Integrated Arctic Observation System

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Synthesis of gap analysis and exploitation of the existing Arctic observing systems

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20	UPM	*x*	**43**	NMEFC	
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EXECUTIVE SUMMARY

This report presents a synthesis of the substantial assessment of Arctic observations within INTAROS. Since the assessed systems mainly belong to the European partners in the project, the assessment is unavoidably biased towards the European sector of the Arctic. The detailed results of the assessment can be found in previous deliverables (D2.1, D2.2, D2.4, D2.5, D2.7, D2.8 and D2.12). Also some higher-level recommendations for future improvements of Arctic observing are taken into account. The assessment addresses a substantial subset of Arctic observing systems, data collections and satellite products across scientific disciplines, also including some data repositories and a brief scientific gap analysis. In the assessment we analysed sustainability, including funding, technical maturity and data handling for the entire chain from observation to users, including metadata procedures and availability of data. The gap analysis includes both technical characteristics, such as spatial and temporal coverage and resolution or accuracy, and a smaller set of scientific gap analyses where models and observations were used synergistically.

Each characteristic of the observing systems were ranked from maturity 1 (lowest score) to maturity 6 (highest score) based on the results of the survey. In the synthesis we first ranked the systems according to general sustainability and then other characteristics were used. The range in maturity of sustainability varied from 1 to 6, and so did the other characteristics. A noteworthy result was that that systems with high sustainability scores tended to score high also on other characteristics, such as data handling and technical maturity. Moreover, many systems with high maturity in sustainability, as well as in data handling and data availability, are supported by national or international monitoring or infrastructure programs. It is also noteworthy that several of these are mostly present at mid-latitudes, but poorly represented in the Arctic.

For observations over Arctic land, the quality of some existing systems would benefit from being enhanced by new instruments or improved methods. As example, adequate observing of snow properties is problematic due to the high spatial variability of snow cover. While this also applies to hydrological observations, the situation improves as a result of large overarching international programmes. Observations of aerosols and some trace gases are also lacking in some specific regions. For the Arctic Ocean there is a lack of in-situ observing systems across all disciplines, which is connected to limited infrastructure provided by ships, icebreakers, and various types of autonomous observing platforms operating on sea ice with capacity to transfer data in near real-time. Subsurface observing systems such as bottom-anchored moorings and sea floor installations are robust and can operate autonomously over several year, but the data can only be delivered in delayed mode. In the atmosphere, icebreaker-based summer science expeditions provide the only reliable information on atmospheric vertical structure. While scientific expeditions likely provide the highest quality observations available for the Arctic Ocean region, the scores for almost all other aspects, sustainability as well as for data handling, in general and especially for atmospheric observations are among the lowest for vessel-based observations.

Satellite observations provide the only possibility to obtain data with sufficient spatial and temporal coverage as well as resolution. Satellite data products have generally high score on data handling aspects, but for some data products the score on quality and uncertainty estimation is low. While retrieved temperature, and to a lesser extent, humidity at levels in the atmosphere is generally adequate for monitoring, satellite profiling of the atmosphere suffers from significant

and seasonally varying biases and errors. Passive satellite sensing of clouds is also problematic; while some bulk products, such as cloud fraction, are useful during the sunlit season, more precise information, such as liquid water path, has high uncertainty as indicated by comparing different retrievals from the same set of sensors. In the dark season, when visible radiation channels vanish, most satellite cloud products are very unreliable. Regarding sea ice observations, there is significant uncertainty in the estimation of thickness and snow layer. There is also uncertainty in ice concentration in the summer season with melt-ponds on top of the ice.

Traditionally, observation network assessments build on the network concept with a "comprehensive" level including all observations, a "baseline" level of an agreed subset of sustained observations, and a "reference" level, with observations adhering to specific calibrations and traceability criteria. An atmospheric example is the "comprehensive" global GCOS radiosounding network, and the "baseline" GUAN (GCOS Upper Air Network) and "reference" GRUAN (GCOS Reference Upper Air Network) networks. With the lack of in-situ observations and the logistical difficulties to deploy new stations, this concept does not work well in the marine part of the Arctic.

In summary, we recommend to

- *Advance Arctic observing systems under national, international or regional programs that provide more sustainable funding than short-term research projects*
- *Coordinate better between operational monitoring systems and research-funded observations, since both systems often use the same data and will have mutual benefit of collaboration*
- *Improve the utilization of existing infrastructures on land and sea for more cost-effective collection of in situ data across multiple disciplines*
- *Deploy more autonomous observing platforms in the sea ice areas for year-round operation and implement data collection from all types of ships operating in the Arctic ocean*
- *Enhance the observing system on existing stations, including supersites, by use of new sensors and methods to validate satellite observations and support modelling and forecasting systems*
- *Improve the exploitation of satellite data and coordinate better in situ and satellite observations for use in data assimilation, modelling and reanalyses*
- *Clarify roles and responsibilities between data producers and managers and establish adequate funding mechanisms to support a functional data management system for multidisciplinary Arctic data.*

The reviewer's comments are not included in the present version, but will be taken into account in the follow-up publications and in the Roadmap document (D1.10) to be developed until the end of the project.

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1. Introduction

This report includes a synthesis of the assessment and exploitation of the existing Arctic observing systems done in the INTAROS WP2. It is, therefore, based on the previous deliverables D2.1 and D2.2 for the ocean and sea ice (Ludvigsen et al, 2018; Sagen et al., 2018), D2.4 and D2.5 for the atmosphere (Tjernström et al., 2018; Asmi et al., 2018), and D2.7 and D2.8 for the land and terrestrial cryosphere (Zona et al., 2018; Ahlstrøm et al., 2018). The analyses carried out in these previous deliverables were, in turn, based on the responses from INTAROS partners to a set of questionnaires. The survey addresses Arctic in-situ and satellite-based observations of the ocean, atmosphere and terrestrial parameters retrieved through established networks and observing systems as well as individual measurement campaigns and projects.

The synthesis presented here also accounts for the outcome of the deliverable D2.12, which explored some observational gaps revealed by model sensitivity to observations. An overview of the data repositories used by the INTAROS partners and of the services offered to data providers and data users is also given. Finally, the conclusions and the recommendations on how to potentially fill the observational gaps are given combining the academic research-based and community-based knowledge and observations, the latter assessed in WP4 and presented in deliverable D4.1.

1.1 Background, motivation and objectives of the work

The Arctic atmosphere is warming at a rate about double the global average (Zhang et al. 2005) causing an accelerating melt of the cryosphere comprised of sea ice, glaciers, ice sheets and permafrost. The melting ice has profound implications for infrastructures and access to the Arctic and the access to the living and non-living resources in the region. At the same time, the Arctic hosts unique ecosystems that both EU and Arctic Council members have agreed to safeguard. Ensuring a knowledge-driven strategy for sustainable development of the region under rapid climate changes requires availability of multidisciplinary data, analyzed and synthesized for decision makers. Such an information and decision-support system is largely absent for most Arctic areas.

However, the impact of Arctic change reaches outside of the region. Melting of the Greenland ice sheet contributes to global sea level rise, thawing permafrost could contribute vast amounts of greenhouse gases to the atmosphere, and potential changes in the deep water formation in the Greenland and Labrador Seas could have implications for global ocean circulation. Some evidence also suggests that Arctic warming and related sea ice decline may affect northern hemisphere mid-latitude weather and climate. However, multiple forcing factors acting simultaneously in a chaotic dynamical system makes the Arctic effects on mid-latitudes inconsistent, episodic, non-linear and hard to distinguish from other effects (Overland et al., 2016).

The societal capacity to adapt to and mitigate these changes depends on our understanding of the Arctic. Management and planning of human activities in the Arctic, and in regions mostly affected by Arctic climate change, depend on understanding of Arctic-specific physical, chemical, and biological processes that can only arise from observations. However, the Arctic is largely inaccessible, and *in-situ* observations are scarce and rarely sustained. The international effort to monitor components of the Arctic ecosystem from *in-situ* and remote sensing platforms is largely uncoordinated, except in frameworks of specific projects and for limited regions. Observations are stored in scattered data repositories, many of which are not

openly accessible or searchable. Hence, a pre-requisite for optimization and enhancement of an Arctic observing system is identification of strengths and gaps in the current set of observing systems, highlighted in the Call to Action launched during the Arctic Observing Summit 2018 (https://cdm.ucalgary.ca/index.php/arctic/article/download/67781/51677).
The work carried out in INTAROS WP2 and synthetized in this report had, as objectives, to assess, exploit, and standardize observations from the existing Arctic observing systems to enable established databases to deliver *in situ* and remote-sensing data and products to a multidisciplinary, integrated Arctic Observing System (iAOS). Specific objectives were:

- Analyze strengths, weaknesses, temporal and spatial coverage gaps, and missing parameters from existing observation networks and databases;
- Exploit selected datasets to increase the quality and number of data products;
- Enhance standardization of data and metadata to ensure that best practices are followed, and to integrate sparse *in-situ* data into established networks, preparing their delivery to the iAOS.

To reach these objectives, extensive information on selected Arctic observations systems were collected through a survey comprising three questionnaires addressing *in-situ* observing systems (questionnaire A), *in-situ* data collections (questionnaire B) and satellite products (questionnaire C). The survey also included an evaluation of the maturity of various aspects of the addressed Arctic data and observing systems, as well as information on the utilized data repositories and associated services (such as access, search, authentication). The answers to these questionnaires provided the foundation for the assessments carried out in the previous deliverables D2.1, D2.2, D2.4, D2.5, D2.7, and D2.8, which are here synthetized.

This report is complementary to the companion report D2.11 on the “Maturity of the existing Arctic in-situ observing systems”. In D2.11 maturity scores on sustainability and data management of the *in-situ* observing systems, and on uncertainty handling, metadata, and documentation of selected data collections belonging to the assessed observing systems are discussed. This discussion follows the approach suggested by the H2020 GAIA-CLIM project, where the observing systems were categorized in a hierarchical structure as reference, baseline, or comprehensive system[1] depending on their maturity classification. Here, only a synthesis of that discussion is reported, and inserted in a more general evaluation of the *in-situ* and satellite-based data and observing infrastructures. The results highlight main gaps of the observing systems and recommendations are provided on how to fill those gaps.

1.2 Addressed data

The results presented in this report are based on the *in-situ* observing systems and satellite products evaluated by the partners of the INTAROS consortium. The analysis focuses on the European observational capacities, particularly on the existing Arctic observational data that

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[1] According to Thorne et al. (2017) and deliverable D2.11:

- **Reference-observing networks** provide metrologically traceable observations, with quantified uncertainty, at a limited number of locations and/or for a limited number of observing platforms, for which traceability has been attained.

- **Baseline-observing networks** provide long-term records that are capable of characterising regional, hemispheric and global-scale features. They lack the absolute traceability of reference observations.

- **Comprehensive-observing networks** provide high spatiotemporal density data information necessary for characterising local and regional features.

are anticipated to be most relevant for the ongoing INTAROS applications targeted toward selected users.

This assessment addresses observations of the ocean, atmosphere, cryosphere and land including physical, chemical, biogeochemical and biological parameters. Most of the assessed observations have been collected or are used by the INTAROS partners. Therefore, some important data are not included in the assessment. The most important Arctic data and/or observing systems not included in the assessment are listed in Appendix A.

