN not intended to be a globally dense network. Rather GRUAN acts as high-quality, metrologically traceable measurement series to enable other applications.
GOS Surface observations	Global and regional NWP; also Climate monitoring	Global (whole Arctic land surface)	Continuous	Firm	OSCAR	

Atmospheric tall tower network for greenhouse gas monitoring	Monitoring and research	pan-Arctic	> 20y time series for climate studies.	Tentative	Mathias Goeckede	Provide high-precision observations of atmospheric greenhouse gas mixing ratios, calibrated against WMO standards. Either continuous data, or episodic flask measurements.
NIVA Barents Sea Ferrybox	Monitoring and Research	Barents Sea Opening	> 20y time series for climate studies.	Tentative	Andrew King	Providing wind speed and hyperspectral radiance/irradiance measurements to assist marine biogeochemical studies
PEEX (Pan-Eurasian Experiment)	Global/hemispheric/regional-scale modelling; Climate research and monitoring; Environmental assessment; Ecosystem research	Russian Arctic, north of 66.31°N	> 20y time series for climate studies.	Moderate	Hanna K. Lappalainen (UHEL), Alexander Mahura (UHEL)	Information on time-series breaks is not available (contact with owners of the stations is required); Observations to be used in NWP, climate, ecosystem, etc. research; for data assimilation in operational forecasting and for models' verification
Airborne atmospheric surface-flux measurements	Inverse emission of atmospheric composition	Local at selected representative sites distributed circum-arctic	Biannual	Firm	Katrin Kohnert	Together with aircraft campaigns for flux measurements
Polish Polar Station Hornsund (WIGOS 01003)	Climate research and monitoring	Represent the terrestrial environment of an Arctic valley in North Atlantic sector of the Arctic, Hornsundfjord	> 20y time series for climate studies.	Firm	IGPAN (Tomasz Wawrzyniak, Piotr Głowacki)	Long term climate monitoring.

(1) "Conf level" is applied as in the OSCAR database. It refers to the confidence on which the given requirement is trusted (e.g., "firm" when the value is a well quantified goal in the pertinent community, "reasonable" when the value is quantified with robust arguments but it is not so widely applied as in the case of "firm", and "tentative" when the value is a first guess, based only on the experience of the person setting it).

Table 3.2 INTAROS spatial and temporal coverage requirements for the in situ Arctic terrestrial observing systems.

Observing system	App. Area	Spatial coverage	Temporal coverage (length of the record, breaks)	Conf Level (1)	Source (name of the person defining the requirement)	Comment
Fluxnet (CO_2 & CH_4 FLUX)	Climate change analysis, time series analysis	Pan-Arctic	20-40 years	firm	Donatella Zona (USFD) Walter Oechel(U Exeter), Mathias Goeckede (MPG)	Min 20 years because the temporal coverage for the statistical analysis of the temporal changes need to include at least one AO or NAO cycle. Min 40 years because this would be the minimum requirement for a time series analysis of climate and flux data.
Fluxnet (CO_2 & CH_4 FLUX)	Climate model calibration	Pan-Arctic	7-10 years	reasonable	Donatella Zona (USFD) Walter Oechel(U Exeter), Mathias Goeckede (MPG)	7-10 years to capture some interannual variability, and allow performance of some regression analysis; a longer dataset would be beneficial for this purpose, but not as critical as the one required for a time series analysis.
Airborne observations of surface-atmosphere fluxes	Climate change analysis	One study area in each mayor arctic zone (Alaska, Canada, Russia, Europe)	20 years with flights at least every second year (including spring/autumn campaigns)	firm	Katrin Kohnert (GFZ)	Min 20 years including spring and autumn campaigns to capture annual changes in the regional patterns
Airborne observations of surface-atmosphere fluxes	Climate model calibration	One study area in each mayor arctic zone (Alaska, Canada, Russia, Europe)	10 years with flights at least every second year including spring/autumn campaigns	firm	Katrin Kohnert (GFZ)	Include spring/autumn measurements to capture intra-annual and interannual changes in the regional patterns. Longer timespan would be beneficial
WGMS FoG database	Glacier dynamics modelling Climate and climate change studies Sea-level rise studies	Pan-Arctic	Minimum 10-20 years	reasonable	Francisco Navarro (UPM)	Minimum 10-20 years because it is the minimum required to detect changes in surface mass balance trends

GTN-G GlaThiDa database	Glacier dynamics modelling Climate and climate change studies Sea-level rise studies	Pan-Arctic	Good single measurement is sufficient	reasonable	Francisco Navarro (UPM)	With a single good (glacier-wide coverage sufficiently dense) radar survey, the ice-thickness distribution can be determined. Afterwards, thickness changes can be determined from surface elevation changes.
Randolph Glacier Inventory	Glacier dynamics modelling Climate and climate change studies Sea-level rise studies	Pan-Arctic	Single measurements repeated every 5 years (ideally every year)	reasonable	Francisco Navarro (UPM)	Calculation of glacier-wide mass balance requires proper outlines. Ideally this should be available for each annual SMB computation, but this is not realistic. 5 years can be a compromise solution providing sufficient accuracy.
Seismic monitoring	Operational services, geo-hazard forecast, research development	Pan-Arctic, evenly distributed stations in onshore and offshore areas.	Continuous and long-term (2-5 yrs)	firm	Mathilde Sørensen (UiB), Peter Voss (GEUS)	Long-term continuous monitoring is required to evaluate long-term seismicity rates and climate-induced seismicity rate changes. The network should be evenly distributed throughout the Arctic to assure reliable earthquake locations. This can only be achieved by including ocean bottom seismomenters (OBS) in the network to cover the offshore areas.
PEEX (Pan-Eurasian Experiment), UHEL	Climate and climate change studies, ecosystem studies, time-series analysis	Arctic regions of Russia (north of 66.31N)	11 measurement stations in total; 4 stations have short 10 years time-series (the longer time series is the better, at least, 20-40 years)	reasonable	Hanna K. Lappalainen (UHEL), Alexander Mahura (UHEL)	Information on time series breaks is not available (contact with owners of the stations is required); observations to be used in climate, ecosystem, etc. research; considering the large area of the Russian Arctic territories it would be desirable to increase the number of the stations; long-term continuous measurements are needed
Polish Station-Hornsund	Climate and climate change studies, ecosystem studies, time-series analysis	Southern Spitsbergen	Long-term	firm	Piotr Głowacki (IGPAN)	Broader area of measurements for comparison
PROMICE	Climate research and monitoring	Greenland ice sheet ablation zone	>10 yrs at min. daily resolution required	tentative	GEUS	Determining the atmospheric near-surface climatology of the Greenland ice sheet ablation area
GC-Net	Climate research and monitoring	Greenland ice sheet accumulation zone	>10 yrs at min. daily resolution required (GC-Net: 1995-ongoing)	tentative	Konrad Steffen	Determining the atmospheric near-surface climatology of the Greenland ice sheet accumulation area
PROMICE	Research	Greenland ice sheet ablation zone	< 1 hr	tentative	GEUS	Process understanding of the surface mass balance of the ice sheet ablation zone
GC-Net	Research	Greenland ice sheet accumulation zone	< 1 hr	tentative	Konrad Steffen	Process understanding of the surface mass balance of the ice sheet accumulation zone
GNET (Greenland	Research	Greenland	22 years	firm	DTU – Shfaqat Abbas Khan	surface ice mass change and bedrock deformation

GPS network)						
Sodankylä supersite	Research	Sodankylä, Northern Boreal Zone	>20 years for climate studies	firm	Anna Kontu (FMI)	Carbon and water cycles in the Arctic
Arctic-HYCOS	Monitoring of river discharge fresh-water flow to the Arctic Ocean and related northern seas	Main river basins (>5000km2) covering >75% of the flow to ocean	>30 years	tentative	David Gustafsson (SMHI) -	The Pan-Arctic drainage basin includes all land areas draining to the Arctic Ocean and related northern seas as defined by the Arctic-HYCOS steering committee.
Arctic-HYCOS	Monitoring of hydrological regime in the pan-arctic drainage basin of the Arctic Ocean and related northern seas	Upstream river basins representing > 75% of the variability of hydrological regimes	> 30 years	tentative	David Gustafsson (SMHI) – requirement translated from the objectives of the Arctic-HYCOS project	The upstream river basins should represent the variability in land cover, topography, climate, soil, permafrost, and runoff characteristics at relevant spatial (basin area 10^2 – 10^6 km2) and temporal (daily, seasonally, annually) scales .

(1) “Conf level” is applied as in the OSCAR database. It refers to the confidence with which the given requirement is trusted (e.g., “firm” when the value is a well-quantified goal in the pertinent community, “reasonable” when the value is quantified with robust arguments but it is not so widely applied as in the case of “firm”, and “tentative” when the value is a first guess, based only on the experience of the person setting it).

3.1.2 Requirements for Arctic in situ data collections

The WMO OSCAR and Copernicus CIS^2 requirements concerning uncertainty, horizontal resolution, vertical resolution, observing cycle and timeliness were utilized to assess key in situ variables that belonged to large, not Arctic-specific networks as well as satellite products. In INTAROS deliverable D2.1 (Ludwigsen et al., 2018), D2.4 (Tjernström et al., 2018) and D2.7 (Zola et al., 2018) the WMO OSCAR requirements and Copernicus CIS^2 requirements for the key observed Arctic variables are listed together with relevant comments on the limits of those requirements for the specified application areas.

For the in situ variables measured by regional and Arctic-specific atmospheric and terrestrial observing systems, we defined alternative requirements, which better reflected the peculiarities of the Arctic environment and the observational needs of Arctic data users. They are illustrated in Tables 3.3 and 3.4 for the atmospheric and terrestrial domains, respectively.

Table 3.3 INTAROS defined requirements for the in situ atmospheric data collections (three levels: threshold, breakthrough and goa)

Variable name	Layers	App. area	Uncert.	Horiz. res.	Vert. res.	Os cycle	Timeliness	Spatial overage	Conf Level (1)	Source (name or reference to literature)	Comments
Air temperature	Atmospheric boundary layer	Processes, Research	0.1 K 0.5 K 1 K	N/A	5 m 10 m 15 m	Irregular; field campaign	1 month 2 months 3 months	Circum-arctic (One area per arctic region)	firm	Katrin Kohnert (GFZ)	Uncertainty should be lower than in Table 4 since the vertical gradient needs to be known
Water vapour concentration	Atmospheric boundary layer			-	5 m 10 m 15 m	-	1 month 2 months 3 months	Circum-arctic (One area per arctic region)	firm	Katrin Kohnert (GFZ)	
Air pressure	Atmospheric boundary layer		0.5hPa 1 hPa 1 hPa	-	5 m 10 m 15 m	-	1 month 2 months 3 months	Circum-arctic (One area per arctic region)	firm	Katrin Kohnert (GFZ)	See comments for above; vertical resolution critical
CH4 concentration	Atmospheric boundary layer			-	5 m 10 m 15 m	-	1 month 2 months 3 months	Circum-arctic (One area per arctic region)	firm	Katrin Kohnert (GFZ)	Has several OSCAR ID numbers, but all are out of date
CO2 concentration	Atmospheric boundary layer			-	5 m 10 m 15 m	-	1 month 2 months 3 months	Circum-arctic (One area per arctic region)	firm	Katrin Kohnert (GFZ)	
Water vapour isotope HDO	Boundary layer, free troposphere	Global NWP, Climate	0.5 permil	500 km		-	1 month	European arctic	moderate	Sodeman	Has OSCAR ID 78, however, without requirements. For station observations
Water vapour isotope H218O	Boundary layer, free troposphere	Global NWP, Climate	2 permil	500 km		-	1 month	European arctic	Moderate	Sodeman	For station observations
Turbulent sensible heat flux	Near surface		2 W m^{-2} 5 W m^{-2} 15 W m^{-2}			5 min 20 min 60 min	30 days 60 days 200 days	Point measurements		Sedlar, MISU	Averaging time required limits temporal resolution
Turbulent latent heat flux	Near surface		2 W m^{-2} 5 W m^{-2} 15 W m^{-2}			5 min 20 min 60 min	30 days 60 days 200 days	Point measurements		Sedlar, MISU	Averaging time required limits temporal resolution
Turbulent momentum flux	Near surface		1 m^2 s^{-2} 2 m^2 s^{-2} 5 m^2 s^{-2}			5 min 20 min 60 min	30 days 60 days 200 days	Point measurements		Sedlar, MISU	Averaging time required limits temporal resolution

Cloud top pressure	Highest present	Climate	50 hPa 100 hPa 20 hPa	0.25 deg		12 hr		Global	Firm	Devasthale, SMHI	CM-SA CLARA-A2 satellite dataset, validation report Requirements on accuracy, precision and stability per decade resp.
Cloud top height	Highest present	Climate	800 m 1700 m 200 m	0,25 deg		12 hr		Global	Firm	Devasthale, SMHI	CM-SA CLARA-A2 satellite dataset, validation report Requirements on accuracy, precision and stability per decade resp.
Cloud ice water path	Total column	Climate	20 gm^2 40 gm^2 6 gm^2	0.25 deg		24 hr		Global	Firm	Devasthale, SMHI	CM-SA CLARA-A2 satellite dataset, validation report Requirements on accuracy, precision and stability per decade resp.
Aerosol in-situ parameters: scattering and absorption, aerosol number, mass and size distribution	Near surface	Climate Applications and Air Quality	10% 20% 30%			5 min 30 min 1 h	5 min 30 min 1 h	Global	Tentative	Eija Asmi	The goal of the Global Atmosphere Watch (GAW) programme is to ensure long-term measurements in order to detect trends in global distributions of chemical constituents in air and the reasons for them. With respect to aerosols, the objective of GAW is to determine the spatio-temporal distribution of aerosol properties related to climate forcing and air quality on multi-decadal time scales and on regional, hemispheric and global spatial scales.
Relative humidity	Near surface	Climate research and monitoring	2 % 5 % 10 %			60 min 3 h 12 h	6 min 30 min 6 h	Global	Tentative	Eija Asmi	Based on OSCAR requirements for near-surface spec. humidity for Global NWP (ID 252), but excluding the horizontal resolution requirement as the station-based measurements cannot deliver the satellite-level of coverage stated in OSCAR.
Hydrometeor classification		Global NWP and Climate applications			10 m 100 m	30 sec 3 min 1 h	5 min 1 h 1 d	Global	tentative	Ewan O'Connor	NWP/Climate model evaluation and assimilation: uncertainties and vertical resolution suitable. For NWP assimilation, timeliness potentially achievable for many

											stations. Horizontal coverage not realistically achievable, especially over ocean/ice.

(1) "Conf level" is applied as in the OSCAR database. It refers to the confidence on which the given requirement is trusted (e.g., "firm" when the value is a well quantified goal in the pertinent community, "reasonable" when the value is quantified with robust arguments but it is not so widely applied as in the case of "firm", and "tentative" when the value is a first guess, based only on the experience of the person setting it).