In order to proceed with a systematic and consistent analysis across different disciplines and spheres, it was necessary to formulate a clear and unambiguous definition of the targeted *in-situ* observing systems and data collections. Below are the adopted definitions used in the previous deliverables D2.1, D2.4, and D2.7.

*An **in-situ observing system** consists of a data collection component (infrastructure) and a data management component (e-infrastructure).*

- *The data collection component is comprised of multiple sensors either belonging to a common fixed platform (such as cabled system, sea floor installation, mooring), which can be a single unit or a collection of units forming a network, or installed on a non-stationary platform (ship, aircraft, gliders, floats, ice buoys). The data collection component stores the datasets internally or transmits them to the data management component.*
- *The data management component includes hardware and software for data repository, data processing, discovery and visualization services. The management can be centralized in a single institution or distributed among several national institutions, which have agreed on common standards for the data and metadata formats, documentation and management.*

An observing system can be multidisciplinary or focused on a specific discipline, and it serves a clearly identified scientific or operational purpose.

There are many types of observing systems, reflecting a large variety in technical solutions, different maturity and organizational levels of the *in-situ* measurements. For the atmosphere there are several mature observing systems, such as international networks that follow standardized data managements. In the marine sphere observations are more diversified and fragmented, providing more types of data with various degree of standardization. The marine observing systems are usually identified based on the utilized platforms (e.g. moorings, floats, gliders), in line with the classification of global observing systems made in the GCOS 2016 Implementation Plan (GCOS, 2016).

*An **in-situ data collection** is defined as a collection of data, or measurement series, that have common characteristics in terms of quality, resolution, and coverage. In most cases, the observation platform and its instrumentation determine the characteristics of the collection.*

The instruments applied to collect the observations range from manual tools to fully automatized sensors, while the observation platform can be moving, drifting or fixed. Thus, a data collection generally includes all the variables measured with a single instrument. *In-situ* data collections may also include derived data products, which result from processing of individual measurements or composition of multiple measurements. *In-situ* data collections can be surface-, subsurface-, and air-borne. In general, each addressed *in-situ* data collection belongs to an observing system, but in some cases data collections were created from the merging of data produced by several different observing systems.

We addressed different kinds of *in-situ* data collections:

- *Data from established in-situ networks, having regional spatial coverage and variable temporal coverage*
- *Data from single stations, having local areal coverage and variable temporal coverage*
- *Data from field campaigns (ship-, aircraft-, UAV-based), with limited temporal coverage and from point to regional spatial coverage*

Concerning satellite observations, their spatial coverage depends on orbital configuration and sensor design. Polar orbiting satellites cover the Arctic region well (see e.g. NASA EOS satellite constellation and ESA Sentinel constellation) while geostationary satellites do not cover the latitudes above 81 degrees (see e.g. NASA GOES Satellite Network and ESA METEOSAT). Another issue is conflicting data collection modes of a satellite instrument, where prioritization has to be made. For instance, optimizing for sea ice or land ice in the important coastal zone has been a problem for radar remote sensing. Compared to *in-situ* observations, the spatial coverage of satellite observations is more uniform and extensive, yet limited to atmospheric, terrestrial, and cryospheric variables (i.e. they cannot sense the deep ocean). While a few satellites target Arctic- or polar-specific features, such as sea ice, they are used globally, which is another source optimization discussion.

In the previous INTAROS assessment reports D2.1, D2.4, and D2.7, a thorough analysis of the selected *in-situ* observing systems, *in-situ* data collection, and satellite products was carried out to untangle their variety in structure and organization. The results summarized here offer an overview of the key problems in the observing system as a whole and in its peculiar components, either located in the continent or in the marine Arctic.

Although the results are based on a limited selection of observing systems, they are generally valid, highlighting issues and deficiencies that are also common to observing systems not directly addressed in INTAROS. To continue and expand the assessment, the ArcticMap project was funded by the Norwegian Directorate for Environment and Climate (2018-2020) as a spin-off of INTAROS WP2. Under ArcticMap the assessment survey will be automatized, made more robust, and designed so that the answers will feed directly into a dynamic, web-based, openly accessible database. This will enable the inclusion of the Arctic data and observing systems that were not addressed in this report or will be established in coming years. Through the database of assessed observing systems, it will be possible to follow the evolution of the Arctic observing "system of systems" and to demonstrate the benefits (in terms of gap closure) of the enhancements and expansions of the observing systems.

1.3 Requirements applied to assess the observational gaps

Each observing system has constraints from technical, practical, economical, and political reasons, affecting the degree in which it can achieve its goals. The gaps of the existing Arctic observing system were identified on the basis of the difference between the performance of the systems and their requirements. For spatial and temporal coverage, requirements were determined with respect to the scientific and/or monitoring purposes of the specific systems. This means that, for instance, a ship-based field campaign designed to observe specific physical or biogeochemical processes is assessed with respect to the spatial and temporal coverage required to achieve the objectives of the campaign. Concerning sustainability, data management, metadata, documentation, and uncertainty characterization, the gaps in maturity were assessed using the maturity criteria developed in the EU projects CORE-CLIMAX (Schulz et al., 2015) and GAIA-CLIM (Thorne et al., 2017). An observing system is characterized by its data management. Hence, maturity in data management and sustainability were assessed for each observing system as a whole. However, some systems include instruments with different complexity and technological readiness, which impose different challenges in uncertainty characterization and documentation. Therefore, to gain a more precise characterization of the system's maturity, metadata, documentation, and uncertainty characterization were separately assessed for selected data collections of the observing systems. This synthesis report will not describe these details (see D2.1, D2.4, and D2.7 for details); the purpose of this report is to extract the key results obtained from the extensive assessment.

When addressing gaps in temporal and spatial coverage and resolution, timeliness, and accuracy of the satellite products and *in-situ* data collections, requirements from the WMO OSCAR-database (https://www.wmo-sat.info/oscar/requirements), Copernicus *In-situ* Component Information System (not yet published), and the POLARIS Gap and Impact Analysis Report (https://www.arcticobserving.org/images/pdf/Board_meetings/2016_Fairbanks/16_Final-Gaps-andImpact-Report---2016-04-22.pdf; prepared for the European Space Agency in 2016) were adopted. These requirements are suited for satellite products, modelling products (such as reanalyses) and for gridded combined *in-situ* products. However, they are not directly applicable to assess *in-situ* data collections that have limited spatial coverage. For these data collections, the same requirements as identified for the *in-situ* observing systems were applied.

1.4 Subdivisions of the assessed observing systems and organization of the report

Observations are performed in different spheres, from different platforms, and for several different purposes. In this report, we consider three meaningful subdivisions of the assessed observing systems.

First, is data collected either in-situ or by *satellite* remote sensing. A special category of observations is so-called supersites[2], where surface-based remote sensing is often a key component (in the case of land-based and ice-sheet-based sites). For the purposes of this report we will consider these as in-situ observations. Contrary to satellite observations, surface-based remote sensing of atmospheric, surface or land properties is typically performed at single locations, capturing a column, single-layer or a vertically-integrated value of some property. For example, the data from a vertically-pointing cloud radar, is principally similar to that of data from a radiosounding, although one is using remote sensing via backscatter of electromagnetic radiation, while the other is based on a probe that sent up by a balloon and senses the environment truly *in situ*.

A second subdivision is according to the use of the data, the application area(s). Often there is considerable overlap between these. Figure 1 illustrates the number of *in-situ* observing systems (a) and of satellite products (b) divided by application category according to the results of the assessment. Note that the total number adds up to more than the sum of the assessed observing systems, reflecting this overlap. Figure 1 reveals that more than half of the assessed observing systems and satellite products have research or monitoring applications (i.e. are not directly associated with services). Among the service-oriented applications, it is worth noting that

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[2] According to the definition of «Geohazard Permanent Supersites» (https://geo-gsnl.org/supersites/permanent-supersites/), «supersites» are such a sites that either have a high representativeness of a specific environment or collect a comprehensive set of multidisciplinary variables. They rely on permanent, sustained infrastructure and have (or plan to have) data infrastructures providing open access to data acquired by in-situ and satellite Earth observing systems. A single supersite can belong to several thematic networks (e.g. Sodankylä-Pallas station belongs to GOS, GAW, ICOS, ACTRIS, Cryonet), generally encompasses an area greater than a conventional observing platform and is comprised of more than one active measuring platforms with varying capabilities that are operated as a coordinated unit.

climate services so far still mostly rely on *in-situ* data. This is directly related to the necessary length of such time series. Long-term measuring stations can provide sufficient length, while time series based on satellite observations are just beginning to reach the temporal length needed for climate applications in some cases. However, for climate monitoring, the length of satellite time series remains problematic, although in some cases, such as sea ice extent monitoring, four decades of continuous data are now available. Also, climate relevant time series from satellites usually require overlapping multi-satellite programs, since the longevity of any given satellite is limited. Moreover, satellite information is mostly limited to observations at and above the Earth's surface. Nevertheless, satellite observations will play an increasingly important role in Arctic observing systems because they cover the whole Arctic regularly throughout the year, with a number of atmospheric, ocean and sea ice variables are provided daily in near-realtime in support of operational monitoring and forecasting services. However, it must be recalled that satellites rarely measure the variable wanted; satellites measure radiative properties which is converted to the variables needed by a retrieval, although some atmospheric data assimilation systems use the radiation directly and hence in a sense use a numerical model to produce these variables. Therefore, common for satellite observing systems is the need for in situ data to develop retrieval algorithms and evaluate the data products.

For *in-situ* observations, the third sub-division we consider is that between the terrestrial and marine Arctic. This sub-division is necessary for atmospheric observations, because essentially no infrastructure for atmospheric *in-situ* observations is available over the Arctic Ocean, except those associated with ship-borne scientific expeditions and satellite systems. This is due to the drifting perennial sea ice prohibiting deployment of permanent observing systems. As a consequence, a synthesis based on a set of comprehensive, baseline and reference observations, as is typical for other regions of the Earth, is rendered useless for the atmosphere over the Arctic Ocean. This also provides limited foundation for assessment of satellite observations over the Arctic Ocean and hence the entire Arctic Ocean becomes a white area on the observation-coverage map, with no traceable reference observations. The only remedy is to include data from ship-borne field experiments in the assessment. These experiments are based on icebreaking vessels and mainly take place in the late summer and early autumn months. As will be seen, data from these experiments have some special characteristics when it comes to maturity and sustainability, but are nevertheless very important to the overall integrated Arctic Observing System. Concerning sustainability, marine and sea-ice observations in the Arctic Ocean, with few exceptions, have commonalities with atmospheric observations. Land-based observations, on the other hand, can rely on permanent stations that, in many respects, have characteristics and maturity similar to the atmospheric terrestrial networks. Observations made from station based on ice sheets are somewhere in between, as they "float" on the ice that moves and changes in elevation.