Table 3.4. INTAROS defined requirements for the Arctic in situ terrestrial data collections (three levels: threshold, breakthrough and goal)

Variable name	**Layers**	**App. Area**	**Uncert.**	**Horiz. Res.**	**Vert. res.**	**Os cycle**	**Timeliness**	**Coverage**	**Conf Level**	**Source (name of the person giving the requirement, or reference to literature)**	**Comments**
Ice ablation	Ice sheet surface	Climate change research	0.05 m	n/a	n/a	1 hr	1 hr	Pan-Arctic	tentative	Andreas Ahlstrøm (GEUS)	This is the melting of the ice surface as it responds to the climate. The 1 hr OS cycle / timeliness is for potential geohazard applications
Temperature profiles of the soil/peat layers (PEEX, UHEL)	Soil /peat layers (depths of 0, 2, 3, 5 and 10 m)	Climate change and ecosystem research	0.1 C	at fixed locations	0, 2, 3, 5, 10 m	6 hr	Real time	Arctic regions of Russia (north of 66.31N)	reasonable	Hanna K. Lappalainen, Alexander Mahura (UHEL)	not currently defined; still under discussion in the community
CO2 FLUX **(USFD, MPG, U Exeter)**	Land surface	Climate change analysis	1%	0.2-1km	Lower boundary layer	30 min	Real time	Pan-Arctic	firm	Donatella Zona (USFD), Mathias Goeckede (MPG), Walter Oechel (U Exeter)	not currently defined. Still under discussion in the community
CH4 FLUX (USFD, MPG, U Exeter)	Land surface	Climate change analysis	1%	0.2-1km	Lower boundary layer	30 min	Real time	Pan-Arctic	firm	Donatella Zona (USFD), Mathias Goeckede (MPG), Walter Oechel (U Exeter)	not currently defined. Still under discussion in the community
Snow depth (U Exeter)	Land surface	Climate change analysis	1%	1 m radius	Lower boundary layer	30 min	Real time	Pan-Arctic	unknown	Walter Oechel (U Exeter)	not currently defined. Still under discussion in the community
Airborne CO$_2$, CH$_4$, and heat flux	Land surface	Climate change analysis	30 %	100 m	Lower boundary layer	Twice a year annual Bi-annual	1 month 6 months	Pan-Arctic	firm	Katrin Kohnert (GFZ)	Horizontal resolution refers to the resolution of the CH$_4$ flux after the calculation, not the coverage with flight tracks. Uncertainty not currently defined. Still under discussion in the community

Airborne CO_2, CH_4, and heat flux	Land surface	climate model calibration	30 %	100 m	Lower boundary layer	Twice a year annual Bi-annual	1 month 6 months	Pan-Arctic	firm	Katrin Kohnert (GFZ)	Horizontal resolution refers to the resolution of the CH_4 flux after the calculation, not the coverage with flight tracks. Uncertainty not currently defined. Still under discussion in the community
Point snow density (winter, summer, annual)	Glacier snow cover	Glacier dynamics Climate change	10 kg/m3	n/a	n/a	1 year	1 year	Pan-Arctic	reason able	Francisco Navarro (UPM)	Horiz. Resol. Does not apply to a variable, like snow density, that is representative of a certain area of undefined extent
Point SMB (winter, summer, annual)	Glacier surface	Glacier dynamics Climate change	0.2 m w.e.	n/a	n/a	1 year	1 year	Pan-Arctic	reason able	Francisco Navarro (UPM)	Horiz. Resol. Does not apply to a variable, like point surface mass balance, that is representative of a certain area of undefined extent
Glacier-wide SMB (winter, summer, annual)	Glacier surface	Glacier dynamics Climate change	0.2 m w.e.	n/a	n/a	1 year	1 year	Pan-Arctic	reason able	Francisco Navarro (UPM)	Horiz. Resol. Does not apply to a variable, like surface mass balance, that is integrated over a certain area (the glacier basin)
Glacier ice thickness	Glacier-covered land	Glacier dynamics Climate change	5%	20-30 m	5 m	n/a	< 1 year	Pan-Arctic	reason able	Francisco Navarro (UPM)	Horiz. Resol. Typically 3-30 m for migrated radar data. For non-migrated data, it depends on the glacier thickness. Vertical resolution depends on the frequency of the radar used
Glacier outlines	Glacier-covered land	Glacier dynamics Climate change	5-10 m	5-10 m	n/a	n/a	< 1 year	Pan-Arctic	reason able	Francisco Navarro (UPM)	Horiz. Resol. Typically 5-15 m, but can be up to 60 m.
Snow depth	Land surface	Glacier mass balance	0,01 m 0,05 m 0,10 m	140 m 320 m 500 m	n/a	1 d 1 m 1 y	7 d 1 m 1 y	Pan-Arctic	reason able	Uncertinity: Østrem and Brugman (1991), other reqirements: M. Grabiec (Uslaski)	Based on Østrem and Brugman (1991) satisfied snow depth density for mass balance purposes on valley glacier is 10-50 per 1 km^2 and less for ice caps

Glacier velocity	Land surface	Frontal ablation	1 m/y 10 m/y	n/a	n/a	1 d 1 m 1 y	7 d 1 m 1 y	Pan-Arctic	tentative	M. Błaszczyk (Uslaski)	Horizontal and vertical resolution is not relevant for in situ glacier velocity records. Data are collected in accessible part of glaciers for validation remote sensing glacier velocity data. At least one measurement site per glacier required.
Seismic ground velocity	Land or sea floor suface	Natural hazards like earthquakes or landslides	1ms	n/a	n/a	0.01s	real time	Pan-Arctic	firm	Peter Voss (GEUS), Mathilde Sørensen (UiB)	Uncertainty is for the timing if done using GPS.
Glacier ice mass change	Land area	Glacier and ice sheet dynamics	0.003 m	n.a.	n.a.	24 h	real time	Greenland	firm	Shfaqat Abbas khan – (DTU)	The system measure land uplift due to ice loss
River discharge	River cross section	Fresh water inflow to Arctic Ocean	20%	n/a	n/a	1 d	1 d	>75% of the flow-to-ocean*	Tentative	David Gustafsson (SMHI	This is for the Arctic-HYCOS flow to Ocean network.
River discharge	River cross section	Climate change research	20%	n/a	n/a	1 d	1 d	>75% of variability in Arctic hydrological regimes	Tentative	David Gustafsson (SMHI	This is for the Arctic-HYCOS Hydrological regime network.

(1) “Conf level” is applied as in the OSCAR database. It refers to the confidence on which the given requirement is trusted (e.g., “firm” when the value is a well quantified goal in the pertinent community, “reasonable” when the value is quantified with robust arguments but it is not so widely applied as in the case of “firm”, and “tentative” when the value is a first guess, based only on the experience of the person setting it).

3.1.3 Maturity requirements for sustainability, metadata, documentation, uncertainty, public access, feedback, update, and usage

As noticed already in the WMO SOGs (Sect. 2.3), assessment criteria such as data management, metadata and sustainability are also important when designing and optimizing the observing system, therefore the System Maturity Matrix (SMM) method developed by the CORE-CLIMAX and GAIA-CLIM projects (Sect 2.4) was adopted to assess the maturity of observing systems and their data collection with respect to best practices in sustainability, metadata, user documentation, uncertainty characterization, public access, feedback, update, and data usage.

3.1.4 Technical readiness

The in situ observing systems are defined by the platform category, the sensors carried by the platforms, and the data management system connected to the observing system. In a sustainable observing system, the Technical Readiness Level (TRL) is important both with respect to the platform used, the sensors, as well as the operational level of the system. The TRL, as defined by the European Commission in the H2020 Work programme, is given on a scale from 1-9, as shown in Table 3.5. The technical readiness was therefore part of the assessment of in situ observing systems done in WP2.

Table 3.5. European Commission definition of technical readiness level

Technology Readiness Level	Description
TRL 1	basic principles observed
TRL 2	technology concept formulated
TRL 3	experimental proof of concept
TRL 4	technology validated in lab
TRL 5	technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 6	technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
TRL 7	system prototype demonstration in operational environment
TRL 8	system complete and qualified
TRL 9	actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

3.2 Requirements from observation campaigns incl. technology (WP3)

INTAROS WP3 aimed to develop and implement new solutions and technologies to fill selected gaps identified in the existing observing systems, based on prior efforts and partially on WP2 gap assessment. The goal was achieved by integration of novel instruments and sampling methods with mature components of existing observatories to increase temporal and geographic coverage of in situ observational data in the Arctic and include key parameters which are currently missing. Three reference sites (Coastal Greenland, North of Svalbard, and Fram Strait with Svalbard fjords) and two distributed systems (for ocean and sea ice, and for atmospheric and terrestrial observations) were selected, based on requirements to provide critical data to understand ongoing climate and environmental changes and their consequences for the Arctic. System design and technical recommendations were defined for each reference site and distributed observatory in the set of initial deliverables (D3.1 for Coastal Greenland, D3.2 for North of Svalbard, D3.3 for Fram Strait, D3.4 for ocean and sea ice, and D3.5 for atmosphere and land).

The cross-cutting requirements for in situ observations, implemented under INTAROS were as follows:

- new observations should build on, complement and extend existing in situ observing systems in the Arctic.
- if/where possible, temporal and spatial resolution of existing in situ measurements collected in key reference sites (or by distributed systems) should be improved.
- implemented measurements should establish new or extend existing time series of Essential Climate Variables (ECVs) and Essential Ocean Variables (EOVs) as defined by existing requirements' documentation (see WP2).
- in selected cases, new technologies (up-to-date modern sensors and platforms) should be implemented in a combination with mature and well-proved components to improve resolution, quality and/or scope of in situ measurements.
- in selected cases, new sensors and platforms should be developed, based on the latest available technology, to provide new in situ measurements of currently missing variables and/or improve quality and resolution of existing measurements.

This section addresses revised requirements, including those for technology development, based on in situ observations in five reference sites and distributed observatories implemented during the INTAROS field campaigns in 2016-2020.

3.2.1 Coastal Greenland

In situ observations covering the coastal region of Greenland included a range of actions both offshore, onshore and on the Greenland ice sheet. The main focus of this reference site is to monitor and assess the impact of changes in the Arctic water and ice cycle on the physical and biological environment. This goal requires monitoring the amount of snow and rain precipitation, improving albedo measurements to qualify meltwater formation modelling and conducting precise ice-velocity measurements. Derived solid and liquid freshwater transport to the ice margin, together with ice thickness measurements help characterize the transition of the ice and meltwater to the fjord systems and surrounding ocean. For the monitoring of the impact of the freshening on the marine ecosystem, observations of the physical ocean characteristics and the ocean CO_2-uptake (carbon system variables) are required.

Requirements for observed variables: on ice sheet – snow-water equivalent (SWE), ice velocity, rain precipitation, meteorological variables (temperature, pressure, humidity, wind speed, and the downward and upward components shortwave and longwave radiation), ice sheet albedo, ice thickness; in the ocean – subsurface temperature and salinity, sea surface temperature and salinity, surface and subsurface currents, oxygen, chlorophyll-a, PAR, turbidity, carbonate system (pCO2, TA), sea ice cover, optical properties under sea ice (radiance, irradiance, absorption, backscattering, chlorophyll-a, nutrients).

Requirements for spatial and temporal resolution: fixed locations (PROMICE stations, moorings) - relatively low spatial resolution, high temporal resolution (hourly to subdaily), year-round measurements, data availability in delayed mode (low timeliness); ship-borne measurements around Greenland – moderate spatial resolution, low temporal resolution (snapshots), data availability in NRT (moderate timeliness).

Requirements/recommendations for technical development and new solutions:

- for SWE measurements, SnowFox instrument works satisfactorily but has high power requirements, in future combined windmill-solar panel should be added (tested in INTAROS), further integration with standard AWS setup is needed,
- for high accuracy positioning, a compact and low power GNSS receiver is required (developed and tested under INTAROS), further integration with standard AWS setup is needed; development of relatively small and very lightweight antennas that are not affected by interference with Iridium transmitters,
- development/application of robust memory solutions (not relying on complex management and allocation of flash pages) or implementation of power backup when using a memory flashcard,
- integration of the precipitation recorders with the standard AWS station and into existing data recording/telemetry (tested and implemented during INTAROS),
- for moored measurements of physical ocean variables with existing and proven (off-the-shelf) sensors, a better estimate of measurement precisions is required (better than nominal calibration accuracy and estimated drift provided by manufacturer),
- for improved accuracy of pyranometers used on GIS it is required to characterizing their thermal and angular response, providing instrument-specific corrections (implemented during INTAROS); future involvement of manufacturers in the calibration efforts is recommended for the benefit of all parties interested in radiation measurements; developed equations for thermal correction of pyranometers can be included in the automatic processing of the raw data,
- for ice thickness measurements: development of radar system, allowing operation close to the calving fronts of tidewater glaciers or floating ice tongues (with strong scattering and large signal energy losses); development of software tools that allow to cancel the effects from lateral reflections (due to nunataks) and enhance the bed reflection (in the areas with water at the glacier surface and within the frontal crevasses) is required,
- for under-ice BGC measurements: development of technology for measurements of nitrates within the brine channels is required as well as improved technologies/methods for integration of different sensors for optical measurements under sea ice.

3.2.2 North of Svalbard

In situ observations covering the ocean shelf to continental slope north of Svalbard were based on the array of ocean moorings and bottom fixed platforms, collecting physical, biogeochemical, biological, and seismic measurements in the key region of the Atlantic water inflow into the Arctic Ocean. The main goal was to extend and complement existing observing system with concurrent multidisciplinary year-round measurements to allow assessment of oceanic physical and biogeochemical fluxes into the Arctic Ocean, their interactions with sea ice and atmosphere, and the impact on Arctic ecosystems. Seismic measurements aimed in monitoring earthquake activity and seismic hazard in the region.

Requirements for observed variables: for ocean moorings – subsurface temperature and salinity, sea surface temperature and salinity (from ship-borne auxiliary measurements), surface and subsurface ocean currents, ocean bottom pressure, sea ice draft and drift, dissolved oxygen, carbonate system (pCO2, pH), nitrates, chlorophyll a, CDOM, particle back scatter, particle abundance, concentration, and composition (from optical measurements), inorganic particles (concentration and composition from passive samplers), ocean sound variables (acoustic travel time, ocean sound); for seismic measurements – seismic waves (four components: vertical, two horizontals and hydrophone channels).

Requirements for spatial and temporal resolution: for ocean moorings – required horizontal resolution depends on the dynamic scales of observed phenomena, in the region north of Svalbard, dynamic scale is defined by the Rossby radius of the order of magnitude O(10 km); required vertical resolution is defined by ocean stratification, at least the main ocean layers (water masses) should be resolved, in the region north of Svalbard the vertical levels of measurements should include the surface (0-50 m) and subsurface (50-100 m) layers (0-50 m), the Atlantic water layer (100-500 m), the intermediate waters (500-1000 m), and deep waters (<1000 m); continuous year-round measurements with sub-daily temporal resolution are required; current data availability in delayed mode (low timeliness) while better timeliness (NRT data availability) is required in future for operational applications; for seismic measurements – remote measurement, covering large spatial scales, high temporal resolution, data availability in delayed mode (low timeliness).

Requirements/recommendations for technical development and new solutions:

- for ocean column physical measurements, development of technology for improved coverage of the ocean surface/subsurface layer is required (subsurface moorings in ice-covered waters lack surface manifestation and do not cover subsurface layer), e.g. development of surface profiles or low-cost, small and light sacrificial sensors for surface/subsurface layer; improved vertical resolution of measurements requires development/implementation of profiling instruments (partially done in INTAROS); improved horizontal resolution of measurements requires development of hybrid systems (a combination of fixed moorings and e.g. autonomous underwater vehicles);
- for sea ice measurements from ocean moorings, development of algorithms and software solutions for interpretation of acoustic measurements, and better auxiliary atmospheric data (SLP) are required;
- for biogeochemical measurements: further development of robust and stable sensors for BGC variables (particularly for carbonate system) is required; sensors' stability is of a key importance due to long-term deployments in the Arctic; development of new BGC sensors (e.g. optical) for robust long-term measurements;
- for improved timeliness of observations from ocean moorings, development of technologies for NRT or short-delay data transfer systems from subsurface moorings is required (including e.g. acoustic data transfer from moored instruments, using UAVs as 'data messengers', system of pop-up data buoys or winched surface profilers capable to transmit data, or using SOOs for opportunistic acoustic data retrieval from moored sensors);
- for integrated multidisciplinary measurements on moored platforms, based on INTAROS experience further efforts and technology developments to concurrently observe physical, biogeochemical, and biological variables on a single fixed platform are highly recommended, taking into account the added value of complementary data

products, collected year-round with similar temporal resolution and spatial representation.

3.2.3 Fram Strait including Svalbard fjords

New and improved observing systems implemented in Fram Strait, including Svalbard fjords, encompassed a moveable experimental set-up (arcFOCE) to study impacts of ocean acidification on benthic organisms and communities, autonomous systems for real-time pCO_2 and pH measurements, supplemented by discrete measurements of dissolved inorganic carbon and total alkalinity, and a passive acoustic system to monitor natural sounds (activity of benthic species), sounds by icebergs (localization and detection), and anthropogenic sounds (e.g. from fishing vessels or tourists ships).

Requirements for observed variables: for ocean acidification and impact on benthic ecosystems – subsurface ocean temperature and salinity, carbonate system variables (pH, pCO_2, DIC, AT), biological variables (bacterial and meiofauna densities, biomasses and community composition), sediment parameters (e.g. organic carbon content, total microbial biomass, chloroplastic pigments indicating the input of phytodetritial matter); for monitoring natural and anthropogenic sound – sound pressure levels (SPL) through different sampling periods and within different frequencies bandwidths (passive recordings).

Requirements for spatial and temporal resolution: observations collected as experimental set-ups in the point (fixed) locations, in this case, spatial representativeness is the key issue (instead of spatial resolution); collected observations representative for the studied deep basin (region) in the case of arcFOCE set-up and for the studied Arctic fjord in the case of real-time carbonate system and ocean sound measurements; required temporal resolution was dependent on the system and varied from sub-yearly resolution (several months long deployment) for the arcFOCE experimental platform, through sub-daily (1-minute raw data measured in real-time) and weekly (discrete sampling) for the carbonate system in Kongsfjorden (year-round), to continuous recordings within observation periods of the lengths from several hours to a few months.

Requirements/recommendations for technical development and new solutions:

- for experimental arcFOCE set-up, improvement of pH sensors integrated in the observing system for long-term deployment was required (exchanging the unreliable glass electrodes for commercially available robust optical pH sensors, done during INTAROS),
- for real-time measurements of carbonate system in Kongsfjorden, protection concepts must be developed and improved to safeguard individual components of the monitoring system against the fundamentally harsh environmental conditions including the threat of drifting ice floes; technical solution for de-icing the frozen pipes supplying seawater in the FerryBox are also required,
- for acoustic measurements of ocean natural and anthropogenic sound, the sufficient battery capacity for 6-month duration of acoustic recordings was challenging (the cold-water environment and the high sampling rate increase the battery consumption); there is a general requirement (shared also by other observing systems and sensors) for development of high-capacity power solutions for cold water environment to enable long-term autonomous measurements in Arctic waters.

3.2.4 Distributed system for ocean and sea ice

Different components of the distributed system for ocean and sea ice measurements included instruments and platforms that drifted freely on the sea ice or in the water column (ice tethered platforms, ice buoys and Argo floats), moved along pre-programmed tracks (gliders), measured autonomously at fixed locations (deep ocean moorings) or along predefined ship routes (FerryBox sensor package and drone-based sensors used from ships of opportunity). The main aim was to provide in situ measurements of physical and biogeochemical ocean variables, and sea ice and snow on ice properties in the deep basins and along variable trajectories in the Arctic Ocean. Due to highly heterogeneous platforms and sensors, the requirements may differ between individual components of distributed system.

Requirements for observed variables: for ocean physical and biogeochemical measurements from fixed moorings – subsurface temperature and salinity, subsurface ocean currents, sea ice draft and drift, dissolved oxygen, carbonate system (pCO_2, pH); for ocean physical and biogeochemical measurements from drifting or mobile platforms (ice-tethered platforms, gliders, floats) - surface and subsurface temperature and salinity, dissolved oxygen, nitrates, chlorophyll-a and CDOM fluorescence, particulate backscatter; for FerryBox measurements – subsurface temperature, salinity, chlorophyll-a fluorescence, carbonate system variables (pH and CO_3 ion concentration), absorption spectra, microplastics concentration and material type by size fraction; for sea ice measurements from SIMBA - air temperature, snow/ice temperature, ocean temperature below ice bottom, snow depth and ice thickness, ice drift trajectories.

Requirements for spatial and temporal resolution: spatial resolution for ice-based drifting systems in the central Arctic (ocean and sea ice measurements) should be less than 500 km, preferably 200 km (as defined in this document), required temporal resolution of ocean and sea ice measurements from surface drifting platforms is sub-daily, data are available in NRT (high timeliness); spatial resolution for water column drifting or mobile platforms (gliders, Argo floats) – locally high spatial resolution (of the order of O(10 km)) but required resolution similar to ice-based platforms, sub-daily to daily temporal resolution, NRT data availability (high timeliness); spatial resolution for measurements from ships of opportunity (FerryBox systems, fixed station and drone-based radiation measurements) low (but locally high along ship route), temporal resolution variable (depending on the SOO regular trips or occasional cruises), data availability with some delay (moderate timeliness).

Requirements/recommendations for technical development and new solutions:

- for ice-tethered platforms for ocean measurements – development of low-cost but more robust platform (system) designed for basic physical measurements that can be deployed in larger quantities, development of systems capable to survive melting and refreezing of sea ice, development of more robust (backed-up) communication systems for positioning and data transfer,
- for SIMBA buoys and ice-snow measurements – development of system for protecting thermistor string against ice-raft and deformation, but also from polar bears; solutions for improving measurements when borehole is unfrozen or filled with air bubbles, technology for improving measurements with sensors exposed in the air (problems with wind vibration, snow drift, frost condensation); development of unified data processing technique to reliably and accurately determine sea ice thickness and snow depth,

- for physical and biogeochemical measurements at fixed moorings – technology development for the upper layer (surface) measurements, better technology for localizing moorings under the sea ice, development of new BGC sensors for robust long-term measurements; technology development for data transfer from subsurface moorings,
- for physical and biogeochemical measurements along trajectories in the water column (Argo floats and gliders) – development of light and power efficient sensors for BGC measurements, development of highly-sensitive radiometer for Argo floats for the very low light levels under sea ice, development of ice detection and avoidance sensors and algorithms, development of under ice positioning and navigation systems, development of high-capacity power sources (batteries) for longer (more efficient) deployments in cold Arctic waters,
- for autonomous FerryBox measurements of microplastic particles, carbonate system variables, and optical properties of seawater – further development of flow control system for autonomous measurements, developing solutions to convert existing methods of measuring CO_3 ion concentration in a benchtop spectrophotometer to a miniaturized and autonomous flow-through system (including fit-for-purpose UV spectrophotometer and designing the flow-through cuvette to use UV-transparent optical windows),
- for fixed station and drone-based radiation measurements – development of power supply back-up system and protection solutions for powering cables (done during INTAROS), development of de-icing/cleaning solutions for fixed upward looking pyranometers and drone propellers, further development of the drone's navigation system to enable safe and automatic piloting also close to the North Pole.

3.2.5 Distributed system for land and atmosphere

Individual components of the distributed system covering terrestrial and atmospheric spheres of the Arctic were highly diverse regarding area of implementation, spatiotemporal scales covered, and observation techniques employed. The main aims were implementation of automated flask sampler for atmospheric trace gases (Greenland), winter-proofing eddy-covariance instrumentation (Alaska), improved collection of vertical profiles of soil temperature (Alaska), multi-disciplinary monitoring of snow and vegetation properties (Canada), improved ground-truthing of satellite remote sensing products (Finland), and implementation of semiautonomous system for monitoring of atmospheric properties (Arctic Ocean).

<u>Requirements for observed variables:</u> for automated flask system – concentrations of six major trace GHG gases (CH_4, CO_2, CO, N_2O, H_2, and SF_6), the ratios of O_2/N_2, Ar/N_2, and the stable isotope signals $d^{13}C\text{-}CO_2$, $d^{18}O\text{-}CO_2$, $d^{13}C\text{-}CH_4$, and $d^{2}H\text{-}CH_4$; for eddy-covariance measurements - CO_2 and CH_4 fluxes, air temperature, three wind components, and auxiliary environmental variables (soil moisture, soil heat flux, net radiation, etc.); for soil temperature measurements - high spatial and temporal resolution temperature profiles; for snow and vegetation properties - atmospheric variables (air temperature and relative humidity, wind speed and direction, upwelling and downwelling shortwave and longwave radiation), snow variables (height, temperature and thermal conductivity), soil variables (thermal conductivity, temperature and liquid water content); for ground-truthing of satellite products - microwave backscatter (and phase) at different frequency bands, SAR image at four frequency bands and

two polarizations, incoming and reflected spectral irradiance and surface albedo spectra; for semiautonomous system for ship-based atmospheric measurements – meteorological variables (atmospheric pressure, wind speed and direction, air temperature and moisture, incoming broadband shortwave and longwave radiation and surface temperature, precipitation and visibility, clouds), vertical profiles of temperature, atmospheric water vapor, winds and pressure, surface turbulence flux (from eddy-covariance), geometry of clouds, precipitation and microphysics (from cloud radar), vertically integrated cloud liquid water and water vapor (from microwave radiometer).

Requirements for spatial and temporal resolution: spatial and temporal resolutions of observations with distributed system for land and atmosphere significantly differ between individual components and applications, their details are provided in the deliverable D3.15.

Requirements/recommendations for technical development and new solutions:

- for eddy-covariance measurements of CO_2 and CH_4 fluxes – technical development of an automatically controlled de-icing system for a sonic anemometer with (done in INTAROS),
- for vertical profiles of soil temperature – improving vertical resolution of soil temperature profiles (done in INTAROS), developing solutions for data collection of sensors that needed servicing when measurements sites are not accessible,
- for snow and vegetation properties – develop/implement less expensive and simpler backup instruments for measured parameters, develop/improve solution for heating of the upper sensors during the polar night to prevent freezing (including better power supplies), develop solutions for broadband satellite transfer of large volumes of collected data in real-time,
- for ground-truthing of satellite products – development of additional mechanical shielding, heating systems and the application of Arctic-quality lubricants to any moving mechanical parts of a ground-based radar system, development of instrument automatically providing irradiance and albedo for the whole solar spectrum at high spectral resolution (done in INTAROS),
- for semiautonomous ship-based atmospheric measurements – development of robust and sustained installation system for autonomous atmospheric instrumentation on a vessel, development of external heating systems for de-icing autonomous instruments (in particular radiometers and open-path gas analysers), implement a proper research lidar and continuous wind profiling system, develop solutions to ease inflating and releasing the balloons for radio-soundings.

3.2.6 Summary

While requirements for observed variables and their spatial and temporal resolution vary across different spheres (ocean, sea ice, atmosphere, land) and different key sites and regions as listed above, some requirements for technology development are shared by several observing systems and platforms, implemented during INTAROS. These cross-cutting recommendations include:

- development of integrated multidisciplinary measurements for existing platforms and systems, better integration of different sensors,
- development of improved, stable and robust sensors for ocean biogeochemical measurements in the Arctic regions,

- development of improved power solutions for cold regions (high-capacity battery packs, auxiliary powering systems as windmills or solar panels for surface platforms),
- development of cost-efficient, simple but robust sensors for ocean and sea ice physical measurements that could be deployed in larger quantities in the Arctic Ocean,
- development of surface platforms for ocean and sea ice measurements that can adapt to fast changing conditions in the Arctic Ocean (surviving ice floe melt and refreezing, capable of measurements from sea ice and when drifting in open water, including MIZ),
- development of ice detection and avoidance technologies and algorithms for drifting and mobile autonomous underwater platforms (also for profiling surface components of subsurface moorings),
- development of autonomous heating/de-icing solutions for terrestrial and atmospheric sensors,
- development of technical solutions for cost-efficient broadband satellite data transfer in NRT.

In general, the efforts on defining requirements for global observing systems (e.g., WMO OSCAR database, Copernicus database in preparation, or IOC GOOS recommendations EOVs) can serve as a basis for further discussion and refinement of requirements for Arctic in situ observations but their fulfilment is hard to achieve due to limitations of in situ observing in the Arctic under harsh and fast changing environmental conditions, difficult access and limited capacity of satellite communication. In particular, horizontal resolution and timeliness of subsurface in situ observations in the Arctic Ocean (and also temporal resolution understood as temporal coverage rather than time interval of measurements) pose a challenge that should be addressed in future by developing new technologies and targeted system design. The spatial representativeness of in situ measured variables determines the required density of observational grid (horizontal resolution) and is strongly domain-, site-, process/phenomenon- and variable-dependent. This was also clearly visibly in requirements for observing systems and platforms, implemented under INTAROS.

3.3 Requirements from demonstration cases (WP6)

3.3.1 Arctic fish stocks and ecosystems

There is substantial knowledge on the commercially most important fish stocks in some parts of the Arctic and sub-Arctic, and also on how climate variability affects them. Areas with good knowledge base include the Barents Sea and waters off West Greenland, both of which have been focused on within INTAROS. However, as emphasized in this report’s sections on Arctic Fisheries Management (Chapter 2.5) and Community-Based Observations (Chapter 2.6), there are clear requirements for more and more easily available observation data, including data and information from community-based monitoring and Indigenous and Local Knowledge. With a shift from single species to ecosystem-based management, observations on other parts of the ecosystem are required (plankton, other fish species and more). Further, for most parts of the (sub)Arctic the data situation is far weaker than in the areas mentioned. For ecosystem understanding and detection of potential new harvestable stocks, there is a strong requirement for expansion of the in-situ scientist-executed as well as community-based (Chapter 3.4) observational basis, especially into the Arctic Ocean. Such an enhanced observational basis and data set is also a requirement for constructing and expanding reliable species distribution models, machine learning techniques and (geo)statistical analyses such as have been demonstrated in INTAROS.

3.3.2 Svalbard avalanche forecast modelling

Avalanche forecast models require input from numerical weather prediction models. On Svalbard, however, the models cannot resolve the complex topography and therefore cannot provide accurate snow precipitation and snow accumulation in the mountain slopes where avalanches can take place. Therefore, in situ observations are crucial both for downscaling weather prediction model outputs used as input to snow models and for initialization of the snow avalanche forecast model themselves. In particular, long time series of collocated snow depth and meteorological observations (especially wind) along the most critical mountain slopes would be needed. Currently, the in-situ snow observations are discontinuous due to changes in location of the stations, changes in the applied instrumentation, and large temporal gaps. Moreover, they are not collocated with wind measurements. These current constraints pose strong limitations to the use of the data for snow model development and improvement of avalanche forecasts.

More and better coordinated in situ observations are therefore a requirement for better avalanche forecasts on Svalbard, where avalanches recently have had fatal consequences.

3.3.3 Barents Sea multi-depth hydrographic maps

Numerical ocean models are useful tools with many applications. However, for model initialisation, boundary conditions, testing and verification purposes actual observations are often required. For example, multi-depth observation-based monthly climatologies and maps of salinity and temperature, as produced in INTAROS, can be used as open boundaries for numerical ocean models. In addition, regional spatial means from such climatologies, and time series of such integrated measures, will be a valuable data set for model validation. To facilitate production of similar climatologies for other regions in situ hydrographic measurements are a requirement.

3.4 Community-based and citizen science observations (WPs 4 and 6)

Community-based monitoring means a process of routinely observing or monitoring environmental or social phenomena, or both, which is led and undertaken by community members and can involve external collaboration and support from visiting scientists and government agencies (Johnson et al. 2015).

This chapter will discuss advances in understanding split into seven categories.