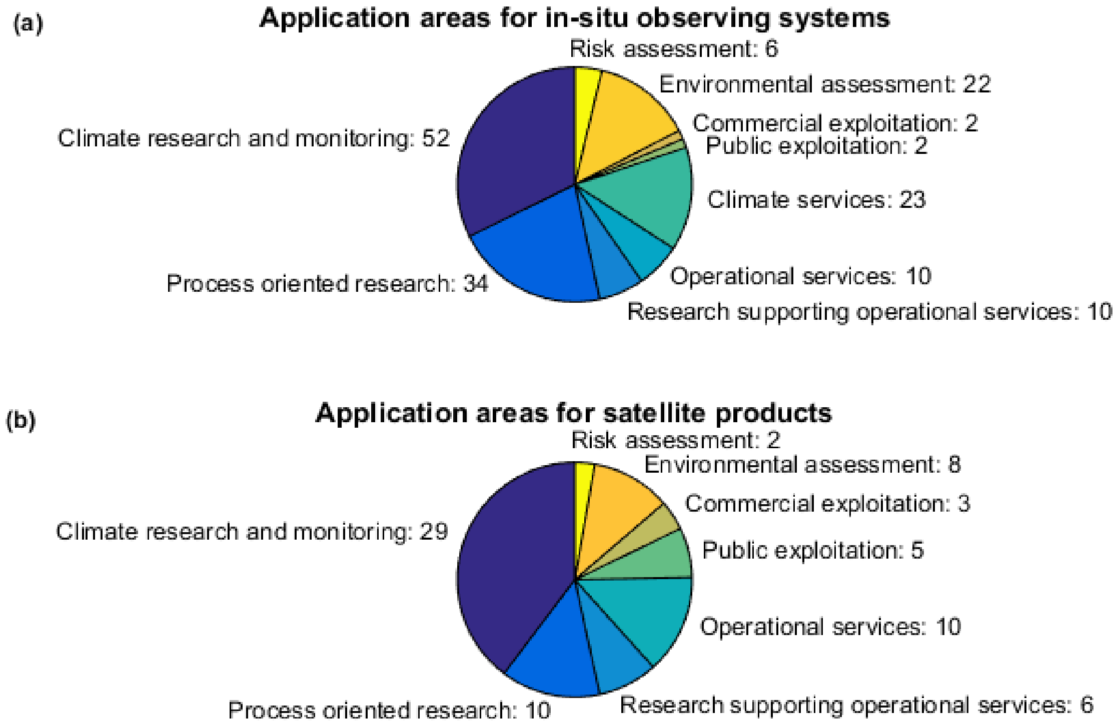

Figure 1. Application areas of the assessed *in-situ* observing systems (a) and satellite products (b), and number of observing systems/satellite products per application area. Note that each observing system/satellite product may have more than one application area.

The report is organized as follows: in Chapter 2 the synthesis of the assessment of selected in-situ observing systems is presented. After discussing temporal coverage and funding support, considerations on the maturity of the observing systems and their data collections are provided separately for the terrestrial and marine Arctic. In Chapter 3 considerations on the evaluated satellite products are presented separately for the three spheres (atmosphere, ocean and sea ice, land and terrestrial cryosphere). In Chapter 4 some observational gaps revealed by model sensitivities to observations are highlighted. Chapter 5 includes an overview of the data repositories utilized by the assessed observing systems, with considerations of some of the provided services (data discovery, access, and user authentication). Conclusions are provided in Chapter 6, and summary and recommendations in Chapter 7. More detailed recommendations for each group of addressed variables are provided in Appendix B.

2. In-situ observing systems

A list of the assessed *in-situ* observing systems is provided in Table 1 for the terrestrial Arctic, and Table 2 for the marine Arctic. Comparing the terrestrial systems (Table 1) and the marine systems (Table 2), the first are dominated by fixed stations, the second by vessels and moored arrays. The platforms utilized by the observing systems to a large degree determine the temporal resolution and length of the data records. Fixed infrastructure, such as towers (over land) or moorings (in the ocean), covers all seasons and provides longer time series, while moving platforms, such as ships and aircrafts are generally utilized during campaigns for short durations, mostly in summer or early autumn when access to the Arctic is easier. Ice-based buoys, floats and gliders, having variable lifetime from single months to over a year (including seasonal cycle) are somewhere in between in terms of temporal coverage.

The assessed observing systems in the terrestrial Arctic (Table 1) include thematic networks that cover large regions as well as single supersites that, with their comprehensive set of observations, are crucial for the validation of models and remote sensing products and belong to different thematic networks. Moreover, aircraft observations and observing systems based on the repeated observation points on glaciers are also included. Among land-based observing systems (Table 1), those that have been established most recently, and thus have the shortest temporal duration, are European Research Infrastructures (RI) ACTRIS (Aerosol, Clouds and Trace Gases Research Infrastructure) and ICOS (Integrated Carbon Observing System). Stations belonging to those networks may be much older, with data records extend for decades in the past, but the management, structure, and organization of the networks according to the criteria of European RI have been established only recently. Long-term observations are also prevalent from international networks (such as Global Atmosphere Watch - GAW or Global Observing System - GOS) and from some targeted networks, such as the Programme for Monitoring the Greenland icesheet – PROMICE. Further description of the land-based systems is presented in section 2.2.1.

The marine systems presented in Table 2 use primarily research vessels as the basic platforms for the observing systems. Data collection is performed by instruments operated directly from ships or from autonomous platforms deployed (and recovered) by ships. Direct ship observations can be part of a time-limited research project or it can be part of a monitoring programme where data are collected repeatedly according to a long-term plan. Autonomous marine platforms play an increasingly important role in ocean observing systems. They include fixed platforms anchored to the seafloor or drifting platforms at the surface or in the deep water. The global Argo programme is based on deployment of profiling buoys that can operate for a year or longer, sending data via satellites to the users. Argo buoys are not yet used in the ice-covered Arctic Ocean, but are used operationally in sub-Arctic areas such as the Norwegian-Greenland Sea and Baffin Bay. In the ice covered areas, the International Arctic Buoy Programme (IABP) has been coordinating operation and data distribution from autonomous buoys deployed on sea ice by aircraft drops. These ice buoys have been collecting surface and subsurface data in the Central Arctic Ocean since the early 1990s. Several national programmes have been developed from research programmes to observing systems with long-term perspective and possibilities for sustainable funding. Examples are the FRAM programme operated by the Alfred Wegener Institute Helmholtz Centre for Polar and Marine Research (AWI) and the Greenland Ecosystem Monitoring Program collecting terrestrial, limnic and marine data, and is operated by Aarhus University. Further description of the marine systems is presented in section 2.2.2.

The map in Figure 2 shows the locations of the addressed observing systems,. Areas enclosed by polygons correspond to observing systems either based on moving platforms (ships, buoys, airplanes) or including thousands of measurement points (such as glacier observations). Points, symbols, and polygons in the map correspond to the location of observing platforms that differ greatly in number of measured variables and site representativeness. Moreover, several multidisciplinary land stations and ship programs (marked in the map with pentagon, square, and star depending on which sphere they cover) serve more than one observing system. The map clearly shows that the assessed *in-situ* observing systems cover the Atlantic sector of the Arctic well, while the Pacific sector and the marine areas far from European waters are less well covered. In the atmospheric and terrestrial domains, the assessed *in-situ* terrestrial observations have a pan-Arctic coverage. Although there are *in-situ* atmospheric observations in the marine Arctic, it is important to realize that they are only based on sporadic field campaigns with typical durations of just one or two months each. In the ocean and sea-ice domains only the Atlantic sector is reasonably well covered by the assessed observing systems. This mainly results from limiting the assessment to European systems operated mostly in the Atlantic sector of the Arctic Ocean. A wide range of observing networks in the Western Arctic, or generally non-European systems in the central Arctic Ocean, were not addressed and should be included in future extensions of the assessment.

A schematic account of the gaps in the present Arctic in situ observing systems revealed by the INTAROS assessment is given in Appendix B for each group of variables. In the following sections 2.1 and 2.2, a reasoned synthesis of the assessment is provided for the terrestrial and marine Arctic, respectively.

2.1. Terrestrial Arctic

2.1.1 Assessment of atmospheric in-situ observing systems

Over the terrestrial Arctic, the main gaps in the spatial coverage of atmospheric variables measured by in situ observing systems concern atmospheric composition and clouds properties, both requiring more sophisticated instruments (mainly ground-based remote sensing) compared to the traditionally variables assimilated into the operational forecast models. These variables are not only essential for validation of models and satellite products, but real-time aerosol observations are also increasingly used as input in atmospheric pollution forecast models.

A compact synthesis of the maturity in sustainability and data handling and documentation is presented in Table 3 for the assessed observing systems in the terrestrial Arctic. The six maturity levels used in survey are compressed into three levels: low maturity (scores 1-2), medium maturity (scores 3-4), and high maturity (scores 5-6). The different observing systems, also shown in Table 1, were first ranked according to broad sustainability (top to bottom) and then the scores in the other data characteristics were subsequently considered. The score in sustainability was given mostly based on the score in funding support, while the score in data uncertainty handling, metadata, and documentation were roughly an average of the scores given for the various assessed aspects of each category. The observing systems that reached the same scores were grouped into the same row to help to identify common features or issues among different observing systems. It is important to realize that the observing systems as a whole were assessed with respect to sustainability and data management, but only selected data collections of the observing systems were assessed with respect to uncertainty handling, metadata, and documentation. The selected data collections for each observing system are described in the previous deliverables mentioned above.

Table 1. List of the assessed observing systems in the terrestrial Arctic, their type of platform (in the following order: aircraft, land stations, ice sheet stations, glacier measurement points, land stations including an ocean component), sphere (A=atmosphere, T = land and terrestrial cryosphere), geographical coverage, and temporal coverage: spring period in pink, summer period in orange, all year in grey, and irregular in green. In the column "Start before 2008", the starting year of the system is marked only when it was before 2008. When stations, platforms, or components of the system started to operate at different years, the year when the first component of the system started is marked. Multi-disciplinary systems are marked in bold: two of them cover also the ocean sphere (O = ocean). In case of global networks, only the Arctic portion of them is reported and assessed.

Observing systems in the terrestrial Arctic	Platform	Sphere	Geographical coverage	Start before 2008	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
Airborne obs. of surface-atmosphere fluxes	Aircraft	A, T	Alaska, Canada, Siberia						🟧	🟧	🟧		🟧		
ACTRIS[1]	Land stations	A	European Arctic: 2 sites								▨	▨	▨	▨	▨
Arctic-HYCOS[2]	Land stations	T	More than 1000 sites in the Arctic drainage basin	**1887-**	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Fluxnet[3]	Land stations	T	2 sites, Russia (Cherski, Pleistocene Park)	**2003-**	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
			4 sites, Russia (Chokurdakh, Seida/Vorkuta, Nadym, Tura)	**2001-**	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
GAW-Regional+Global[4]	Land stations	A	Regional: 47 sites. Global: 4 sites	**1989-**	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
GOS - surface synoptic measurements[5]	Land stations	A	~200 Arctic sites	**1807-**	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
GRUAN[6]	Land stations	A	3 Arctic sites	**2006-[5]**	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Hornsund Supersite[7]	Land stations	A, T	Hornsund station and glacier (Svalbard)	**1978-**	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
NNSN[8]	Land stations	T	19 Arctic sites, Norway	**1905-**	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
PEEX[9]	Land stations	A, T	Eurasian Arctic	**1930-**	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Radiosounding network[10]	Land stations	A	73 Arctic sites, Pan-Arctic	**1919-**	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Sodankylä-PallasSupersite[11]	Land stations	A, T	Sodankylä and Pallas Finland	**1908-**	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Tower network for atmospheric trace gas mixing-ratio monitoring[12]	Land stations	A, T	23 Arctic sites	**1971-**	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Greenland Climate Network (GC-Net)	Ice sheet stations	A, T	18 stations, Greenland plateau	**1995-**	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	
Greenland ice sheet monitoring network (GLISN)	Ice sheet stations	T	19 stations in Greenland	**1930-**	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
GNET - GPS network	Ice sheet stations	T	60 stations, Greenland	**1995-**	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
Program for Monitoring of the Greenland Ice Sheet (PROMICE)	Ice sheet stations	A, T	25 stations, Greenland ablation area	**2007-**	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
GlaThiDa[13]	Glacier measurement points	T	AMAP boundaries	**1955-**	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪	🟪
RGI[13]	Glacier measurement points	T	AMAP boundaries						🟧	🟧	🟧	🟧	🟧	🟧	🟧
WGMS- FoG[14]	Glacier measurement points	T	AMAP boundaries	**1959-**	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
GEM[15]	Land stations, moorings, vessels	A, O, T	3 main supersites in Greenland[5]	**1994-**	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨	▨
ICOS[16]	Land stations, ships, moorings, buoys	A, O, T	European Arctic: 9 land-based stations and 1 marine station									▨	▨	▨	▨

[1] The European Research Infrastructure for the observation of Aerosol, Clouds and Trace Gases (ACTRIS) has two sites located above the Arctic circle: Sodankylä-Pallas (Finland) and Ny Ålesund (Svalbard, Norway).