1. **Increased understanding of the need for CBM to improve decision-making.**

In recent years, there has been a step-change in understanding among key actors in the Arctic of the critical need for engaging community members in observing efforts to improve environmental decision-making (Danielsen et al. 2021a; Eicken et al. 2021) exemplified by:

- The recently signed Central Arctic Ocean fisheries agreement, ratified by Russia, Greenland, Canada, USA and the EU (see Chapter 2.5) requires that decisions on living resources in the Central Arctic region take into consideration both Indigenous and Local

Knowledge (ILK) and scientific knowledge. How ILK and scientific knowledge can be cross-weaved in this context, however, needs to be explored (Chapter 2.6).

- In Greenland, the government body responsible for decision-making on the management of living resources on land and at sea, the Ministry of Fisheries and Hunting, has begun developing an executive order on user knowledge (PAIKA). While an upcoming hearing phase on the executive order has been announced, the details of PAIKA have not yet been made public. The executive order is expected to set aside government staff time and operational funds for the systematic involvement of user knowledge in resource management.
- The North Atlantic Marine Mammal Commission (NAMMCO), an international organization for regional consultation and cooperation on small and large whales, seals and walruses in the North Atlantic, has shown interest in strengthening the inclusion of knowledge from hunters in the development of scientific research and management advice. The rationale is that "*management advice should be based on the best available knowledge"* and this requires *"balanced inclusion of knowledge from both hunters and scientists*"(https://nammco.no/wp-content/uploads/2021/03/press-release-nammco28_post-am28-.pdf). NAMMCO is one of the international management bodies of greatest importance to the lives and livelihoods of hunters and fishers in Greenland.

2. Requirements for enabling CBM observations.

With the increased interest in CBM in the Arctic, it is important to know how to enable CBM observations. Under what conditions are community members likely to be interested in making observations, and when do their observations lead to informed decision-making on natural resources? CBM programs depend on local people making a significant investment in monitoring. It is found that CBM programs are most appropriate:

- where local people have a significant interest in natural resource use and ecosystem services (e.g. water);
- when the information generated can have an impact on how the resources are managed and the monitoring integrated within the existing management regimes; and
- when there are policies in place that legally require government agencies to listen to, and to use, the knowledge and observations of community members in their decision-making (modified from Danielsen et al. 2021b).

If the community members' observations are to lead to informed decision-making on natural resources, the willingness of government agencies to incorporate CBM observations into decision-making is not sufficient. The use of CBM observations in decision-making needs to be a legal requirement (e.g. Lefevre 2021, see https://www.uarctic.org/media/1601510/lefevre-jessica_arctic-user-knowledge-22-feb-2021.pdf).

3. Insights on how to obtain, and how to use, CBM observations.

Over the past years a better understanding has been achieved of the different ways environmental observations from citizens can be obtained and used for decision-making (see examples of CBM manuals and CBM programme organizers' reflections of key lessons learnt, available at the link: https://mkp28.wixsite.com/cbm-best-practice; Deliverable 4.2).:

- *Test of citizen seismology*. The use of four garage-type geophone devices has been tested, two in each of Greenland and Svalbard, over two years. The test was led by Peter

Voss of GEUS and Mathilde Sørensen of the University of Bergen (findings published in Jeddi et al. 2020). The citizen-generated seismic data from the geophones was tested with existing scientist-executed seismic sensors. In Disko Bay, Greenland, the citizen geophones enabled the location of 23 events and improved the location of 209 events, thus significantly improving the understanding of the cryo-generated and tectonic events that occurred in the area. In Svalbard, however, it was impossible to find suitable locations for the instruments due to the physics of the land and infrastructure (Voss et al. 2019; Jeddi et al. 2020). The findings suggest that citizen seismology may be useful in Arctic communities where the buildings are constructed on bedrock and trusted relationships exist between government agencies, scientists and the local residents. If seismic events detected by the geophones are discussed with the communities and the authorities, citizen seismology may help build community awareness of natural hazards and contribute to improved decisions on safety.

- *Test of expedition cruise operator-based observing*. Cruise guests already make observations of the environment in the Arctic, but the number of attributes observed and the volume of records are limited and very few of the observations are used by decision-makers (Poulsen et al. 2019). A dialogue was initiated on coordinated expedition cruise operator-based observing with the expedition cruise industry, scientists, and the authorities. The use of four citizen science programs among cruise operators in Disko Bay and Svalbard for one cruise season has been tested. A total of 165 people contributed observations, mostly bird checklists to eBird and marine mammal encounters through photos to Happywhale. Cruise guests and cruise guides can contribute large volumes of observations from areas visited by expedition cruises during the Arctic cruise season, April to September. Findings suggest that enabling factors may include:
  - i) Equipping cruise vessels with tablets that allow for easy uploading of records,
  - ii) Prompt feedback to observers and decision-makers directly from the citizen science programs using digital platforms,
  - iii) A well-funded intermediate organization facilitating communication.
  - iv) Further work is necessary to fully understand the feasibility and potential of coordinated expedition cruise operator-based environmental observing in the Arctic.
- *Test of focus group discussions with resource users*. In Disko Bay systematic focus group discussions with fishermen and hunters were tested for monitoring and managing living resources as part of the PISUNA program (*Piniakkanik Sumiiffinni Nalunaarsuineq*). A total of 30 fishermen and hunters summarized observations from 4,287 field trips, of 33 attributes of the marine and coastal ecosystems, including sea-ice and climate/weather, plus 10 fish, 11 mammal and 10 bird taxa, over four years. The community members used the observations as a basis for submitting 197 management proposals to the local and central authorities. The findings suggest that focus group discussions with resource users are useful where community members depend on living resources for their livelihood and where government policies are supportive of collaborative resource management. To achieve their full potential, focus group discussions require government staff time and funds to be prioritized for facilitating the fishermen and hunters' monitoring and for making decisions and taking action on the basis of the management proposals

The three programs piloted represent approaches with varying levels of participant and scientist involvement and with different linkages to decision-making processes and actions (details in Deliverable 4.3). The case of the geophones is an example of automated data collection among Arctic residents. The role of the participants is limited to installing the geophones and providing electricity and Internet. The expedition cruise operator-based observing is an example of human production of data by visitors to the Arctic. The observers are cruise guests and guides, and their role is limited to making observations and taking measurements and photos. In both cases, if the data is to inform decision-making, it will need to be interpreted and analysed by scientists and the findings made available to the appropriate decision-making bodies. In the third field-based data-gathering activity tested, the focus group discussions with resource users, the participants not only submit records to scientists but they also themselves interpret and discuss their records and propose management interventions to the authorities. In this case, communicating findings and proposing decisions are in-built components of the monitoring process.

4. Guidance from models.

During the INTAROS project, two models in particular have informed the CBM work:

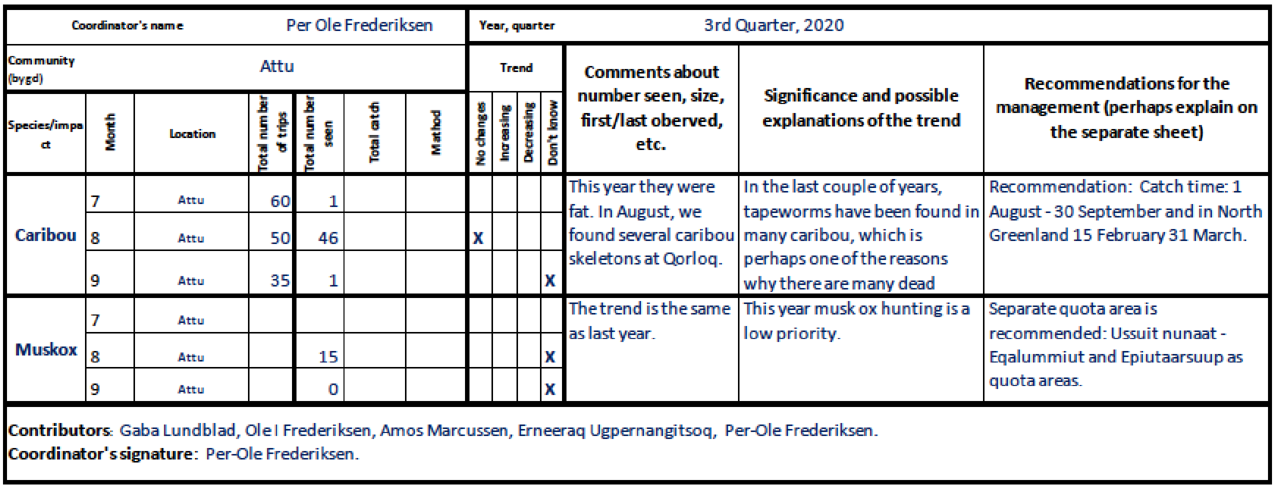
a) The Multiple Evidence Base (MEB) model, which is an approach for working with diverse knowledge systems to produce an enriched picture of a given phenomenon identified in collaboration between different stakeholders (Tengö et al. 2014, 2017, 2021). The MEB positions ILK and researcher/manager knowledge as different manifestations of valid and useful knowledge that generates complementary evidence for sustainable use of land areas or natural resources (see Table 3.6 from Tengö et al. 2021). The model is primarily for use in situations where management decisions regarding a specific area of land or sea territory or on specific natural resources (water, fish etc.) require the establishment of a knowledge base. The MEB model has been used to provide guidance to the Greenland Fisheries Commission on how to incorporate local knowledge into coastal fisheries management in Greenland (Lyberth et al. 2021). The MEB model can ensure that both local user knowledge, research knowledge and manager knowledge contribute to creating an understanding of the fish status and fisheries situation.

b) The other model used extensively in the CBM work in INTAROS is a quarterly summary form, developed and tested together with fishermen and hunters in the Disko Bay, Greenland, for documentation of ILK for the purpose of informing natural resource management decision-making. Through its structure, the form encourages self-evaluation of local observations and knowledge and, at the same time, promotes local discussion of trends in resources, their possible reasons and relevant actions. If the aim is for ILK to systematically inform government decisions, then the format used in this quarterly summary form is a simple and pragmatic solution (Table 3.6). The quarterly summary form is now also being used by different Indigenous community members for CBM in Yakutia and Kola Peninsula, Russia, with good results.

5. Requirements for observations from community members.

Comparisons between community-based and scientist-executed surveys across a range of ecosystems and socio-political settings have shown that CBM approaches are capable of providing accurate and precise information independent of external experts. When comparative studies of community-based and scientist-executed surveys sometimes yield different results, this is often because the surveys are not undertaken in the same habitats and there are differences in scale, place and time of the survey effort by community members and scientists (review in Danielsen et al. 2021b).

Table 3.6. Excerpt from a completed quarterly summary form (Attu, July-Sep. 2020). Source: Pisuna.org and https://eloka-arctic.org/pisuna-net/en .



Coordinator's name			Per Ole Frederiksen				**Year, quarter**				3rd Quarter, 2020		
Community (bygd)			Attu				**Trend**				**Comments about number seen, size, first/last oberved, etc.**	**Significance and possible explanations of the trend**	**Recommendations for the management (perhaps explain on the separate sheet)**
Species/impact	**Month**	**Location**	**Total number of trips**	**Total number seen**	**Total catch**	**Method**	**No changes**	**Increasing**	**Decreasing**	**Don't know**			
Caribou	7	Attu	60	1							This year they were fat. In August, we found several caribou skeletons at Qorloq.	In the last couple of years, tapeworms have been found in many caribou, which is perhaps one of the reasons why there are many dead	Recommendation: Catch time: 1 August - 30 September and in North Greenland 15 February 31 March.
	8	Attu	50	46			X						
	9	Attu	35	1						X			
Muskox	7	Attu									The trend is the same as last year.	This year musk ox hunting is a low priority.	Separate quota area is recommended: Ussuit nunaat - Eqalummiut and Epiutaarsuup as quota areas.
	8	Attu		15						X			
	9	Attu		0						X			

Contributors: Gaba Lundblad, Ole I Frederiksen, Amos Marcussen, Erneeraq Ugpernangitsoq, Per-Ole Frederiksen.
Coordinator's signature: Per-Ole Frederiksen.

6. Data management: connecting CBM datasets to international databases.

Only a tiny proportion of Arctic CBM programs are registered in international data catalogues (Danielsen et al. 2021a). Most data catalogues and international data repositories are not suitable for hosting CBM data collections because CBM observations often do not have geographical coordinates attached to each observation. During 2019, INTAROS established a data catalogue (https://catalog-intaros.nersc.no/). The data catalogue comprises brief descriptions of the data collections (meta-data) and links to each dataset. As of June 2021, this data catalogue comprises more than 130 data collections. Meta-data was entered on a total of 15 Arctic CBM and citizen science (CS) data collections into the data catalogue. Seven of the data collections comprised data from Disko Bay and five from Svalbard. A brief description is given of each data collection and a link, or an email address is provided so that readers of the catalogue interested in obtaining access to the data will know where to find it. In a separate deliverable (Deliverable 4.4), each of the CBM and CS data collections, the tags and the parameter names used, the links to the datasets and the potential uses of the data are described. It is shown that it is possible to incorporate CBM datasets into data catalogues and we hope this will encourage other data catalogues and international data repositories to adjust their formats and procedures so that CBM data collections can be incorporated.

7. Observation networks enhancing CBM observations.

Over the course of the INTAROS project, from Dec. 2016 to May 2021, the project has organized or co-organized 40 workshops, dialogue meetings, seminars and other events on CBM in the Arctic (summarized in Deliverable 7.14). The events have been attended by at least 600 people, including representatives from five Arctic Indigenous Peoples (Inuit, Sami, Evenk, Gwi´chin and Komi Izhma), and citizens of all eight Arctic nations.

There may be very substantial benefits from enhancing networking among CBM programs in the Arctic (Johnson et al. 2021). Most CBM programs are running independently and in isolation from each other, with limited exchange of experiences, and there is no obvious institutional home for networks of Arctic CBM programs. Any effort to connect CBM programs is therefore important. The INTAROS project has contributed to the development of a UArctic Thematic Network on Collaborative Resource Management and Community-Based Monitoring (see https://www.uarctic.org/organization/thematic-networks/collaborative-resource-management/). Additionally, the establishment of a network of small-scale resource user organizations and representatives of the international management bodies NAMMCO and CITES (the Convention on International Trade in Endangered Species) has been facilitated with a view towards further incorporating CBM observations and ILK into the decision-making and management advice of international management bodies.

4. Requirements for temporal and spatial resolution, timeliness and quality

The design of a Sustained Arctic Observing System (SAOS) should be based on observing objectives addressing relevant societal needs which could, for example, be a routine product that informs society about the status of a part of the Arctic, but which may ultimately ask for a decision to be taken – this process involves close interactions with relevant stakeholder groups. The societal needs must thereafter be translated into a production line that involves observation, data management, analysis, numerical modelling and generation of tailored information, products and services. This process involves identification of important phenomena and processes to monitor and which variables it is essential to measure.

It is foreseen that monitoring of the Arctic region will rely heavily on satellite observations supplemented by more conventional in situ scientist-executed and community-based monitoring platform, such as surface stations and ships, Especially the ocean community will also use several other platforms such profiling floats, gliders, moorings, AUVs etc. to monitor the interior of the Arctic Ocean. On the other hand, earth observation satellites rely heavily on precise in situ observations for calibration of satellite sensors and validation of satellite measurements. To design a fit-for-purpose SAOS it is therefore crucial to establish a clear set of requirements for in situ observation in the Arctic Regions. When the requirements are settled, they can be compared with the exiting data availability to reveal the gaps in the present observing system.

Requirements are expressed in terms of resolution in space and time, quality and timeliness. Especially the spatial resolution expressed as a gridded network (Fig.4.1) is still untraditional and complex in the environmental observing community and therefore the most difficult part of the requirement definition process.