[2] The Arctic Hydrological Cycle Observing System (Arctic-HYCOS) extends over the Arctic Ocean Drainage Basins defined according to Shiklomanov et al, 2000.

[3] Only 6 of the 32 stations belonging to the Arctic section of Fluxnet were assessed: Cherski (Russia, data from 2003 until present), Pleistocene Park (Russia, data from 2003 until present), Chokurdakh (Russia, data from 2001 until present), Seida/Vorkuta (Russia, data from 2007 until present), Nadym (Russia, data from 2009 until 2012), Tura (Russia, data from 2004 until present).

[4] The Arctic Global Atmospheric Watch (GAW) sites are Sodankylä-Pallas (Finland), Ny Ålesund (Svalbard, Norway), Alert (Canada), and Utqiagvik (previously Barrow, Alaska, USA).

[5] The Global Observing System (GOS) for surface synoptic measurements comprises about 4000 stations, about 200 of which are located above the Arctic Circle.

[6] The Arctic GRUAN sites are Sodankylä-Pallas (Finland), Ny Ålesund (Svalbard, Norway), and Utqiagvik (previously Barrow, Alaska, USA). GRUAN data collection started in 2006 at Ny Ålesund, in 2007 at Sodankylä-Pallas, and in 2009 at Utqiagvik

[7] Hornsund Station is one of the 4 main research sites of the Svalbard Integrated Arctic Earth Observing System (SIOS) and belongs to the WMO Integrated Global Observing System (WIGOS). The other SIOS supersites are Longyearbyen, Ny Ålesund, Hopen and Bear Island.

[8] The Norwegian National SeismicNetwork (NNSN) comprises 49 sites, 19 of which are located above the Arctic Circle.

[9] The Pan-Eurasian Experiment (PEEX) includes over 200 land-based stations, 27 of which are located above the Arctic Circle. Several of the PEEX stations belong also to GOS, GAW, Fluxnet, and “Tower network for atmospheric trace gas mixing-ratio monitoring” networks. In INTAROS, 11 PEEX Russian Arctic stations were assessed: Urengoy - sourthern forest-tundra, Urengoy-southern tundra, Kashin, Bolvanskiy, Marre-Sale, Belyy, Heiss Island, Seida Vorkuta, Igarka GeoCryLab, Tiksi, Chersky.

[10] The assessed Arctic radiosounding data were obtained from the Integrated Global Radiosonde Archive.

[11] This is the only assessed supersite among those belonging to the International Arctic System for Observing the Atmosphere (IASOA) network. Other supersites belonging to the IASOA network are Utquiaġvik (former Barrow) and Oliktok Point in Alaska, Eureka and Alert in Canada, Summit and Vilum in Greenland, Ny-Ålesund in Norway, and Tiksi and Cherskii in Siberia.

[12] The data collection Tower network for atmospheric trace gas mixing-ratio monitoring started in 1971 at Barrow (Alaska, USA), in 1994 for the ICOS stations (Finland and Sweden), in 2002 for the Japan-Russia Siberian Tall Tower Inland Observation Network, in 2006 for the Russian stations run by the Max-Planck-Institute for Biogeochemistry, in 2008 for the Pleistocene Park Station in Russia, in 2010 for the Canadian Stations, and in 2013 for the Kjolnes Station, Norway.

[13] Measurements on a specific glacier are done only once every several years, but the network includes a lot of glaciers, thus every year may glaciers are measured.

[14] Measurements are usually done every year, at end of summer or both at beginning or end of summer. Values are representative of the whole year.

[15] Among the 3 supersites (Zackenberg, Nuuk, and Disco) of the Greenland Ecosystem Monitoring (GEM) Program, only two were assessed (Zackenberg and Nuuk).

[16] he Integrated Carbon Observing System (ICOS) is a European Research Infrastructure that includes ecosystem stations, atmospheric stations, and ocean stations. Of the whole ICOS observing system, only management and sustainability have been assessed in INTAROS.

Table 2. List of the assessed observing systems in the marine Arctic, their type of platform (in the following order: vessels, vessel+ sea ice station, aircrafts, gliders, buoys, moorings, ocean systems including a land component, tide gauges), sphere (A=atmosphere, O = Ocean and sea ice, T = terrestrial), , geographical coverage, and temporal coverage: summer period in orange, autumn period in brown, winter period in blue, all year in grey, and irregular in green. Multi-disciplinary systems are marked in bold.

Observing systems in the marine Arctic	Platform	Sphere	Geographical coverage	Start before 2008	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018
AREX summer survey	Vessel	O	Nordic Seas, Fram Strait, North of Svalbard	🟧 **1987-**	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
ASCOS; ACSE[1]	Vessels	A, O	Central Arctic Ocean		🟧						🟧				
FRAM-Vessel[2]	Vessels	O	Fram Strait and high Arctic	🟧 **1999-**	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
IMR Barents Sea winter survey	Vessels	A, O	Barents Sea	🟦 **1976**	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
IMR-PINRO Ecosystem Survey	Vessels	A, O	Barents Sea	🟧 **2004-**	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
IMR fixed hydrographic sections[3]	Vessels	A, O	Norwegian water	🟩 **1936**	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
IMR SI_Arctic vessel mounted ADCP system	Vessels	O	Around Svalbard								🟧	🟧	🟧	🟧	🟧
IOPAN Long-term Monitoring in Svalbard Fjords	Vessels	O	West Spitsbergen fjord Hornsund	🟧 **1999-**	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧	🟧
NIVA Barents Sea Ferry Box	Vessels	A, O	Barents Sea opening						▒	▒	▒	▒	▒	▒	▒
Polarstern cruises	Vessel	A, O	Central Arctic Ocean	🟧 **2007-**	🟧	🟧	🟧	🟧	🟧	🟧					
N-ICE2015[4]	Vessel, sea ice station	A, O	Atlantic sector of Arctic Ocean, Beaufort Sea									🟦			
Sea State 2015[5]	Vessel, sea ice station	A, O	Atlantic sector of Arctic Ocean, Beaufort Sea									🟫			
FRAM-Gliders[2]	Gliders	O	Fram Strait	**2007-**	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
FRAM-buoys[2]	Buoys	O	Fram Strait and high Arctic	▒ **1999-**	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒
International Arctic Buoy Programme (IABP)[6]	Buoys	O	Arctic Ocean	▒ **1979**	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒
A-TWAIN (including A-TWAIN Poland)[7]	Moorings	O	North of Svalbard and southern Nansen Basin						▒	▒	▒	▒	▒	▒	▒
FRAM-Moorings[2]	Moorings	O	Fram Strait and high Arctic	▒ **1997-**	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒
Fram Strait Multipurpose acoustic system	Moorings	O	Fram Strait		▒	▒	▒	▒	▒		▒	▒	▒		
IMR Barents Sea Opening mooring	Moorings	O	Barents Sea	▒ **1997-**	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒
UNIS ocean observing system	Moorings	O	Svalbard	▒ **2005-**	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒
Greenland Ecosystem Monitoring program	Vessels, moorings and land stations	A, O, T	2 stations in Greenland	▒ **1994-**	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒
IOC Tide Gauges in Greenland	Tide gauges	O	4 stations	▒ **2004-**	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒	▒

[1] The "Arctic Summer Cloud Ocean Study" (ASCOS) and the "Arctic Cloud Summer Expedition" (ACSE) were ship-based field campaigns lasting few months during summer.

[2] FRAM (FRontiers in Arctic Marine Monitoring) is a long-term observatory where stationary devices (such as moorings) are complemented with diverse mobile components such as vessels, deep-sea robots, ice buoys and gliders. The observatory enables year-round observations of essential ocean variables from the surface to the sea floor.

[3] IMR fixed hydrographic sections started in 1936 at Eggum, Ingøy, and Skrova, in 1953 at Fugløya-Bear Island and Vardø-N, in 1956 at Sem Islands, in 1957 at Gimsøy-NW, in 1969 at Bear Island-W, and in 2012 at Polhavet.

[4] The "Norwegian Young sea ICE cruise" (N-ICE2015) was a 6-month long experiment where the ship was frozen to the ice and drifted with the ice floe from January to June 2015.

[5] The "Sea State and Boundary Layer Physics of the Emerging Arctic Ocean" (Sea State 2015) was a one and half month expedition in the Arctic sea ice during autumn 2015.

[6] IABP is composed of 20 different research and operational institutions from 9 different countries. In INTAROS, a full assessment was made only for ArgoPoland and NorArgo, which are the buoy networks managed by Polish and Norwegian institutes, respectively, operating in the Nordic Seas and Fram Strait. Both national networks were initiated in 2012.