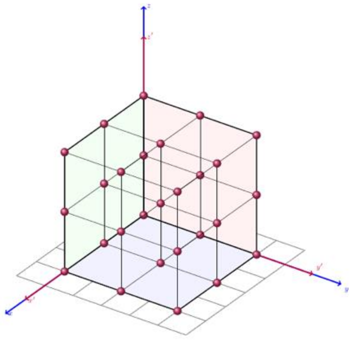


Figure 4.1 Observation grid defining horizontal and vertical resolutions.

It is expected that the required spatial resolution will differ from one region to another, between spheres and for different variables, and it will also be expected to vary locally within individual regions, where specific processes or phenomena require higher observation resolution in certain areas.

Another important component of this requirement definition process is a realistic judgement about what is feasible to implement in practice from a logistical and economic point of view.

To illustrate this the number of observation points for the Arctic Ocean for different horizontal resolutions are calculated, Table 4.1

Table 4.1 Number of observations points in the Arctic Ocean versus different requirements for horizontal resolution.

Horizontal resolution (km)	**Number of observations points**
50	5622
100	1405
200	351
300	156
400	88
500	56

Additionally, WMO SOG and INTAROS WP2 assessments of observing systems (Sect. 2.3 and 3.1, respectively) evidenced the inadequacy of utilizing requirements set for global, integrated variables at level 3 and 4 to evaluate in situ observations distributed at level 1 and 2, i.e. with the heterogeneous spatial distribution and the limited spatial and temporal coverage characteristic of all terrestrial and marine networks and observing assets. In particular, the heterogeneity of the spatial distribution of in situ observing platforms makes the concept of “horizontal resolution” inapplicable. What users of level 1 and 2 data need to know to be able to use the data in whatever application is how much local observations are representative of the area of interest (e.g., the satellite footprint for satellite validation, or the model grid for modelling applications).

Spatial representativeness is very much site and variable dependent, and it is one of the most important factors to consider when designing/optimizing the observing system or when doing a gap analysis (Wohner et al., 2021). When the spatial representativeness is limited to 1 m^2 or less, as is often the case for snow properties, a single observation set may include a cluster of observational points distributed along transects, or their average. In this way, the spatial representativeness of the data cluster/average significantly increases compared to the single point observation, and uncertainty decreases.

Experience and advanced research using OSSE experiments may reveal that there are key locations where observations have higher impact than others, but the present understanding of the physical, chemical and biological processes in the Arctic Region do not yet allow for such differentiation.

It is therefore important to have a constructive dialog within the observing community on how to formulate realistic requirements in a differentiated spatial grid. WMO has for some years worked on establishing a database – OSCAR – that contains quantitative user-defined requirements for observation of physical variables in the application areas of WMO (i.e., related to weather, water and climate). Copernicus are presently working on establishing a similar database containing requirements for in situ data needed by Copernicus Services. These efforts can serve as a basis for further discussion and refinement of requirements for Arctic in situ observations and therefore serves as a basis for the requirements presented in this chapter.

Requirements presented in the following sections have been split into three levels:

- Threshold is the minimum requirement to be met to ensure that data are useful
- Goal is an ideal requirement above which further improvements are not necessary
- Breakthrough is an intermediate level between threshold and goal which, if achieved, would result in a significant improvement for the targeted application. The breakthrough level may be considered as an optimum, from a cost-benefit point of view, when planning or designing observing systems

4.1 Atmosphere

Atmospheric observations are necessary for a number of important activities that can for simplicity be summarized in three categories, with differing requirements:

- Operational products, such as weather forecasts and warnings on timescales from days to months.
- Climate monitoring and modelling, containing observations for single locations or areas but also using so-called reanalysis; climate modelling extends over timescales of decades.
- Research, necessary for improved process understanding leading to improvements of tools for weather forecast, including data assimilation, and climate (or Earth system) models, and for evaluation such models and also of satellite products.

The requirements for each category have different foci. For operational forecasting, continuity and hence sustainability, spatial coverage and timely delivery are more important than accuracy (which is not to say that accuracy is unimportant). Accuracy is much more important for research observations, while availability is seldom a concern and lack of sustainability is the nature of a science project. Climate monitoring is dependent on long, reasonably accurate but well-defined time series, and therefore also needs sustained efforts to achieve consistent quality, for example, for trend analysis, but coverage and timeliness are relatively less important.

However, to complicate matters, there is considerable overlap between the categories. Research observations may suffer from under-sampling and hence there has to be a sufficient number of observations under the many varying conditions that the highly variable atmosphere may provide; however, these do not have to be continuous as long as seasons and regions are reasonably well covered. It is the ensemble average that is important, not trends or continuity. Reanalysis, on the other hand, is typically based on global weather forecasting technology and therefore has the same general requirements as weather forecasting. Hence, although the reanalysis is run off-line after the fact, the observations that drive the effort are the same as for weather forecasting. All three categories are important, and an observing system cannot be without any one of them.

The WMO OSCAR database provides observation requirements for various variables appropriate for different activities. However, while it is easy to wish for high accuracy and resolution in time and space, the scientific underpinning is not always clear and some requirements seem unobtainable, especially in the Arctic and certainly with in situ observations, while some requirements hint at some future satellite technology. Below is a comparison using vertical temperature profiles as an example to illustrate this (Table 4.2). Similar comparisons can be performed for other variables with different details but essentially similar results, although the instruments with which to compare would be different, e.g., radar wind profilers instead of microwave radiometers for winds and DIAL lidars for water vapor, etc.

Table 4.2. Requirements for vertical profiling of temperature, as an example, over the planetary boundary layer (PBL) and/or free troposphere (FT), taken from OSCAR and INTAROS D2.2 contrasted to different observation systems (sounding, microwave, current and future satellite sensors). Colours are used in the requirement part to indicate threshold, breakthrough and target values, as in the OSCAR data base.

Application	**Levels**	**Accuracy**	**Horizontal resolution**	**Vertical resolution**	**Interval**	**Availability**	**Coverage**	**Assessment**
Global NWP	PBL + FT	0.5 K 1.0 K 3.0 K	15 km 100 km 500 km	300 m 1 km 3 km	1 h 6 h 24 h	6 min 30 min 6 h	Global	OSCAR
High Res. NWP	FT	0.5 K 1.0 K 3.0 K	1 km 25 km	300 m 450 m 1 km	15 min 1 h 6 h	15 min 30 min 2 h	Global	OSCAR
High Res. NWP	PBL	0.5 K 1.0 K 3.0 K	500 m 10 km	100 m 250 m 1 km	15 min 1 h 6 h	10 min 20 min 2 h	Global	OSCAR
Process research	PBL	0.1 K 0.5 K 1.0 K	-	5 m 10 m 15 m	Irregular, field campaign	1 month 3 month	Regional, circum-polar	INTAROS D2.4
Instruments								
Radiosonde	PBL + FT	< 0.5 K	Deployment dependent	O(10 m)	1-3h, manpower dependent			Vaisala RS41 & RS92 manuals, Dirksen et al. (2014), Jensen et al. (2016)
Microwave radiometer (HATPRO G5)	PBL & FT	1K	Deployment dependent	200 m (PBL) 0.6 – 0.8 km (Tree Trop)	15 min			RPG, Tjernström et al. 2019
AIRS L3	PBL, FT	3K 1 K	100 km	1 km	Twice daily		Global	Sedlar & Tjernström (2019)
Soundings (from surface or by dropsonde)	PBL Free Trop.	0.5 K	1000 km, for representative surfaces	< 100 m	At least daily, preferably every 6h	30 min by GTS	Global and Arctic Ocean	This report
Satellite hyperspectral IR	PBL Free Trop.	1 K	25 km	100 m	3 h	1 h	Arctic Ocean	Teixeira et al. (2021), e.g. highly elliptical orbit

The target accuracy for temperature profiles is the same, 0.5K, for different atmospheric while the threshold accuracy is 3K. Instead, the factor that sets the different applications apart is the resolution, frequency and timeliness of data delivery. The breakthrough horizontal resolution ranges from 500 m to 15 km while the corresponding vertical resolution ranges from 100 to 300 m, depending on application. The corresponding range for the observation cycle is 15 min to 1 h and for timeliness 6 to 15 minutes. The INTAROS assessment (D2.4, Tjernström et al. 2018) for research use notes the need for accurate temperature gradients and for breakthrough gives an accuracy of < 0.1K at a 5 m vertical resolution for breakthrough, but since this is for research applications there is no requirement for horizontal resolution and lenient requirement on frequency and timeliness. For this it is likely that permanent, e.g., mast-borne, sensors are needed. Even if radio soundings can reach this accuracy in the laboratory, the free-flying character of the measurement leads to representativeness issues; sensor time constants probably make resolutions < 10 m unreliable, at least in the presence of sharp inversions and the passing of the sonde through a layer is merely a snapshot.

One should also note here that the WMO No. 544 (Manual on the Global Observing System) recommends that the resolution of sounding networks in densely populated areas be at least 250 km and for sparsely populated distances should not exceed 1000 km; these recommendations are rarely met, and especially not over oceans. Hence, while reasonable accuracy and vertical resolution requirements can be fulfilled by radiosondes (or dropsondes), to get even in the vicinity of the requirements for horizontal resolution, observation update frequency and delivery times is going to require something entirely different than a sounding network. Sacrificing some accuracy and vertical resolution, microwave radiometers could replace soundings; these can be deployed autonomously but still need deployment on ships, while soundings additionally typically require some manual intervention.

The only type of observing system that theoretically stands a chance of meeting the requirements for resolution, observation frequency and availability are measurements from spaceborne platforms: satellites. There are already today plenty of satellite data available in the polar regions due to the convergence of polar orbiting satellite tracks. Currently, however, this comes at the price of sacrificing both accuracy and vertical resolution. While having dramatically improved global weather forecasting globally, and hence also reanalysis, satellite sensors simply do not have the accuracy needed to replace a completely non-existent radiosonde network (e.g., Naakka et al. 2019), which is the situation in much of the central Arctic, especially the Arctic Ocean.

Although the above discussion uses only one variable – temperature – as an example, it illustrates that an Arctic Observing System for the atmosphere needs a different concept. First, it is necessary, from purely practical considerations, to divide the Arctic into two regions with different horizontal representativeness, land and ocean. The continental Arctic and the Arctic Ocean have different requirements simply based on the present observing system and on differing characteristics.

First and foremost, over Arctic land there are existing observing networks to build on, whereas over the Arctic Ocean there are almost no in situ observations at present, while the constantly moving and deforming sea ice and harsh environmental conditions, especially in winter, poses overwhelming logistical challenges. According to Lawrence et al. (2019), only between 2 and 4% of all observations assimilated into the ECMWF Integrated Forecasting System (IFS) are so-called conventional observations, typically dominated by near surface observations and radio soundings but also including aircraft observations (which are few in the Arctic); the rest are satellite observations dominated by microwave and infra-red sensors.

Second, the increasing annual melting of sea ice causes additional challenges to representativity over the Arctic Ocean. In summer, observation locations over sea ice are not representative even for nearby locations with open ocean; the distribution of open water and sea ice also varies interannually and gradually over time. The summer melt also exercises large control over near-surface meteorology, making in situ atmospheric near-surface observations less important in summer than in winter, possibly except for surface pressure which integrates changes in the entire atmospheric column. Lawrence et al. (2019) also finds that conventional observations, although being only 2-4% of all observations, have the largest impact on forecasts in winter, but only second largest in summer.

Hence, while the OSCAR requirements can serve as a baseline, it is unavoidable and would be irresponsible not to consider intermediate requirements for the time being, when appropriately accurate satellite sensors with suitable vertical resolution (Table 4.2, last row) and adequate models for reanalysis do not exist. This is based on the concept launched in Tjernström et al. (2019b; INTAROS D2.10) in which the *comprehensive* level of the observing is filled by reanalysis, in a sense using models and data assimilation to extend the use of the little data available in the Arctic, the *baseline* level is primarily driven by satellite observations, the only data in the Arctic that has pan-Arctic coverage, while the *reference* network is the so-called super-sites, importantly including also time-limited icebreaker-based expeditions for the Arctic Ocean.

Arctic land

- For the GOS the most urgent requirement is to sustain the existing station network, while enhancing the accuracy of the observations with modern instruments. The latter is, for example, significant for the Russian sounding network that appears to have a lower accuracy than state-of-the-art systems (Naakka et al. 2019, Ingleby 2017).
- Enhance the network of super-sites along the Arctic coast, especially in the Russian Arctic where only a few exist today, but also in northern Canada. Along the coast there should be a maximum distance of ~1000 km between stations. However, in a choice between implementation of new stations and enhancing existing stations, the latter should have priority.
- For trace gases and aerosol observations, land areas with observational gaps should be prioritized, especially in areas like Central Siberia.

Arctic Ocean

- For surface observations, buoy programs must be sustained to continuously set out integrated ocean/ice/atmosphere buoys at least at the pace that they are exiting the Arctic with the sea-ice drift. The spatial resolution should be less than 500 km, preferably 200 km.
- Lacking permanent sounding stations, even a few ships carrying out soundings has a large effect on modelling (Naakka et al. 2019). Hence, ships navigating the Arctic Ocean for any purpose should be required to release at least daily soundings. Even as few as 5 or 10 soundings daily spread out over the Arctic Ocean domain would have a tremendous effect. Ships without capability to do soundings should be equipped with microwave radiometers.

- UAV technology should be prioritized and developed, for example with already existing technology, UAVs transecting the Arctic could be deployed at high altitude releasing dropsondes at ~1000 km distance.
- There should be atmospheric super-site observations, including surface fluxes, clouds, aerosols and trace gases in the Arctic Ocean by icebreaker for at least some months every year, preferably continuously, also in winter and there should be simultaneous observations in open water, the marginal ice zone and pack ice.

4.2 Ocean including sea ice

Essential Ocean Variables (EOV) are identified by the IOC GOOS Expert Panels, based on the following criteria:

- Impact: The variable is effective in addressing the overall GOOS Themes – Climate, Operational Ocean Services, and Ocean Health.
- Feasibility: Observing or deriving the variable on a global scale is technically feasible using proven, scientifically understood methods.
- Cost effectiveness**:** Generating and archiving data on the variable is affordable, mainly relying on coordinated observing systems using proven technology, taking advantage where possible of historical datasets.

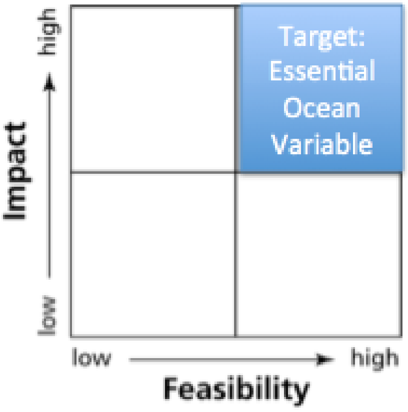


Table 4.3 List of Essential Ocean Variables and their readiness level (Green = Mature, Blue =Pilot; Red = Concept)

Physics	**Biogeochemistry**	**Biology and Ecosystems**
Sea State	Oxygen	Phytoplankton biomass and productivity
Ocean surface vector stress	Inorganic macro nutrients	HAB incidence
Sea Ice	Carbonate system	Zooplankton diversity
Sea level	Transient tracers	Fish abundance and distribution
Sea Surface Temperature	Suspended particulates	Apex predator abundance and distribution
Subsurface temperature	Nitrous oxide	Live coral cover
Surface currents	Carbon isotope (^{13}C)	Seagrass cover
Subsurface currents	Dissolved organic carbon	Mangrove cover
Sea Surface Salinity	Ocean colour	Macroalgal canopy cover
Subsurface salinity		
Ocean Sound		

The IOC GOOS Expert Panels has for each EOV prepared a series of recommendations including what measurements are to be made, various observing options, and data management practices (Table 4.3). Based on these recommendations a set of requirements for the EOVs most relevant for the Arctic Ocean was prepared; see Table 4.4.

Table 4.4 Requirements for Essential Ocean Variables relevant for the Arctic Ocean

Name	Uncertainty	Update Frequency	Timeliness	Horizontal resolution	Vertical resolution
Sea Surface Salinity	Threshold: 0,3psu Breakthrough: 0,1psu Goal: 0,05psu	Threshold: 7d Breakthrough: 3d Goal: 1d	Threshold: 3d Breakthrough: 2d Goal: 1d	Threshold: 500km Breakthrough: 400km Goal: 300km	
Subsurface salinity	Threshold: 0,1psu Breakthrough: 0,07psu Goal: 0,05psu	Threshold: 7d Breakthrough: 3d Goal: 1d	Threshold: 3d Breakthrough: 2d Goal: 1d	Threshold: 500km Breakthrough: 400km Goal: 300km	Threshold: 10m Breakthrough: 5m Goal: 1m
Sea surface Temperature	Threshold: 0,1K Breakthrough: 0,05K Goal: 0,05K	Threshold: 7d Breakthrough: 3d Goal: 1d	Threshold: 3d Breakthrough: 2 d Goal: 1d	Threshold: 500km Breakthrough: 400km Goal: 300km	
subsurface temperature	Threshold: 1k Breakthrough: 0,5k Goal: 0,1k	Threshold: 7d Breakthrough: 3d Goal: 1d	Threshold: 3d Breakthrough: 2 d Goal: 1d	Threshold: 500km Breakthrough: 400km Goal: 300km	Threshold: 10m Breakthrough: 5m Goal: 1m
surface currents	Threshold: 5cm/s Breakthrough: 2cm/s Goal: 1cm/s	Threshold: 7d Breakthrough: 5d Goal: 1d	Threshold: 3d Breakthrough: 2d Goal: 1d	Threshold: 500km Breakthrough: 400km Goal: 300km	
Subsurface currents	Threshold: 5cm/s Breakthrough: 2cm/s Goal: 1cm/s	Threshold: 7d Breakthrough: 3d Goal: 1d	Threshold: 3d Breakthrough: 2d Goal: 1d	Threshold: 500km Breakthrough: 400 km Goal: 300km	Threshold: 100m Breakthrough: 50m Goal: 10 m
Sea level	Threshold: 0,05m Breakthrough: 0,02m Goal: 0,01m	Threshold: 1h Breakthrough: 30min Goal: 10min	Threshold: 1h Breakthrough: 10 min Goal: 2min	Threshold: 200km Breakthrough: 50km Goal: 10km	
Sea state	Threshold: 0,25m Breakthrough: 0,25m Goal: 0,1m	Threshold: 7 d Breakthrough: 3d Goal: 1d	Threshold: 3d Breakthrough: 2d Goal: 1d	Threshold: 500km Breakthrough: 400km Goal: 300km	
Sea Ice Cover	Threshold: 15% Breakthrough: 10% Goal: 5%	Threshold: 7d Breakthrough: 3d Goal: 1d	Threshold: 3d Breakthrough: 2d Goal: 1d	Threshold: 500km Breakthrough: 400km Goal: 300km	
Sea Ice drift	Threshold: 2km/d Breakthrough: 0,5 km/d Goal: 0,1 km/d	Threshold: 7d Breakthrough: 3d Goal: 1d	Threshold: 3d Breakthrough: 2d Goal: 1d	Threshold: 500 km Breakthrough: 400 km Goal: 300 km	
Sea Ice thickness	Threshold: 40% Breakthrough: 20% Goal: 5%	Threshold: 7d Breakthrough: 3d Goal: 1d	Threshold: 3d Breakthrough: 2d Goal: 1d	Threshold: 500 km Breakthrough: 400km Goal: 300km	
Nutrients	Threshold: 25% Breakthrough: 10% Goal: 10%	Threshold: 90d Breakthrough: 30d Goal: 7d	Threshold: 7d Breakthrough: 3d Goal: 1d	Threshold: 500km Breakthrough: 400 km Goal: 300 km	Threshold: 10m Breakthrough: 5m Goal: 1m
Oxygen	Threshold: 25% Breakthrough: 10% Goal: 10%	Threshold: 90d Breakthrough: 30d Goal: 7d	Threshold: 7d Breakthrough: 3d Goal: 1d	Threshold: 500km Breakthrough: 400km Goal: 300km	Threshold: 10m Breakthrough: 5m Goal: 1m
Chlorophyll	Threshold: 30% Breakthrough: 10% Goal: 5%	Threshold: 90d Breakthrough: 30d Goal: 7d	Threshold: 7d Breakthrough: 3d Goal: 1 d	Threshold: 500 km Breakthrough: 400 km Goal: 300 km	Threshold: 10m Breakthrough: 5m Goal: 1m
Inorganic carbon (DIC, TA, pCO2, pH)	Threshold: 30% Breakthrough: 10% Goal: 5%	Threshold: 90 d Breakthrough: 30 d Goal: 7d	Threshold: 7d Breakthrough: 3d Goal: 1d	Threshold: 500 km Breakthrough: 400 km Goal: 300 km	Threshold: 10m Breakthrough: 5m Goal: 1m
Bathymetry	Threshold: 1m Breakthrough: 0,5m Goal: 0,1m	Threshold: 10y Breakthrough: 5y Goal: 1y	Threshold: 1y Breakthrough: 1y Goal: 1y	Threshold: 100km Breakthrough: 50 km Goal: 2km	Threshold: 10 m Breakthrough: 5m Goal: 1m
Greenland Ice Sheet Mass Change		Threshold: 5y Breakthrough: 1y Goal: 1m	Threshold: 1y Breakthrough: 6m Goal: 3m	Threshold: 8 areas Breakthrough: each terminal glacier Goal: each terminal glacier	
River Discharge	Threshold: 25% Breakthrough: 10% Goal: 5%	Threshold: 7d Breakthrough: 1d Goal: 6h	Threshold: 7d Breakthrough: 1d Goal: 6h	Threshold: 10km Breakthrough: each hydrological basin Goal: each hydrological basin	

Table 4.4 also includes requirements for three additional parameters – bathymetry, Greenland Ice Sheet Mass Change & river discharge – which are important inputs to understanding and modelling of the Arctic Ocean Environment.

These requirements for observations of ocean variables in the Arctic Ocean is a first attempt to qualify the needs for ocean monitoring that can form the basis for planning of a future observing strategy including logistics and economics, but also for further refinements considering areas needing higher resolution or identification of focus areas based on model experiments and/or satellite observations. A horizontal resolution of 500-300 km implies 56-156 observation points delivering data preferably in near-real-time. This is ambitious but not impossible in a well-coordinated international effort that includes technology and communication developments. The ARGO community formulated in the 1990s a clear goal to always have one float present in each 300 x 300 km cell. It was a very ambitious goal at the time but has now been achieved for large parts of the world's oceans. There are however still areas not fulfilling this goal and the Arctic Ocean is one of them. The Arctic Ocean therefore is a focus area for EuroARGO in the coming years but achieving this goal requires a breakthrough technological development for operating ARGO floats in ice-covered areas and marginal ice zones (solutions for ice detection/avoidance, subsurface positioning and data transfer).

4.3 Land

4.3.1 Surface and near-surface variables

For in situ observations, the concept of "spatial resolution" should be replaced by "spatial representativeness" because that is the specification needed in:

- data assimilation procedures (to translate sparse in situ observations into a gridded space)
- validation of satellite products.

In principle, the spatial representativeness of a variable determines how many observation points of that variable there should be to map the desired surface (thus, the spatial resolution). In practice, logistical constraints determine the spatial distribution of the observing points. When the spatial representativeness is limited to 1 m^2 or less, such as for snow properties, a single observation set often includes a cluster of observational points, frequently distributed along transects, or their average. In this way, the spatial representativeness of the data cluster/average significantly increases compared to a single point observation, and uncertainty decreases. Spatial representativeness is, however, very much site-dependent, and is one of the most important factors to consider when designing the observing system (the location and amount of observing points should be selected to maximize their spatial representativeness).

Table 4.5 provides an extract of requirements defined in INTAROS WP2 for in situ terrestrial data collections (see Table 3.4 in Sect.3.1), where the requirement criteria "horizontal resolution" has been replaced by "horizontal representativeness".

Table 4.5: Requirements for selected variables from Table 3.4, in which "horizontal resolution" has been replaced by "horizontal representativeness".

Variable name	Layers	App. Area	Uncert.	Horiz. Representativeness	Vert. res.	Os cycle	Time-liness	Coverage	Conf Level	Comments
albedo	Land surface	NWP, Hydrology	1 % 5 %	100 m 10 m 2 m		60 min 6 h 7 d	24 h 44 h 6 d	Global land and ocean	tentative	Assessment done by R. Pirazzini
Snow depth	Sea surface	Ocean applications	0.5 cm 2 cm 5 cm	100 m 20 m 1 m		24 h 24 h 24 h	7 d	Global ocean	tentative	
Snow depth	Land surface	Nowcasting / VSRF, climate change	0.1 cm 0.5 cm 2 cm	100 m 20 m 1 m		10 min 60 min 24 h	10 min 60 min 24 h	Global land	reasonable	Time limits are reasonable, but uncertainty of 0.1 cm is very difficult to reach. Now measured with 1 cm accuracy.
Snow depth	**Land surfaces**	Glacier mass balance	0,01 m 0,05 m 0,10 m	140 m 320 m 500 m		1 d 1 m 1 y	7 d 1 m 1 y	Glaciers	reasonable	Uncertinity: Østrem and Brugman (1991), other reqirements: M. Grabiec (Uslaski). Based on Østrem and Brugman (1991) satisfied snow depth density for mass balance purposes on valley glacier is 10-50 per 1 km2 and less for ice caps.
Snow water equivalent	Land surface	Agricultural meteorology	5 mm 23.2 mm 50 mm	100 m 20 m 1 m		7 d 11 d 30 d	24 h 46 h 7 d	Global land	reasonable	
Snow water equivalent	Land surface	Global NWP	10 mm 20 mm	100 m 20 m 1 m		24 h 5 d	24 h 5 d	Global land	reasonable	
Snow water equivalent	Land surface	High res NWP	8 mm 20 mm	100 m 20 m 1 m		60 min 6 h	60 min 24 h	Global land	tentative	
Snow water equivalent	Land surface	Hydrology	8 mm 20 mm	100 m 20 m 1 m		24 h 46 h 7 d	24 h 44 h 6 d	Global land	reasonable	
Snow water equivalent		SSLP	10 mm 20 mm	100 m 20 m 1 m		24 h 7 d	24 h 2 d 7 d	Global land	tentative	
Soil temperature	Land surface	Agricultural meteorology		5 km 7 km 19 km	-5, -10, -20, -50 and -100 cm	60 min 2 h 7 h		Global land		
Permafrost (used for soil frost)	Land surface	Hydrology	5 % 8.5 % 25 %	0.1 km 1 km 100 km		6 h 14 h 3 d	6 h 17 h 6 d	Global land	reasonable	
snow temperature and density profile, snow grain size and	Land and sea ice surface	research, NWP, snow avalanche forecast	10 % 20% 50%	100 m 20 m 1 m	every 0.1 cm every 3 cm	12h 1d 7d	12h 1d 7d	Representative areas		Assessment done by R. Pirazzini

shape profile, SSA profile, snow impurity content					every 10 cm					

4.3.2 Below-surface variables

Requirements for monitoring natural seismic events in the Arctic region are decided at national level and are based on the frequencies, magnitudes and types of events that are the focus. Seismic networks for observation and forecasting of, e.g., landslides, often operate with sub-kilometre sensor distances (e.g., Roth et al. 2006), whereas seismic networks for earthquake monitoring require sensor distances in the range from tens to hundred kilometres (e.g., Ottemöller et al., 2015). In addition to the sensor density, the seismic magnitude detection threshold and the uncertainty of event locations vary depending on the ambient seismic noise level. At sites with high ambient seismic noise, seismic events need to be larger to be detected, and the location uncertainty will be larger than for sites with lower ambient noise. It is therefore part of the quality assurance of a seismic network to examine the level of ambient seismic noise. In comparison, the requirements for seismic monitoring in the Directive 2009/31/EC of the European Parliament on the geological storage of carbon dioxide does not specify seismic network sensor densities. For operational monitoring of, e.g., earthquakes, tsunamis or landslides, real-time data flow, well-established processing procedures and experienced staff are further key requirements.

5. Gaps

The INTAROS project (Ludwigsen et al, 2018; Tjernström et al, 2018; Zona et al, 2018) and the Copernicus In Situ Coordination Group (Buch et al, 2019) has recently analysed the environmental monitoring of the Arctic region and has identified some general characteristics and gaps:

- In situ observations are generally sparse in the Arctic and in particular in the Arctic Ocean.
- Some users state that the limited amount of data is a bigger problem than the quality of data, although poor data quality is itself problematic
- Most observation programmes are nationally funded and therefore primarely meet national priorities and lack international coordination
- Environmental in situ data from the Arctic are managed by national or international data centers, funding agencies and individual research projects, both in countries with an Arctic coastline and countries with an Arctic interest.
- A major part of Arctic environmental observations is funded via time-limited research projects, which compromises the sustainability of observations and additionally only around 1/3 of the projects have an open and free data sharing policy.
- Insufficient data management structures at data producer level constitutes a big problem which negatively affects:
    - Formats of data and metadata
    - Accessibility
    - Timely delivery
    - Quality documentation
- Access to Russian data is extremely limited and calls for a dedicated action to free more critical observations in cooperation with Russian authorities
- Due to lack of good communication facilities many data are delivered in delayed mode thus being untimely, particularly for NRT productions. Other data, e.g., research data, are made publicly available too late to be available even for interim reanalysis purposes, i.e., there is a need for internationally agreed standards for timely delivery delayed mode data taking into account scientists' right to publish.
- The Arctic environment puts high demands on robust technology and there is a widespread demand to pursue innovative technology development.

In addition to these general gaps, more thematic area-specific gap details were identified that will be presented in the following. The general characteristics and gaps in community-based monitoring programmes in the Arctic have been identified and discussed in Deliverable 4.1 (Danielsen et al. 2021a) and will not be discussed here.

5.1 Missing observations

5.1.1 Atmosphere

Essentially the whole Arctic Ocean is an observational gap for in situ atmospheric observations. In particular information on the vertical structure of the atmosphere is missing; temperature, humidity, winds and clouds. Even considering satellite platforms, there is no useful information on such important observations as clouds, or even on such bulk variables as total cloud water path. Also for Arctic land areas there is a lack of cloud, aerosol and trace gas observations. Funding for upkeep and replacements of existing buoy networks and for science expeditions and sustained support and for technology development is clearly insufficient.

5.1.2 Ocean incl. sea ice

Understanding the dynamics of the Arctic Ocean depends on a well-functioning fit-for-purpose in situ observing system, since it is the only way monitor subsurface processes.

There is a good coverage of temperature and salinity profiles in ice-free waters. The data have been well collected and quality controlled and are openly accessible from WOD, UDASH, iAOS, SeaDataNet, ICES and EMODnet. The estimated amount of non-Russian profiles is > 20000 per year, i.e., 54 profiles per day. However, since consisting of mostly ship-borne observations, these profiles are not evenly distributed over the year but tend to be collected during summer and autumn months. Only moored systems and a part of drifting platforms, both being scarce in the Arctic, provide year-round in situ measurements in the water column. More than 90% of these data are open and free, but the data availability is not evenly distributed: few data are accessible from the Russian Arctic, and few data exist in under-ice waters, see Fig. 5.1. Under-ice T/S profiles are mainly observed with Ice Tethered Profilers (ITP), which are currently providing about 400 profiles per year (down to 500-800 m depth). More ITP profiler data are needed. Research cruises from fishery monitoring (e.g. ICES data) tend to follow fish cohorts, so the sampling is seasonally biased.