[7] "Long-term variability and trends in the Atlantic Water inflow region" (A-TWAIN)

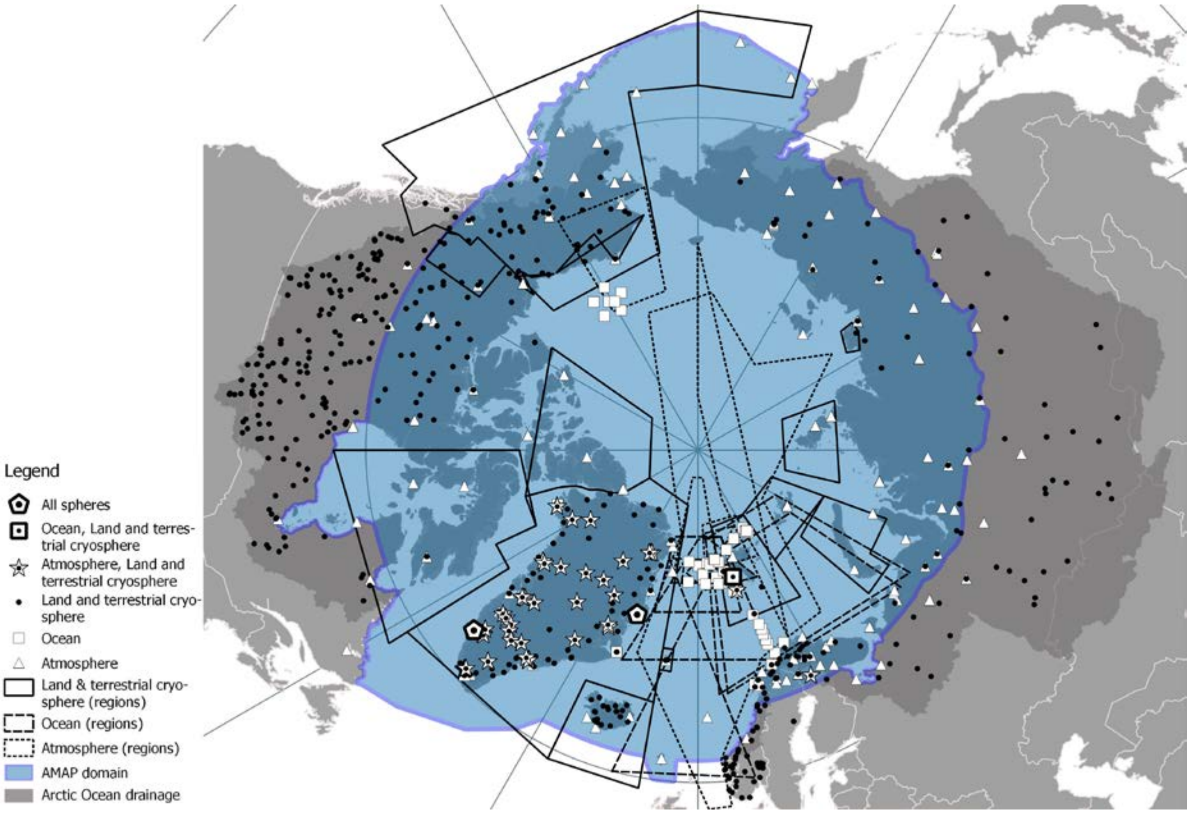

Figure 2. Map illustrating the location of the assessed in-situ observing systems and their domain. The area covered by observing systems based on moving platforms (ships, buoys, aircrafts) or including thousands of measurements points (as in the case of glacier observations) is represented with polygons.

This ranking is a somewhat subjective synthesis of the detailed maturity score presented in D2.4 and D2.5. It is clear that observing systems that rank high on most data aspects are in general those that result from national commitments under international agreements with an overarching organization. The highly ranked systems are usually part of a global or regional programme and not specifically established for the Arctic. They are either global systems, such as GRUAN and GAW, or European Research Infrastructures, such as ACTRIS and ICOS. However, with only a few systems with a high rank, it is difficult to conclude that this is a significant result. Similar systems exist also in other Artic regions but were not assessed here.

Among systems that rank high on sustainability but lower on some of the other data characteristics, we also find international systems such as surface and upper-air soundings (stored at IGRA) under the World Meteorological Organization's Global Observing System (GOS), established primarily for weather forecasting purposes. We also find a few systems that were not designed to provide atmospheric observations, but to monitor properties or processes where the atmosphere is an integral part. Examples are the Programme for Monitoring of the Greenland Ice Sheet (PROMICE) and IMR's shipborne oceanographic and ecosystem surveys in the Barents Sea. This suggests that atmospheric observing systems in the Arctic will benefit from integration with other observing systems.

Table 3. Summary of maturity of the Arctic land-, ice sheet-, and glacier-based *in-situ* observing systems, marked with different colors according to their domain: atmosphere in orange, land and terrestrial cryosphere in green, and multidisciplinary systems in black. The shades of red correspond to the maturity scores: low maturity (scores 1-2) in light red, medium maturity (scores 3-4) in red, high maturity (scores 5-6) in dark red.

Observing systems	Sustainability	Data management	Uncertainty handling	Metadata handling	Documentation
GRUAN, ACTRIS, ICOS, GNET-GPS Network, GLISN, NNSN, Arctic-HYCOS	High	High	High or medium-high	High	High
Global/regional GAW, PROMICE, GlaThiDa, WGMS-FoG, RGI	High	High or medium-high	Low	Medium-high	Medium
Radiosoundings network, GOS Surface synoptic measurements, Sodankylä supersite	High	Medium-high	Medium-high	Medium	Low
Radiosounding network, GEM	High	Medium-high	Low	Low	Low
Hornsund supersite	Medium	Medium	Low	Medium	Low
GC-Net	Medium	Medium	No information	No information	No information
Tower network for atmospheric trace gas mixing-ratio monitoring	Medium	Low	High	Medium	Medium
luxnet, PEEX, Airborne observations of urface-atmosphere fluxes	Low-Medium	Low-Medium	Low	Medium	Low

Well-conceived and well-funded international programs with clear but somewhat broader common targets seem to work well. PEEX aims to develop an in situ observing network that spans large parts of the Eurasian continent (http://www.atm.helsinki.fi/peex/index.php/peex-in-situ-observation-network) connecting a large number of Russian in situ stations assessed to be at medium or low maturity. PEEX and the other terrestrial observing systems (such as Fluxnet and the tall tower network for trace gas observations) are often connected to larger networks that have broader aims, either internationally or nationally.

Gaps in technological readiness were evaluated by assessing the Technology Readiness Level of the instruments applied to measure/derive the assessed atmospheric data. The assigned levels varied in a scale from 1 to 9, following the criteria established by the ISO standard 16290. The vast majority of the instrumentation fell into the category of fully ready technology (scores 8-9). The only exceptions were some instruments at the Russian PEEX stations (different instruments used in different stations, without certified quality), and instruments to collect aerosol observations at the GAW stations (using experimental technology). Complex aerosol measurements systems are still under research development, although applied methods have already been proven.

2.1.2 Assessment of terrestrial in-situ observing systems

Generally, the assessed terrestrial observing systems have medium or high sustainability, impacting investments for data infrastructure resulting in medium to high data management maturity (Table 3). Similar to the atmospheric observing systems, those terrestrial systems that are sustained through well-established national or international monitoring programs have higher sustainability than those that do not have specific national commitments.

In addition to the PROMICE network, which also has an atmospheric component (mentioned earlier), other terrestrial observing systems with high sustainability include the Greenland Ecosystem Monitoring, the Greenland Ice Sheet Monitoring Network, the Arctic-HYCOS network, the Greenland GPS network, the Norwegian National Seismic Network. Moreover, glacier inventories and databases (Randolph Glacier Inventory, Glacier Thickness and Fluctuations of Glacier databases) that have been developed in the framework of large projects such as GLIMS (Global Land Ice Measurements from Space), the World Glacier Monitoring Service (WGMS) and the U.S. National Snow and Ice Data Center (NSIDC), also have high sustainability scores.

The terrestrial observing systems include a few stations/areas that collect multidisciplinary and comprehensive observations (Sodankylä, Greenland Ecosystem Monitoring Programme, and Hornsund). These stations are particularly important for achieving a broader scientific understanding of multiple linked processes and have medium-high maturity in sustainability and data management, but not necessarily high maturity in documentation, and uncetainty and metadata handling. While Sodankylä has a routine quality check and automated data and metadata provision, documentation is poor. For the Greenland Ecosystem Monitoring stations and Hornsund, uncertainty handling also has low maturity. As these stations have long data records, a relatively small investment to improve metadata and uncertainty handling, and hence the usability of the data, would provide a large benefits and would be cost-effective given the already installed infrastructure.

Terrestrial observing systems with stations located in Northern Russia (the assessed Russian subgroup of Fluxnet stations and PEEX) have low-medium sustainability due to weaker funding commitments. This is also the case for the airborne observations of surface-atmosphere fluxes, which are funded through short-term projects.

Most of the assessed terrestrial observing systems cover specific regions (e.g. Greenland), are formed by few stations distributed over a very vast area (e.g. Tower network for atmospheric trace gas mixing-ratio monitoring, Fluxnet, PEEX), or are single supersites. This spatial coverage is close to sufficient for broader-scale monitoring of some variables, such as Greenhouse Gases (see Sect. 4.3) and river runoff (see Appendix B6), but is insufficient for many others, especially those that have large spatial variability and therefore would require a much denser network. This is in particular the case for data on glaciers and for snow.

Glaciers are not monitored over the Russian Arctic and are also poorly monitored along the peripheral Greenland and Canadian Arctic. The variability of snow parameters such as snow depth, snow water equivalent, and snow albedo, can be extremely large even within a very limited area, well-illustrated by that covered by the Sodankylä supersite where dozens of automatic snow stations are distributed over few square kilometres. This means that *in-situ* snow observations are lacking for most of the terrestrial Arctic. Pilot studies with drone-based daily surveys along predefined routes can be a viable solution to address the high variability of snow properties over small spatial ranges. A more sustainable solution, however, could be having *very* detailed observations at a limited number of sites combined with satellite observations.

As for the case of the atmospheric observations over the land, we did not observe relevant technological gaps in the assessed terrestrial observing systems. The Technology Readiness Level of the methods applied to measure/derive the terrestrial data is generally high, except for the soil measurements carried out in the PEEX stations (the accuracy of the instruments is not proven). Measurement methods with medium readiness level were the radar system to retrieve snow depth at the Hornsund Station in Svalbard, and the system to measure fluxes of greenhouse gases in the FluxNet network. Mature and cheap solution to automatically measure soil and snow properties are available and should be adopted. An internationally coordinated effort to harmonize snow and soil measurements under the patronage of WMO Global Cryosphere Watch is undergoing through the establishment of the CryoNet network.

2.2. Marine Arctic

2.2.1 Assessment of atmospheric in-situ observing systems

There are essentially no permanent atmospheric in-situ observing systems over the Arctic Ocean, except for a few surface observations from automated buoys under the International Arctic Buoy Program. The drifting perennial sea ice prohibits fixed observational infrastructures like on land. The Russian Arctic and Antarctic Research Institute operated the manned so-called North Pole Drifting Stations quasi-continuously for many decades; this programme was, however, ended in 2013, while the thinning of the ice made the operation both difficult and dangerous. The most important atmospheric *in-situ* observing systems rely on ship-borne observations which are typically limited to the summer – autumn period. Data collection in the ice-covered Arctic requires research vessels with icebreaking capacity, which is limiting factor from both access, logistics and funding perspectives. The observing systems assessed in this study include the Arctic Summer Cloud-Ocean Study (ASCOS) and the Arctic Clouds in Summer Experiment (ACSE) on the Swedish icebreaker *Oden*, the SeaState2015 expedition on the US R/V *Sikuliaq*, the N-ICE2015 expedition on the Norwegian R/V Lance and operational soundings from the German icebreaker *Polarstern*.

Table 4. Summary of maturity of the Arctic marine *in-situ* observing systems, marked with different colors according to their domain: ocean and sea ice in blue, atmosphere in orange, land and terrestrial cryosphere in green, and multidisciplinary systems in black. The shades of red correspond to the maturity scores: low maturity (scores 1-2) in light red, medium maturity (scores 3-4) in red, high maturity (scores 5-6) in dark red.