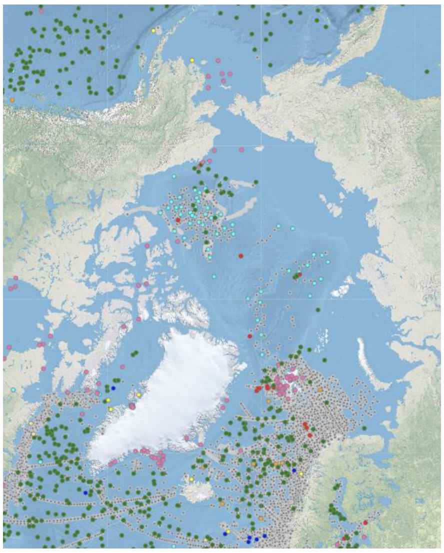


Figure 5.1 T/S profile observation points from the last 10 years stored in the EMODnet Arctic Marine Data Portal

In situ SST is mainly used for calibrating and validating the satellite products and model validation and assimilation. Currently SST data from about 132 surface drifters and 80 Argo profilers are available, but it is expected there will be more high-quality data added from EUMETSAT/Copernicus Trusted projects. There are presently no significant data gaps identified for validation of satellites, and assimilation of SST data into models will rely heavily on satellite observations.

Existing datasets on sea ice (e.g., from national data centres and research projects) need to be collected and further consolidated. International Arctic Buoy Program ice drifting buoys do not cover the Arctic homogeneously; satellite products provide better spatial coverage, but poorer temporal coverage and data is less trustworthy in summer. Airborne snow radar has played a big role in snow and ice monitoring. Snow depth and sea ice thickness and ice temperature can be measured by using Ice Mass Balance buoys, but they are very sparse. An Ice Mass Balance array has been operated in the central Arctic with interruptions since 2012. It should be noted, however, that when validating satellite products, point observations have weaknesses in their representativeness. Accurate Ice Surface Temperature can be measured by using near surface radiometers which preferably could be installed at weather stations.

Snow on sea ice: in situ observations are rare, manual only, and made only during field campaigns, so there are no sustained programmes.

There is currently a minimum of about 60 tide gauge stations operated along the Arctic coastline, including 13 Russian stations. From the PSMSL database more stations with historical time series can be found. Existing observations are regarded as adequate to fit most purposes. The priority is to improve data sharing, standardized format and quality control.

Currently about 30-40 wave buoys are operating to the north of 60 N. Most of the data are found in Norwegian waters, measured at oil platforms. These data have restricted access. On the other hand, due to existence of ice, requirements on in situ wave data are higher in the Arctic than other seas for validating satellite wave products and forecasting wave conditions. Significant gaps in in situ wave observations exist due to both lack of observations and lack of data sharing with the private sector.

There are very few observation points for ocean currents, especially in under-ice regions. Most of subsurface current measurements are provided by moored arrays that are sparce and unevenly distributed in the Arctic Ocean. New developments are ongoing that include ocean current measurements from ships of opportunity (equipped with acoustic profiling systems) or from ice-based drifting platforms. In ice- free regions surface ocean currents can be also retrieved from satellite observations.

Biogeochemical (BGC) in situ observations in the Arctic are less than 10% of the T/S profiles. Oxygen is most closely associated with T/S profiles. Other biogeochemical parameters are much less frequently measured. Moorings may have oxygen sensors but rarely sensors for other BGC variables. Stability of BGC sensors for long-term mooring deployments in the Arctic (dictated by limited access) is a serious issue that needs to be addressed by dedicated technology development. BioArgo floats can measure oxygen, chl-a, nitrate, suspended particles, downward irradiance and pH but do not necessarily measure all the parameters. All BioArgo operated in the Arctic region have oxygen sensors but only 2-3 of them measure chl-a. Most of the BGC profiles are measured by research vessels, while the data are assembled and disseminated in a late stage via ICES, SeaDataNet, WOD and GLODAPv2. This counts for about 4000 oxygen profiles, 2000 chl-a profiles and 500-1000 nutrient profiles per year. The oxygen data spread over all Arctic ice-free waters except for the Russian side. Chl-a and nutrients are mainly measured in the Nordic Seas. More data are available from SAOS but may have restricted access. In summary, even for ice-free waters, significant data gaps exist for BGC parameters, mainly due to lack of data but also due to restrictions on accessing existing data.

The LTER (Long-Term Ecological Research) observatory HAUSGARTEN is the only open-ocean observatory in a polar region with focus on natural and anthropogenically-induced changes in the Arctic marine ecosystem (Soltwedel et al., 2016). The observatory is located in the Fram Strait, the only deep-water connection between the Nordic Seas and the central Arctic Ocean. Since 1999, repeated sampling in the water column and at the seafloor during yearly expeditions in summer months was complemented by continuous year-round sampling and sensing using autonomous instruments on anchored devices.

Time-series studies at HAUSGARTEN provide insights into processes and dynamics within an arctic marine ecosystem and act as a baseline for further investigations of ongoing changes in the Fram Strait, including variations in gas exchange between the ocean and the atmosphere and shifts in the carbonate system of seawater that are expected to affect the composition of planktonic communities and thus the entire marine food web.

Long-term observations at HAUSGARTEN will significantly contribute to the global community’s efforts to understand variations in ecosystem structure and functioning on seasonal to decadal timescales in an overall warming Arctic and will allow for improved future predictions under different climate scenarios.

Comprehensive and well-structured ecological long-term studies comparable to those carried out at HAUSGARTEN are completely lacking in other parts of the Arctic Ocean, although they are urgently needed to detect and track the impact of large-scale environmental changes on the marine Arctic ecosystem.

5.1.3 Land

General considerations on the observational gaps in terrestrial variables were summarized in the INTAROS D2.7 report (Zola et al., 2018):

- For the land cover there is need of a more specific set of cover types for the Arctic than appears in some land cover schemes. In particular, shrubs, mosses and water tolerant grasses/sedges need to be included.
- For GHG measurements: more measurements are needed in autumn/winter, in the discontinuous (or melting) permafrost zone, and in Siberia. Also, the GHG fluxes measurements need to be linked to simultaneous soil water status measurements and vegetation type/wetland type. These co-located measurements should be done in situ for the small (local) scale and from satellite for the larger scale (with the exception of permafrost, which should be monitored via in situ measurements). Besides ground-based flux observations, we recommend continued aircraft eddy-covariance measurements bi-annually in Alaska and Canada and extending them to Russia and

Europe to cover the major Arctic regions, and to detect interannual variability. While the total site coverage of eddy-covariance sites across the Arctic domain is moderate, with currently flux data available from >130 individual locations, only a small fraction of the towers measures non-CO_2 greenhouse gases. To move forward towards monitoring a total carbon budget of Arctic ecosystems, other species such as e.g., CH_4 need to be covered as well. With far less than half of the current sites covering this gas, and continuous wintertime observations only available at a very small fraction of those, the addition of sensors to capture fluxes besides fCO2 was identified as one of the most pressing issues to improve our understanding in the feedback mechanisms between global climate change and the Arctic carbon cycle.

- Soil carbon in the Arctic is the largest store of terrestrial carbon, but there are only very sparse measurements of it. However, addressing this would be highly labour, intensive and expensive and may not be practical. Still, it is a gap.
- The measurements of some key snow variables (such as snow depth, snow water equivalent, and snow grain size) are still mostly manual and time consuming: this strongly limits the spatial extension of the measurement network. Snow grain size and albedo are very rarely measured, but time series across the snow season would be needed. Any kind of snow measurements is rarely done near greenhouse gas observation towers, although snow observations would be very important for the interpretation of the measured greenhouse gas fluxes.
- Regarding the geographical coverage of snow and ice surface mass balance (SMB) series for glaciers in the Arctic regions (excluding the Greenland Ice Sheet), there are 3 glacier regions that are not sufficiently covered at present (with “present” we mean here with glaciological SMB measurements for 2014 and 2015, or after 2005 for the geodetic SMB measurements): the Russian Arctic, Greenland periphery, and the Canadian Arctic. The Russian Arctic is by far in the worst situation, with no SMB series, neither glaciological nor geodetic. Greenland Periphery follows, with only 3 glaciological and 1 geodetic SMB series, despite its quite large total glacierized area widely distributed over an extensive geographical area. The Canadian Arctic has 4 glaciological and 3 geodetic SMB series, which is not much taking into account its large glacierized area. The rest of Arctic regions (Svalbard and Jan Mayen, Alaska and Iceland) are well covered. Svalbard and Jan Mayen region has no reported geodetic series to the World Glacier Monitoring Service (WGMS) but has 9 glaciological series. Alaska has a huge amount of geodetic SMB measurements (1007). Though the support of SMB measurement series is not the responsibility of the WGMS, but of the national funding agencies, the WGMS should put all efforts on approaching international organizations such as UNESCO and ICSU so that these organizations ask the national funding agencies to support SMB monitoring programs. To improve our estimates of the current and future contribution of the Greenland ice sheet to sea level rise, we recommend that three variables are included on the current PROMICE station network in the ice sheet ablation zone: 1) Snow water equivalent (SWE), 2) High-precision elevation and position measurements of automatic stations on the ice sheet surface and 3) Liquid precipitation (rain).
- The World Glacier Monitoring Glacier Thickness Dataset (GlaThiDa) is lacking a more homogeneous coverage of the various glacier regions of the Arctic. Only the regions where intensive airborne echo-sounding campaigns (e.g., IceBridge Operation) have been performed (Canadian Arctic, Greenland Periphery, and Svalbard and Jan Mayen)

have a large set of available data, though in many cases these data are limited to ground-penetrating radar (GPR) profiles along the glacier centerline. For Svalbard, the availability of many echo-sounded glaciers stems from a combination of airborne and ground-based campaigns. Something similar happens with the Russian Arctic, though in this case the number of glaciers with ice-thickness measurements is much lower, though still reasonable. The number of glaciers with ice-thickness measurements reported to the GlaThiDa dataset is very low for both Alaska and Iceland.

- Concerning Greenland altimetry and ice mass loss measurements, though the GNET network is relative dense there are few spots in West Greenland with only a few stations. Adding a few more stations would improve the spatial resolution of ice-sheet-wide mass loss.
- Concerning the variables required to monitor the seismic activity in the Arctic region, there is a need for denser observations both onshore as well as offshore, to provide accurate information on source mechanisms of seismic events.
- Considering the Arctic-HYCOS river discharge observation network, 8 additional stations were identified as potential flow-to-ocean stations that could improve the spatial coverage from 52% to 58% of the total pan-arctic drainage basin of the Arctic Ocean and northern seas (PADB), mainly as a consequence of improved spatial coverage in the Russian Federation (from 59% to 69%). The spatial coverage was also high for the North American part of the PADB (around 60%), whereas the coverage is only 15% in Iceland, Scandinavia and Svalbard. Greenland is practically not covered at all. The representation by the Arctic-HYCOS observations of the total river discharge to the ocean (excluding Greenland) was estimated to about 55% and could be further increased to 61% by including the additional 8 flow-to-ocean stations. Flow-to-ocean in Russian rivers is represented to 65% (75%) by the observations and in North American rivers by 54 % (56%) - numbers for the extended flow-to-ocean network in brackets. Overall, the spatial coverage can be considered very good regarding drainage area and flow-to-ocean. The actual numbers (around 60%) is somewhat below the tentative requirement of 75%. The low spatial coverage in Scandinavia and Iceland is partly due to the limitation to drainage basins >5000 km^2. The low spatial coverage on Greenland is not critical, given that the fresh-water flux from Greenland is estimated through an enhanced dataset developed by GEUS in the INTAROS project. The main recommendation to the Arctic-HYCOS project is thus to re-consider the list of flow-to-ocean stations to improve the spatial coverage as much as possible with stations available in the existing national networks.

5.2 Observations exist but data are restricted, quality is poor or technology is insufficient

5.2.1 Atmosphere

Satellite platforms cover the Arctic well, especially from polar orbiting instruments, but the accuracy of the observations is insufficient. Technology development can rectify some of this, but the underpinning in situ observations are also essentially absent over the Arctic Ocean.

Most in situ atmospheric observations in the Arctic Ocean are carried out by research expeditions, with excellent quality but almost always supported by national research funding with too weak incentive for timely publication of the data. It is important to understand that this is not due to an unwillingness by the scientists to share the data; it is primarily due to insufficient support for data management and publication of data.

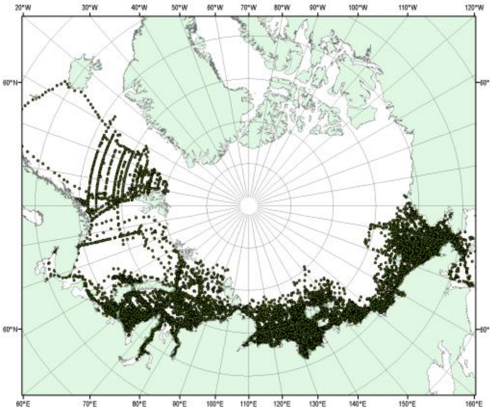
Real-time in situ data provision of atmospheric composition parameters could serve for various climate and air quality applications (such in Copernicus services). For their majority, these are at their very early stages of establishment lacking the automated data production and archive chains. In the Arctic there are also large areas where the quality of the atmospheric composition observations is insufficiently quantified in metadata and access to the data are limited.

5.2.2 Ocean including sea ice

The development of operational oceanography over the past two decades has raised a request for easy and fast access to reliable, high-quality ocean in situ data. Over the past decades, Europe has spent huge resources in building central marine data management facilities (CMEMS INSTAC, EMODnet, SeaDataNet) to facilitate open and free data sharing to the benefit of the users and endorsing the FAIR principle.

Many organizations have an open and free data policy as well as a well-functioning data management system allowing them to make their data available in near-real-time. Surveys and data ingestion activities have however demonstrated that there exist large quantities of ocean data that are not freely available for various reasons:

- National or institutional data policies prevent sharing of data
    - Russia performs a detailed monitoring of the waters north of their Arctic coastline, but these data are not openly available
    - Some organisations follow a financial model that includes sales of observation data
- Lack of sufficient institutional data management structure and facilities, either because it is of low priority to top management or due to lack of resources
- Research projects often have a reservation on sharing data until they have been analysed and the results published, or the data have got a DOI. A recent survey carried out by the Copernicus In Situ Coordination Group showed out of 159 Arctic projects funded over the past 10-15 reporting in situ observing activity, only 50 projects (31,4%) have open and free data availability. There is therefore a need for funding agencies to require a free exchange of data along the FAIR principle using existing European data management infrastructures as part of the funding contract. A dedicated data ingestion effort is needed to open up these good and highly needed Arctic Ocean data resources.



Timeliness of data availability is another critical issue to address. For example, the data from fixed and mobile underwater platforms such as moorings and seafloor observatories (i.e., bottom-lander, benthic crawler) can only be obtained after retrieval of the instruments which typically operate for 1-2 years. Moreover, many ocean data are shared in delayed mode because data owners want to carry out their QA-procedure before releasing the data and this constitutes a problem for operational use of the data and can potentially also be a problem in reanalysis activities. It does however ensure that the released data are of high and documented quality.

Near-real-time transmission of data from the Arctic Ocean is challenged due to low capacity on the existing commination lines and further investments is needed improve this situation. Better communication capacity could for instance support near-real-time transmission of scientific data from research vessels and ships of opportunity as well as from moored oceanographic platforms carrying hydrographic and biogeochemical sensors.

There is a strong need for innovative technology developments focussing primarily on instrumentation that can operate under ice, e.g., optimisation of gliders, under-ice ARGO floats, etc. Additionally, the seasonal marginal ice zone is growing broader and none of the platforms we have today can survive there. This will be an increasing problem as the ice retreats and animal-borne observations should be encouraged. Customization of existing technology to Arctic conditions such as FerryBox systems on cruise ships, HF radars and sensors mounted on fishing gear could help filling existing observation gaps.

5.2.3 Land

For all greenhouse gas datasets from the Arctic domain, the time for data preparation should be reduced by possibly further automatizing data processing. This way, observations could be made available to the wider research community with only marginal time lags, so that the general public could be informed on e.g., extreme events within the Arctic, and their impact on greenhouse gas emissions, while the public attention is still high. Moreover, the documentation and publication of the data collection and processing should become publicly accessible in the near future.

Near-real-time snow observations are unavailable and quality assessment of in situ data is lacking. There is a lack of high-quality satellite products partly because of the lack of validation data. Generally, storage and documentation of in situ snow data should be improved.

Regarding improvements to the snow and ice surface mass **balance** data reported to the World Glacier Monitoring Service databases, we suggest that a mechanism is established that allows tracking the changes applied to the various versions of the databases. Under current conditions, if a researcher submits corrections to already available data, these corrections are applied to the database, but the database users would not notice the change that has been applied. While recognizing the difficulty of applying a track changes mechanism, we believe that it is a much-needed improvement.

Concerning Glacier Thickness data, in many cases there are echo-sounded glaciers whose data have not been reported to GlaThiDa, so the GlaThiDa working group should continue to encourage the research groups owning the data to make them available to the wider community (even if this happens after a few years of restricted use by the researchers of the data-collecting institution).

To improve the monitoring of the **seismic activity** in the Arctic region, there is need to:

- Keeping analytical resources at a high level at the national and international centres.
- Adoption of real time data exchange on an international level among the nations and researchers that conduct seismological monitoring in the Arctic region.
- Application of improved earthquake location techniques to the Arctic region.

The Arctic-HYCOS River discharge observation system can be improved through improved timeliness of the data, improved metadata including uncertainty characterization and supporting documentation, as well as publication of additional data such as the original water level measurements.

5.3 Sustainability

Uninterrupted, multi-decadal observations of the Arctic Region are critical to understanding the Arctic environmental system as a whole and managing its resources on which Indigenous Peoples and Local Communities lives and economies depend. Short-term national funding cycles challenge the continuity of environmental observations over the long term and make support of a new generation of the workforce, technology development, and the observation infrastructure vulnerable.

Sustained Arctic observations benefit many users and societal goals but could benefit many more. Such information is critical for using natural resources responsibly and sustainably as the Arctic becomes increasingly important to society. The contributions of many nations have resulted in basic Arctic observing networks. However, enhancement of the existing observation system has been constrained by flat funding and limited cooperation among present and potential actors.

Nations as well as the private sector are focusing on the Arctic Region for more resources and expanded uses. The Arctic community has recognized that understanding and adapting to climate change - with Arctic impacts ranging from increased temperatures, reduction in sea- and land ice and sea level rise to poleward shifts of valuable fisheries - will require additional monitoring of ecosystems and biogeochemical and physical properties. However, the drivers for sustained Arctic observations are much broader and the support developed to date for Arctic climate observations is insufficient to support the necessary sustained Arctic observing system.

For further planning it is important to have an overview of the sustainability of the existing observations system. In 2018 the Copernicus In Situ Component conducted a survey to map the source and sustainability of funding for ocean, meteorological and atmospheric composition in situ observations in Europe (Buch et al, 2019) i.e., not with a particular Arctic focus.

Organisations operating observation platforms within the three mentioned fields were invited to reply to a web-based questionnaire. In total 233 replies (91 for ocean, 122 for meteorology and 20 for atmospheric composition) were received, which formed the basis a detailed analysis. The number of replies for ocean and meteorology were satisfactory, while the number of replies for atmospheric composition was below expectations for which reason the analysis results are not as differentiated as for ocean and meteorology.

The analysis focussed on funding sources and sustainability of the funding. Regarding the funding source a summary is given in the table 5.1.

Table 5.1. Funding sources for in situ observations

Funding source	**Ocean**	**Meteo.**	**Atm. composition**
Institutional funds (annual budget)	28.6%	73.0%	45,0%
National research fund	15.4%	4.1%	
EU Research Funding	4.4%	0.8%	
Institutional funds (annual budget), National research fund	8.8%	5.7%	25.0%
Institutional funds (annual budget); EU Research Funding	3.3%	5.7%	
Institutional funds (annual budget); National research fund; EU Research Funding;	7.7%	0,8%	15.0%
Institutional funds (annual budget) + various combinations of external funding	9,9%	4.9%	15.0%
National research fund; EU Research Funding	7.7%	0.8%	
Various combinations of external funding	14.2%	4.2%	

The analysis shows clear and remarkable differences in funding for the ocean, meteorological and atmospheric composition communities: 73% of meteorological observations are funded purely by institutional core funds, for atmospheric composition the number is 45%, while for ocean observations this funding source only covers just above 28% of the expenses. The remaining part of the observation activity involves additional support from external funds such as research funds (national, EU) and other funds (EU, private) in various combinations.

Table 5.2. Funding sustainability

Funding sustainability	**Ocean**	**Meteo.**	**Atm. Composition**
Solved today, no problems foreseen in the future	28%	68%	30.0%
Solved today, but problems foreseen in 2-3 years	52%	27%	40.0%
No funding today, but plans for funding in the near future is under	7%	3%	
No funding today and no plans for funding in the near future way	9%	2%	30.0%
Other	4%		

A similar marked difference is displayed in the analysis of funding sustainability (table 5.2):

- 68% of meteorological observation networks have sustained funding; for the rest, 27% is subject to some uncertainty in the near future and only 2% of the networks seem to have severe problems.
- For ocean the picture is nearly opposite: 28 % of the networks have sustained funding, 52% face problems in the near future and 9% have severe problems.
- For atmospheric composition the situation is very similar to that of the ocean: 30% have funding sustainability, 40% have problems in the near future and, most worrisome, 30% have severe problems.

The conclusions from the funding sustainability survey and analysis of responses are:

- The relatively high degree of sustained institutional funding for meteorological in situ observations clearly reflects the way the meteorological community is organised via one national meteorological service with national responsibilities but also with clear international commitments to contribute to the global meteorological observation network under WMO.
- Only around 30% of ocean and atmospheric composition in situ observations have sustained institutional funding, while the remaining part is dependent on external funding primarily linked to research funds (national or EU) with the uncertainty and time limitation that this implies.
- The clear difference in the funding sustainability in the meteorological, ocean and atmospheric composition communities reflects the fact that the ocean and atmospheric composition communities – as opposed to the meteorological community- do not have the same national and international commitments to monitor the environment on a regular and operational basis, and a majority of their observations are linked to research activities. The ocean and atmospheric composition communities therefore need to take a different strategic approach towards a sustained in situ observation network than the meteorological community.
- Important components of future strategies towards sustained in situ observations will be regular mapping of user requirements, cost benefit analysis and national and international commitments, as well as free and open exchange of data.

The sustainability survey did not have an Arctic focus, but INTAROS analysis of present observing capacities and gaps in the Arctic (Ludwigsen et al, 2018; Tjernström et al, 2018; Zona et al, 2018 (INTAROS reports D2.1, D2.4, D2.7)) together with analysis performed by the Copernicus In Situ Team focusing on the availability of in situ data in the Arctic Region (Buch el al, 2019) indicates that the sustainability problems of Arctic in situ observation systems may be more pronounced than for the European systems. Especially meteorology gave reasons for concern since it is very expensive to maintain Arctic stations. Some of the stations are only visited every 2nd or 3rd year, and there is a risk that all data from these stations will be unavailable for a longer period. Such stations are often in regions with poor coverage. There is also a fear that stations in data-sparse regions will be closed because they are too expensive to maintain.

In the planning of a Sustained Arctic Observing System (SAOS) it will be important to:

- Intensify the international cooperation (nations, data providers, users) to emphasize the importance of and demand for sustained in situ observations and free exchange of data using the FAIR principles.
- Improve the Arctic coordination and governance structure for in situ observations, including requirement definition and system design, based on national and stakeholder interests to pave the way towards more efficient, fit-for-purpose and economically optimised SAOS.
- Work actively towards fostering and realizing international collaboration, innovation, sharing of observing platforms, infrastructure and systems. This will involve engagement with SAON, WMO, IOC/GOOS, GEO etc.
- Liaise with funding agencies and instrument manufactures to promote relevant observing technology and ensure data communication developments are included in future research calls and manufacturing business plans. The focus could be on multi-purpose and autonomous observing platforms.

6. Summary and conclusions

The ongoing changes in the global climate have resulted in increased focus on the Arctic region since it is warming at roughly twice the global average rate, with a dramatic reduction in summer sea ice extent as one of the clearest indicators of this trend. Physical and biological processes are being transformed across the entire region, while climate feedback mechanisms in the Arctic's changing atmospheric and oceanic dynamics impact at global scales. This substantial change in the Arctic environment opens the Arctic Region for development and increase in commercial activities and thereby also strong political attention. Climate change itself, combined with the related increase in commercial activities, puts severe pressure on existing professions, such as hunting, the life and culture of Indigenous Peoples and Local Communities, and on the vulnerable Arctic environment and ecosystems.

In order to secure responsible and sustainable development of the Arctic economy there is urgent need to call for a more coherent, integrated, fair and evidence-based approach to managing the economic development of the Arctic, balancing the desire to improve economic profit, human living standards and wellbeing with the imperative to sustain ecosystem health.

An evidence-based management approach and operational support to business activities must build on accurate and detailed information on the Arctic environment, but at present the knowledge and understanding of the environment of the Arctic Region is limited: critical physical processes are poorly understood, ecosystems remain unstudied and undiscovered, and voices of Indigenous Peoples and Local Communities go generally unheard. This lack of knowledge makes it impossible to detect, predict or manage the interrelated physical, biological and social impacts of climate change whereby sustainable development strategies are almost impossible to implement.

Increased knowledge and understanding of the Arctic environment and ecosystems and their subsequent monitoring and management must build on a coordinated and Sustained Arctic Observing System including both remotely sensed and in situ observations. The first step towards building such an observing system is to establish evidence-based requirements for observations of essential variables (spatiotemporal resolution, quality, timeliness) taking into account logistical and economic feasibility.

Early in the INTAROS project requirements for an Arctic Observation System were addressed giving a comprehensive analysis of phenomena to focus on, requirements in general terms, essential variables and existing observing technology. The aim of this Revised Requirement Report has primarily been to:

- Take note of recently articulated user need from EU and international organisations
- Capitalise on INTAROS achievements
- Define more concrete requirements for the identified essential variables
- Address gaps in the present observing system

Some communities – EU Copernicus Programme, WMO, IOC – work on formulating concrete requirements for in situ observations in a global perspective, i.e., not with a particular Arctic focus, while other communities express the importance of their needs for observational data in more general terms.

The INTAROS project and the Copernicus In Situ Group has in recent years performed a detailed analysis of existing in situ observations in the Arctic and, by comparing these to a "global" set of requirements, the most important gaps in the Arctic observing system have been identified. INTAROS has actively contributed to filling some of these gaps. These analyses have formed a good basis for the requirement considerations presented in this report.

Requirements for in situ observations address resolution in space and time, quality and timeliness. Users of data generally have clearly articulated needs for time resolution, quality and timeliness, while defining the spatial resolution gives rise to serious considerations because:

- There is a need to find a balance between what would be "nice to have" and what is feasible to achieve from a technical, logistical and especially economical point of view
- There is still a debate among scientists on how to address spatial resolution:
    - A gridded format with fixed horizontal and vertical distances between observation points
    - Identifying key locations with great impact and representativeness

It is therefore important to continue a constructive dialog between the user and observing community to find ways to address spatial resolution for an Arctic Observing System in a way that accommodates the needs for data for:

- achieving knowledge of the Arctic environment
- assimilation into and validation of models
- validation and calibration of satellite observations

The outcome shall be rigorously substantiated, and feasible to implement and sustain technically, logistically and economically.

The INTAROS community has in the present report taken as a starting point the requirements articulated by the WMO OSCAR and Copernicus Systems – both using a gridded approach – and used them as a baseline for a critical review, which points to:

- For the Arctic Ocean atmosphere, a new paradigm is necessary. A sustainable pan-Arctic observation network must be based on a core set of satellite data, but for comprehensive information and for Arctic weather forecasting, data assimilation of all available observations into sufficiently accurate models is key. To evaluate the results and to improve models and observations, in situ super-sites, including science expeditions to the Arctic Ocean are imperative. This trinity (satellite and extensive in situ observations along with modelling) is the key to an Arctic observing system.
- Observations of snow properties would benefit greatly from coordination with other land-based observing system, e.g., the WMO/GOS network of weather observations and the quality of observations from land-based observatories could be greatly enhanced by a coordination of instruments and calibrations, especially in Russia. The CryoNet network recently established by Global Cryosphere Watch will serve this purpose, if national institutes that manage the observation infrastructures commit to following the recommendations and adhere to the measurement, data management and metadata protocols.

A gap analysis has been performed by comparing requirements with the existing observation system. Taking into account that the spatial resolution requirements are still open for discussion, the following conclusions are highlighted:

- In situ observations are very sparse in the central Arctic
- Existing observation programs often are time-limited research or national observation initiatives generally meeting specific scientific or national priorities and thereby lack international coordination
- Due to lack of good communication facilities many data are delivered in delayed mode thus being untimely for particularly NRT productions.
- Other data, e.g., research data, are made publicly available too late to be available even for interim reanalysis purposes, i.e., there is a need for internationally agreed standards for timely delivery delayed mode data taking into account scientists' right to publish.
- The Arctic environment puts high demands on robust technology and there is a general demand to pursue innovative technology development
- Insufficient data management structures at data producer level constitutes a big problem which negatively affects:
  - Formats of data and metadata
  - Accessibility
  - Timely delivery
  - Quality documentation
- Access to Russian data is extremely limited and calls for a dedicated action to free more critical observations in cooperation with Russian authorities

The requirement and gap analysis results in the following recommendations:

- Ensure work towards a robustly substantiated definition of spatial resolution in an Arctic observing system, involving analytic tools such as numerical models (OSEs and OSSEs), cost and feasibility studies
- Establish an international coordination and governance structure involving nations, SAON, WMO, IOC, EU Copernicus, Indigenous people organizations to:
  - Ensure a forum for dialogue between users of Arctic information, observation program leaders and sensor and application developers to understand evolving needs and capacities
  - Secure long-term coordination and continuation of measurements
  - Ensure sustained funding for a fit-for-purpose Arctic Observing System
  - Enhance and optimize multidisciplinary observations
  - Ensure open and free real time data exchange following the FAIR principle
  - Increase involvement of indigenous people in data collection and data integration
  - Promote training and teaching as a key value and basis for capacity building
- Initiate data rescue activities to ingest existing data presently not freely available, incl. Russian data

- Pursue innovative cost-effective technological solutions for Arctic observations securing continuous NRT data flow from this harsh environment also during wintertime

The INTAROS experiences with Arctic CBM programs suggest that connecting CBM programs and scientist-executed observing approaches leads to *improved information products* and *enhanced efficiency and sustainability* of observing programs (Deliverable 4.1). Moreover, it can promote stronger linkages between environmental monitoring programs and government decision-making processes.

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