Observing systems	**Sustainability**	**Data management**	**Uncertainty handling**	**Metadata handling**	**Documentation**
FRAM	High	Medium	Low-medium	Medium-high	Low-medium
IMR PINRO Ecosystem Survey & Barents Sea Winter Survey, Greenland Ecosystem Monitoring Programme	High	Low-medium	Low	Low	Low
NorArgo	Medium	High	Low-Medium	Medium	Medium
IOPAN Long-term Monitoring in Svalbard Fjords	Medium	High	Not assessed	Not assessed	Not assessed
Argo Poland	Medium	Medium-High	Medium-high	Medium	Low-Medium
A-TWAIN / A-TWAIN Poland	Medium	Medium-High	Low	Low-medium	Low
NIVA Barents Sea FerryBox	Medium	Low-medium	Medium-high	Medium	High
IOC Tide Gauges in Greenland, AREX	Medium	Low-Medium	Low	Low	Low
International Arctic Buoy Programme	Medium	Low-Medium	Not assessed	Not assessed	Not assessed
Atmospheric field experiment (ASCOS, ACSE, N-ICE), Polarstern soundings	Low	Low-medium	Low-medium	Low-medium	Medium
Fram Strait Multipurpose Acoustic System	Low	Low	Low	Low-Medium	Low

Similar to Table 3, Table 4 presents a compact synthesis of the maturity in sustainability, data handling, and documentation for the marine Arctic. Essentially all assessed characteristics score low for ship-borne field campaigns in the central Arctic Ocean. Not only are they by nature not sustainable; they also rank low when it comes to data management, uncertainly and metadata handling. However, the data coming from field campaigns are not inferior in quality to that coming from a permanent infrastructure. Quite the contrary, they follow internationally agreed “best practices” for methodology, calibration and quality control informally established over decades. Field campaigns are by definition a time-limited activity collecting data over a period of typically a few weeks. Research-funded campaigns with short-term funding cannot be expected to provide sustainable data production over longer time. So, there is little incentive to invest money in building and maintaining systems for data management, uncertainty handling and metadata. Therefore, such observation systems score very low on all the formal assessments used in this project, although the data may be of excellent quality. The incentive for any scientists to make their data more easily available for other scientists is just not sufficient to warrant the investment, so this is just a logical choice in a soft-money driven environment. The moral incentives for such investment has been increased over the last decade, in the Arctic probably with a start during the 2007-08 International Polar Year (IPY). Funding agencies now require data to be made available there, but there has not been a corresponding increase in funding to make this happen.

As for the case of the atmospheric observations over the land, the Technology Readiness Level of instruments applied to measure/derive the assessed atmospheric marine data is generally high, except for the radar and microwave radiometers used to measure cloud and thermodynamic properties onboard research vessels, and the anemometers used to measure wind speed onboard the IMR vessels. The systems observing cloud microphysical variables are highly sophisticated and under research development, although validation and intercomparison studies have been made. The basic meteorological observations made onboard the IMR vessels, can easily be upgraded, applying standards used for operational meteorological stations.

2.2.2 Assessment of ocean and sea ice in-situ observing systems

The existing ocean and sea ice observing systems are mainly driven by the needs of the scientific communities concerned with climate and environmental changes in the Arctic. Sea ice monitoring is an important activity which is based on using several types of satellite data. But some of the sea ice variables, such as ice thickness and snow cover are difficult to obtain from satellite. Therefore, in situ sea-ice data is needed by many user groups, in particular the operational sea ice services, but funding for collection of such data comes from research programmes, implying that the sustainability of the observations is limited. The Copernicus marine services – CMEMS – are building up monitoring and forecasting systems based on satellite observations and modelling systems with extensive and long-term funding from the European Commission. The in situ data needed by the marine services are mainly funded from national research programmes.

There is a growing scientific community providing ice and ocean data, but there are large gaps in spatial and temporal coverage for many of the essential ocean variables (EOV). This is because in situ observing systems require use of conventional ships, which have limited access to the Arctic Ocean due to the sea ice cover, or ice-going vessels. The management of ocean data is also affected by a lack of long-term funding of sea-ice and ocean observing systems (Ludvigsen et al. 2018). During INTAROS, data collectors, data managers and harvesters have been encouraged to work together. This has revealed unclear work flow and responsibilities, from obtaining the data to publishing data collections that hampers the process of making data accessible.

A diversity of platforms is available for ice and ocean measurements such as research vessels and ships of opportunity, icebreakers, ocean moorings and bottom installations, buoys, and drifting floats and gliders. Platforms and instruments for collection of in-situ data in the open ocean generally has a high technologic readiness level, but in Arctic conditions with ice-cover there are severe limitations in present observing technologies. Most of the data from platforms under the ice can only be obtained after recovery of the platforms. These data are important for year-round and long-term monitoring of climate and environment. For assimilation into ocean forecasting systems, the spatial coverage, robustness and near real-time capability is essential, but few such observations are available.

Among the assessed platforms, only ice-based observatories, floats and gliders provide data in the NRT mode. Ship-borne surveys have capabilities to provide NRT observations; however, only very few have implemented this mode of operation. Fixed moored arrays are mainly located in the Arctic gateways and shelf seas, while drifting ice-based observatories dominate in the central Arctic Ocean. Ship-borne surveys cover the entire Arctic and sub-Arctic domain but with substantially different spatial temporal coverage in the central Arctic and in the Arctic shelf seas and gateways. Glider and float observations assessed in this study are very sparse and limited to the open ocean areas (except floats in the Baffin Bay Observatory).

Each platform can host a cluster of different sensors for the collection of physical, biogeochemical and biological parameters. While the technical readiness of sensors for observations of physical ocean variables are high, technologies and sensors to measure sea-ice/snow properties, biological and biogeochemical parameters are much more limited for autonomous platforms. Therefore, these observations are sparse and mostly dependent on expensive manned platforms such as vessels, ice breakers, and ice stations. Promising new approaches exist to monitor ocean acidification, anthropogenic carbon uptake and changes in ocean physics (for more details D. 2.1 and 2.2) along the Western Greenland Coast (Disco Bay), Fram Strait, North of Svalbard and in fjords of Svalbard. In general, obtaining measurements of sufficiently high quality to contribute to estimates of changes in climate, biogeochemical cycles and rate of change in ocean acidification is a major challenge.

However, biological observations, along with physical and biochemical observations for resource management, are carried out in regular and systematically designed research cruises in some key areas, e.g. in the Fram Strait and Barents Sea. Here vessel-based monitoring programs in key economic regions provide the most sustained and long-term observations, however, mainly collected in open ocean regions with a seasonal bias towards summer and early fall. Semi-autonomous observations from ships of opportunity (e.g. Barents Sea FerryBox system) provide an alternative to enhance repeated observations in designated areas. Vessels themselves also influence measurements in different ways, for example, by acoustic noise, turbulent mixing, and pollution. Autonomous systems could significantly reduce these adverse impacts provide data of better quality than those from ship-borne systems.

The number of ice-tethered profilers, important for providing NRT data for assimilation into forecast models and for reanalysis, is low and lifetimes vary significantly, from a few weeks to over a year, and a very limited number provide biogeochemical data. The sparse coverage can be partially linked to relatively high cost and large risk combined with logistic challenges with deployments in the desired areas. A potential solution is development of simpler, more cost-effective ice-based ocean profilers, deployed in larger numbers during all cruises of opportunity in the central Arctic. Ice-based buoys for sea ice observations (e.g. sea ice drift, thickness and properties) and snow measurements are available in larger numbers than profilers, but with uneven distribution in the central Arctic. Sea ice *in situ* information (e.g. thickness and ice drift) for calibration and evaluation of satellite remote sensing products is primarily obtained over the Canadian Basin, with fewer systems in the Nansen and Amundsen Basins.

The Argo program is the main observing system for the global ocean, and ocean forecasting systems heavily depend on data from profiling Argo floats. Argo systems have high technical readiness for physical measurements in the open ocean but very low in terms of operating in ice-covered areas or within the marginal ice zone. Therefore, spatial and temporal coverage by Argo floats is extremely low in the Arctic. While Argo floats drift freely, ocean gliders can navigate autonomously between specified waypoints. Similar to Argo floats, the glider measurements assessed here are limited to open ocean areas thus provide only limited spatial and temporal coverage. Both floats and gliders need surface access for data transmission and geo-positioning, and are currently not suitable for ice-covered regions. For this to change, an underwater geo-positioning system (UW-GPS) is necessary. This could be provided in future by an underwater acoustic network, supporting both under-ice positioning and oceanographic and acoustic measurements (e.g. Mikhalevsky et al. 2015, Howe et al. 2019, Baggeroer et al. 2018).

Bottom anchored ocean moorings are robust and well-established systems with vertical arrays of instruments for sub-surface measurements of physical and biogeochemical parameters. They can be deployed under ice, in deep waters and operate for several years, depending on sampling rate and battery capacity. Most of the mooring systems included in this assessment, represented arrays in the Arctic Ocean gateways prioritized by multiple national and international research projects, have medium to high sustainability. Technical readiness level for physical ocean variables is high while biogeochemical and biological observations are not yet regularly collected and instrumentation has lower readiness level. Temporal resolution of measurements by moored instrumentation is among highest possible while spatial coverage is low. Most of the assessed moored systems are located in the Arctic straits, shelf seas or fjords. Moored systems are rarely used in the central Arctic Ocean. Due to sea ice, Arctic Ocean moored systems are limited to the subsurface and deeper layers. The ice also hampers NRT data delivery. Despite these limitations, ocean moorings still represent a superior solution for long-term observations in the key areas. Acoustic moorings provide integrated measurements from the Arctic Ocean interior but the measurement method results in very low spatial resolution.

Seafloor observatories include a wide range of observing systems from single instruments to complex designs with many instruments. One example is the HAUSGARTEN observatory, built up since 1999 as a multidisciplinary deep-sea observing system in the Fram Strait. Seafloor observatory sustainability, spatial and temporal coverage, and technical readiness is similar to ocean moored systems. In INTAROS, a small network of Ocean Bottom Seismometers (OBS) has also been deployed in the Fram Strait to study earthquakes in a region of ridge spreading.

The synthesis of the assessment in Table 4 shows that systems with high maturity of sustainability are ocean monitoring programs for resource management and European infrastructure programmes. These include NorARGO and Argo Poland, which are nationally funded infrastructure projects under the EuroARGO ERIC, which is the European contribution to the global Argo network. As infrastructure projects, sustainable funding can be expected for these systems. Several oceanographical and marine ecology observing programmes in the Barents and Norwegian Seas are run by Institute of Marine Research in Norway. Some of these programmes have been operational for many decades and have sustainable national funding. Parts of the programmes are also performed in collaboration with PINRO in Russia. The FRAM program is also a long-term funded German research infrastructure program with deployment of moorings, buoys, hydrographic sections and the Hausgarten observatory in the Fram Strait. The Barents Sea Ferrybox system operated by NIVA has national infrastructure funding for up to 10 years. The IOC Tide Gauge Network for Greenland is assessed to have medium sustainability, but it is part of the Permanent Service of Mean Sea Level network which has been operating since 1990. The network in Greenland is operated by DTU under IOC (www.psmsl.org). Other observing systems have a medium to low score on sustainability. In practice this means that these observing systems depend on new funding when the present projects are completed.

NorARGO has the highest score in data management while EuroArgo also has established data management, with NorARGO. Argo Poland follows the same procedure. The Norwegian Marine Data Center is used for management of all the data collected by IMR and other Norwegian institutions. Data collected under the Fram programme and other German projects are stored in the PANGAEA data repository (http://pangaea.de). Uncertainty handling, metadata handling, and documentation have variable maturity from high to low.

3. Satellite products

The assessed satellite products are listed in Table 5 according to their domain. In the following, the results of the gap analysis are separately presented for the atmospheric, ocean and sea ice, and terrestrial domains.

3.1 Atmospheric satellite products

Only polar orbiting satellites are important for Arctic atmospheric observations; both poles are ideal locations for access to polar orbiters since their orbital tracks all converge near the poles several times per day. Ideally, this wealth of satellite data combined with data assimilation would make these areas the best covered in the world for reanalysis.

The entire Arctic Ocean is only covered by satellites with passive sensors, while the across-track for active sensors is too narrow and the orbital tracks have a poleward limit. The INTAROS assessment of atmospheric products therefore focused on temperature and moisture profiles from the AIRS hyperspectral sensor and on several different retrievals of cloud characteristics from a series of Advanced Very High Resolution Radiometer (AVHRR) sensors (see D2.4). For both we now have data-records lengths that start to approach climate data requirements. We have also developed and assessed a vertically integrated water-vapour product from microwave observations.

As expected, all the satellite products rank high on formal requirements. Sending instruments to space is so monumentally expensive and complicated, that any other cost surrounding the deployment becomes minor in comparison. Conversely to the case for field campaign data, this does not mean that the end-user products based on satellite data have high quality.

The temperature and moisture of the AIRS Level 3 twice daily product was evaluated against a large number of in-situ soundings from long records at three different coastal stations (Sedlar and Tjernström, 2019), from field campaign soundings and from several years of operational soundings from IB *Polarstern*. In general, temperature and moisture time series at a given height retrieved from AIRS observations are of sufficient quality to serve as a climate record. However, the vertical profiles of temperature, and even more so of atmospheric moisture, have significant seasonally varying biases such that they cannot easily be used to answer questions about the atmosphere’s vertical structure. In fact, the analysis shows that with low vertical resolution and shallow atmospheric boundary layers in the Arctic, in combination with the sensitivity to cloud cover in a very cloud region, AIRS is more likely to mislead and must be used with great caution.

Likewise, different retrievals based on the identically same AVHRR irradiance observations concur for some first order data, such as total cloud fraction, providing some level of confidence, but only in the sun-lit season. For a more complex characterization, for such parameters as cloud liquid water path or cloud top temperature, the different methods start to deviate, hence indicating significant uncertainty and during the dark season, when information from the visible wavelengths is lost, the AVHRR clouds data becomes essentially useless.

That the AIRS temperatures as such are reasonable provides some hope that when AIRS data is assimilated into a numerical model, the model might represent the correct structures. One may argue that the utility of satellite observations in the Arctic atmosphere is primarily for assimilation, numerical modelling and reanalysis. This would be true if the numerical models included adequate physics to generate realistic structures given a few satellite information of the atmospheric mean state. However, currently the models are not adequate for this purpose (e.g. Sedlar et al. 2019), and therefore it is imperative to invest in model development so that these, and other data, can be adequately utilized in the Arctic.

A new satellite-based total water vapor (TWV) product developed in INTAROS fills a gap because continuous TWV values over ocean and sea ice were not previously available. The horizontal resolution achieved exceeds the OSCAR requirements, but the required uncertainty of 1 kg/m2 is not always met. However, at the typically low WV values in the Arctic this threshold is frequently achieved. The temporal resolution and timeliness for operational applications according to the OSCAR requirements are not met. However, this can be improved by processing individual swathes (overflights) instead of the daily averages.

3.2 Ocean and sea ice satellite products

Satellite products are fundamental for a consistent spatial-temporal mapping of the Arctic Ocean and monitoring of pan-arctic changes. Satellite retrievals are based on measurements of electromagnetic radiation, reflected or emitted from the surface. Depending on the information needed, satellites sensors range from optical to microwave wavelengths. The satellite information is complemented by in-situ observations, providing information from the interior of the ocean/ice/snow at different spatial-temporal scales from satellite data.

The ocean surface height has been monitored with satellite altimeters since 1991. Until the launch of CryoSat-2 (2011), the orbital parameters of these satellites limited spatial coverage to below 82°N; the latest generation of polar orbiting altimetric satellites (Sentinel-3A/B, CryoSat-2, SARAL/Altika) covers up to 88°N. Synthetic Aperture Radar (SAR) has improved the ability to observe the sea level in narrow sea-ice leads. The 28-year record of Arctic sea level is used to make an Arctic mean sea surface which is used as reference for the Arctic sea level anomaly and Arctic mean dynamic topography, which is the mean sea surface relative to the geoid. With a spatial resolution at breakthrough level, sea level data from satellites are useful for detecting spatial patterns and thereby revealing currents and change of water mass or density. In-situ tide gauge measurements are used to evaluate satellite-based sea levels, but only few tide gauges with sufficient temporal coverage and without land contamination exist. In particular, the Siberian Arctic and Arctic interior sea levels are uncertain. No uncertainty estimates are available for the satellite-based Arctic sea level products.

Several products of Arctic sea ice concentration and thickness are prepared in the INTAROS-project (Table 5). The spatial resolution is in general at goal-level, with resolutions below 10 km. By reprocessing of atmospherically corrected brightness temperatures from passive microwave sensors (SSMR, SSM/I, SSMIS), sea ice data is available since October 1978.

The consortium is contributing four new or improved data products: sea ice displacement at large and at medium scale and thin sea ice thickness and sea ice type, i.e. the multiyear ice concentration. For the two assessed products, spatial and temporal coverage and timeliness are fulfilled at the breakthrough requirements according to the WMO-OSCAR requirements. The required spatial resolutions are missed by a factor of two, with exception of the sea-ice type product where the requirement is nearly met. For sea-ice displacement, no uncertainty requirements are given in the OSCAR data base. All products have been validated, but the uncertainty quantification provided is limited. Automated quality monitoring is not established.

Table 5. List of the assessed satellite products, satellite instruments, platforms, data repositories, and body managing the products, organized per domain. Acronyms of names of data repository are explained in the notes below the table. INTAROS partner institutions are marked with the acronyms reported at page 2 of this report.

	Satellite Products	Instrument	Platform	Data repository	Coordinating Bodies
OCEAN AND SEA ICE	Arctic high-resolution ice edge	Synthetic Aperture Radar (SAR)	Radarsat2 Sentinel-1	CMEMS OSI-TAC[1]	Norwegian Meteorological Institute
	Arctic Ocean - Sea Ice Concentration Charts - Svalbard	Synthetic Aperture Radar (SAR), visual and infrared	Envisat, RADARSAT, Sentinel-1, MODIS and NOAA	CMEMS OSI-TAC[1]	Norwegian Meteorological Institute
	Arctic Sealevel anomaly	Altimeter	ERS-1, ERS-2, EnviSat, SARAL, CryoSat-2, Sentinel 3A/3B	DTU Space Data Repository	DTU Space
	ASI Sea ice concentration	AMSR-E/2	AQUA + GCOM-W	University of Bremen	UB
	Global Ocean Sea Ice Concentration Time Series REPROCESSED	SMMR / SSM/I / SSMIS	Nimbus 7 / DMSP	CMEMS OSI-TAC[1]	Norwegian Meteorological Institute
	Ifremer/CERSAT Arctic sea ice drift at large scale	SSMI, QuikSCAT, ASCAT	DMSP, SeaWinds, MetOp	CERSAT[2]	Ifremer
	Ifremer/CERSAT Arctic sea ice drift at medium resolution scale	AMSR-E, AMSR2	Aqua, GCOM	CERSAT[2]	Ifremer
	Ifremer/CERSAT Sea ice concentration	SSMI	DMSP	CERSAT[2]	Ifremer
	Mean Dynamic Topography (MDT) and Mean Sea Surface (MSS)	Altimeter	ERS-1, ERS-2, EnviSat, CryoSat, Sentinel 3A/3B	DTU Space Data Repository	DTU
	Multiyear sea ice concentration	AMSR-E/2 + ASCAT	AQUA + GCOM-W + METOP	University of Bremen	UB
	OSI-205: OSI SAF High Latitudes L2 Sea and Sea Ice Surface Temperature	AVHRR	Metop	OSI-SAF[3]	Norwegian Meteorological Institute
	Sea Concentration from passive microwave data	Passive microwave	NIMBUS, DMSP	Arctic ROOS[4]	NERSC
	Thickness of thin sea ice	SMOS and SMAP radiometers	SMOS + SMAP	University of Bremen	UB
ATMOSPHERE	Cloud fractional cover Cloud type Cloud top temperature Cloud top height Cloud top pressure Cloud optical thickness Cloud phase Cloud water path	AVHRR	NOAA and MetOp	CM-SAF[5]	Deutscher Wetterdienst
	Cloud fractional cover Cloud type Cloud top temperature Cloud top height Cloud top pressure Cloud optical thickness Cloud phase Cloud water path	AVHRR	NOAA and MetOp	ESA Cloud-CCI[6] project	European Space Agency
	Cloud data from AIRS hyperspectral IR-sensor	AIRS (Atmospheric Infrared Sounder)	Aqua	NASA JPL[7]	California Institute of Technology
	Integrated Water Vapor	AMSR-E, AMSR2, AMSU-B, MHS	AQUA, GCOM-W, NOAA, METOP	University of Bremen	UB
LAND AND CRYOSPHERE	AMSR-E/Aqua Daily L3 Global Snow water equivalent v2	AMSR-E	Aqua	NSIDC[8]	NSIDC[8]
	ERA-CLIM2 NH Snow water equivalent	SMMR SSM/I AMSR-E	Nimbus-7 DMSP Aqua	FMI Arctic Space Centre	FMI
	ESA DUE GlobSnow v2.0 Snow water equivalent	SMMR SSM/I AMSR-E	Nimbus-7 DMSP Aqua	FMI Arctic Space Centre	FMI
	GlobSnow Snow extent	ATSR-2 AATSR	ERS-2 Envisat	FMI Arctic Space Centre	FMI
	IMS Daily NH Snow and Ice Analysis	AMSU-A, ATMS, AVHRR, GOES I-M IMAGER, MODIS,	AQUA, DMSP, DMSP 5D-3/F17, GOES-10, GOES-11, GOES-13,	NSIDC[8]	NSIDC[8]

		MTSAT 1R Imager, MTSAT 2 Imager, MVIRI, SAR, SEVIRI, SSM/I, SSMIS, VIIRS	GOES-9, METEOSAT, MSG, MTSAT-1R, MTSAT-2, NOAA-14, NOAA-15, NOAA-16, NOAA-17, NOAA-18, NOAA-N, RADARSAT-2, SUOMI-NPP, TERRA		
	JASMES snow depth	AMSR2	GCOM-W1	JAXA[9]	JAXA
	MODIS/Aqua Snow cover daily L3	MODIS	Aqua	NSIDC[8]	NSIDC[8]
	SMAP L3 Radiometer NH daily freeze/thaw state	L-band radiometer	SMAP	NSIDC[8]	NSIDC[8]
	GRACE Gravity - Ice Sheet Mass Change	Gravity Recovery and Climate Experiment (GRACE)	GRACE	NASA JPL[7]/GFZ	NASA JPL[7]/GFZ
	SMOS soil frost	SMOS	SMOS	FMI Arctic Space Centre	FMI
	Ice Sheet Surface Velocity Maps	C-SAR (Synthetic Aperture Radar working in C-band)	Sentinel-1A & -1B	PROMICE	GEUS

[1] Copernicus Marine environment monitoring service (CMEMS) Ocean and Sea Ice Thematic Assembly Center (OSI-TAC)
[2] Centre ERS d'Archivage et de Traitement (CERSAT)
[3] Ocean and Sea Ice Satellite Application Facility (OSI SAF)
[4] Arctic Regional Ocean Observing System (Arctic ROOS)
[5] Climate Monitoring Satellite Application Facility (CM-SAF)
[6] European Space Agency Climate Change Initiative (ESA CCI)
[7] National Aeronautics and Space Administration Jet Propulsion Laboratory (NASA JPL)
[8] National Snow and Ice Data Center (NSIDC)
[9] Japanese Aerospace Exploration Agency (JAXA)

The common flaw of all available sea ice concentration data products is high uncertainty at low ice concentrations. This is exacerbated by greater uncertainty and potential biases during summer months when surface meltwater ponding impacts retrievals (e.g., Kern et al., 2016). Sea-ice related data products are required at higher resolution both for operational applications and assimilating into ocean and atmospheric circulation models. Because of these limitations in the current satellite observational capacity, sea ice concentration was identified as one of the key parameters that should be targeted in the Sentinel expansion mission dedicated to polar and snow monitoring (Duchossois et al., 2017)

Another well-known gap for of observations of the Arctic Ocean with microwave imagers is the unobserved region around the pole due to the orbit inclination and the limited swath width of the conical scanning scheme. As a consequence, the AMSR-E/2 observations only reach up to 89°N; SSMI/S only to 85°. Among the microwave sensors, only sounders like AMSU-A have a wider swath so that the Arctic Ocean is completely covered daily.

Arctic sea and sea-ice surface temperatures (SST and IST) are observed at high latitudes by the AVHRR (Advanced Very High-Resolution Radiometer) sensor measuring thermal emission. Surface temperatures are generated by combining observations with Numerical Weather Prediction models and sea-ice concentration products. These Level-2 SST/IST products started in December 2014 and has a low 5 km resolution with corresponding error estimates.

3.3 Terrestrial satellite products

A range of satellite products have proven useful over the years for remote sensing of land ice properties in the Arctic, based on both microwave sensors (passive and active) and passive visual/infrared sensors. Although many crucial feedback processes governing the future evolution of land the terrestrial cryosphere in the Arctic can only be observed and understood through *in-situ* monitoring, the inaccessibility and vastness of the ice sheets, ice caps, glaciers, and snow-covered areas in the Arctic emphasizes the strength of satellite remote sensing in providing high spatiotemporal coverage. Key land cryospheric observations from satellites include altimetry, gravimetry, albedo, brightness temperature, ice velocity, ice extent, snow water equivalent, snow extent, soil freeze/thaw (see Table 5). These observations are crucial to current estimates of the sea level contribution from land ice in the entire globe, for hydrology and water resource management, and for the many land and biological processes dependent on soil frost.

Almost all the assessed satellite products fulfilled the requirements in spatial/temporal coverage and resolution defined for a variety of applications, including climate change hydrology, numerical weather prediction, glacier and ice sheet dynamics, sea level rise estimation. Exception were the snow products derived from passive microwave sensors, which have too coarse spatial resolution (~25 kilometres) compared to the threshold requirements (< 5 km). The threshold requirements for timeliness[3] set for operational activities (near-real time) were not met by some of the assessed satellite products such as the JASMES snow depth or the GRACE Gravity - Ice Sheet Mass Change.

Compared to in-situ land and terrestrial cryospheric observations, satellite products had higher accessibility and more mature metadata and documentation but scored equally low in user feedback (except for the GRACE Gravity - Ice Sheet Mass Change). Clearly, enabling the user feedback is considered of low priority by most in-situ and satellite observing systems, although it would help in highlighting the user needs and the gaps in the observing system.

The uncertainty characterization was the weakest aspect of the assessed satellite products, reaching high scores in all addressed aspects (standards, validation, uncertainty quantification, automated quality monitoring) only for GRACE Gravity - Ice Sheet Mass Change and the ERA-CLIM2 NH SWE. This suggests that a good uncertainty characterization requires a time frame that is hard to reconcile with operational applications, as the first of the two above mentioned products is released with one-month delay after acquisition, while the second is a not-updated record reprocessed for climate applications. This also points out the essential role of *in-situ* observations for the validation and calibration of these satellite-based time series. For instance, numerical models driven by in-situ measurements of snow height changes, surface energy fluxes, and snow structural properties (density and microstructure) are needed for the translation of snow volume change into mass change, which enables the estimation of ice sheet mass change and snow water equivalent. Analogously, ice thickness measurements recorded from ground-borne or airborne field campaigns are needed to translate ice velocities retrieved from satellite observations to direct ice loss to the ocean as icebergs and melt at the ice-ocean interface.

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[3] Timeliness is the time in which products are released to operational services after observations have been acquired

4. Observational gaps revealed by model sensitivity to observations

Models can be effective tools to assess gaps in observations, using different methods of assimilation or initialization procedures or inverse modelling. This is very a large research field in itself, worthy of its own work package or even its own project. Hence, in INTAROS D2.12 we performed only a few attempts, one in each sphere. Therefore, this section is by no means an exhaustive survey, but its results are nevertheless generally valid.

4.1. Atmosphere

Since the vertical structure of the atmosphere plays such a central role both for understanding of the atmosphere's role in the climate system and in weather forecasting on all time scales, INTAROS carried out a separate assessment of the sounding network in the Arctic. Apart from these soundings, the only information available on the atmospherically vertical structure comes from satellite information, which was evaluated as part of D2.4 and discussed above.

We used information from the data assimilation in the European Centre for Medium Range Weather Forecasts (ECMWF) Integrated Forecasting System (IFS) numerical model. The analysis was based on comparing short forecasts (here used as "first guess" for the analysis), the analysis (the initial conditions for the next short forecast) and the available sounding observations.

The most prominent result is that single accurate soundings in the central Arctic, for example from field campaigns, in an area where no other information except from satellites is present, can have a dramatically positive impact on the data assimilation and hence on the quality of both the model forecast and the subsequent analyses. Comparisons of results for expeditions when data was assimilated or not, in the same Arctic Ocean region, also show that the assimilation of satellite information alone in fact sometimes degrade the result.

Another conclusion is that the main problem in regions where the sounding network is reasonably dense is the quality of the soundings combined with how these are used in the assimilation. As an example, in some regions in Siberia the impact of the soundings is limited by the quality of the soundings, although the network here is reasonably dense. In comparison, individual sounding stations in sparser networks, for example in the northern North Atlantic, have a significantly larger positive impact, because of the quality of the soundings. However, even here the radius of influence of the soundings is rather small.

4.2. Ocean sphere

Potential effects of satellite altimetry and mooring observing systems on monitoring Arctic changes was evaluated, using a suite of forward and adjoint model simulations. The model is the MIT general circulation model (Marshall et al., 1997) covering the entire Arctic Ocean north of the Bering Strait and Atlantic Ocean north of 33°S, with different resolutions (about 32, 16, 8 and 4 km) and different simulation lengths from 1948. A dynamic-thermodynamic sea ice model (Zhang & Rothrock, 2000) was employed to model the sea ice parameters.

First, we compared the model simulations with tide gauges and bottom pressure records to identify the dynamic processes that the model can simulate. Second, based on model simulations we identified regions with high and low sea level variability as a function of timescale, indicating to key regions and the observing frequency required.

Contributions of halo/thermosteric effects (salinity/temperature changes) and mass effects on sea level variability were analysed, which gave alternative observing options if sea surface height cannot be observed. Then, five adjoint model simulation were performed. Two adjoint model runs were performed to demonstrate the importance of observing upstream variability for monitoring the high-frequency sea-level variability in marginal seas. In a third adjoint model run, we analysed the potential effect of sea surface height from satellite altimeter on monitoring the Beaufort Gyre decadal variability. Based on the last two adjoint model runs, we then analysed the potential effect on monitoring the Arctic circulation of observed freshwater/heat transport from the mooring system.

The main conclusions are:

(1) Satellite altimeter data combined with tide gauge and bottom pressure data provide sea level data which are crucial for ocean circulation studies. Satellite altimeter is the only system that provides regular spatial and temporal coverage up to a latitude determined by the satellite inclination angle. Satellite altimeters work well in open water, but have limitations in the ice-covered areas. Tide gauge data are mainly located along the Arctic coasts, where sea level is affected by freshwater runoff and other local processes. Bottom pressure data are only available at a few locations.

(2) Moorings provide time series of temperature, salinity, density and currents on different depths, which are needed for estimation of water mass circulation, heat and freshwater fluxes. Moorings with time series of more than a decade are only available in the Fram Strait and a few other places. Other ocean observations including data on sea ice were not used in the studies.

4.3. Terrestrial sphere

Here we evaluated the spatial representativeness of the data coverage provided by a network of 29 pan-Arctic atmospheric monitoring sites that provides continuous, well-calibrated observations on atmospheric greenhouse gas mixing ratios. Each of these towers has a field of view covering several thousands of km^2, with ‘footprints’ shifting over time with atmospheric transport and mixing conditions. Atmospheric transport modeling was used to simulate what areas are ‘seen’ by the network at each given point in time.

Our network representativeness analysis demonstrated that basic footprint coverage is available for most regions in Canada, Europe, and Western Russia. This implies that atmospheric inversion studies to quantify surface-atmosphere greenhouse gas exchange processes can be conducted at coarser spatio-temporal scales based on the obtained datasets. This is particularly the case when assuming that carbon exchange processes are homogeneous on the ecoregion scale – in this case, even single sites can represent larger domains, extending the network coverage substantially into formerly poorly sampled areas, mostly in Russia. Also, the Arctic Ocean has good overall footprint coverage, even though this region is remote and has no observational infrastructure. This can be explained by the overlapping footprints from the large subset of sites situated at or close to the Arctic coastline.

Major regions showing persistently limited coverage include the Russian Far East, Western Alaska, and the Eastern Canadian Provinces. Areas where footprint coverage gaps additionally exist seasonally include parts of Western Russia and Central Siberia. Accordingly, investments in additional observational infrastructure in any of these areas would be the most efficient approach to increase the overall coverage of the pan-Arctic atmospheric network for greenhouse gases.

5. Overview of the utilized data repositories and their services

This section focuses on the information technology infrastructure, i.e. that part of the data management generally developed and maintained by experts and institutions different from those who have collected, analysed and curated the data. In fact, the funding sources and mechanisms for the data infrastructure are often separated from those who are responsible for data collection, data processing and publishing. As a result, there are in many cases a gap between the data producers on one side and the data repositories on the other side,

Table 6 lists the data repositories[4] (white and blue background for national/institutional and international repositories, respectively) and the data portals[5] (green background) utilized to store the data assessed in INTAROS. The table shows if the data repositories provide data discovery service, data access service and a permanent data identifier PID. The data discovery service is an intrinsic part of the data infrastructure, providing a common protocol to search data based on user defined criteria. The protocol also depends on the content and structure of the metadata used to describe the data, and on the hierarchic levels in which data are organized. The data discovery service basically enables users to identify specific data collections or temporal/spatial subsets of them, applying keywords in search engines. Data access services may involve authorization to access data from a repository. A data access service provides an interface (protocol) between the stored data and the user that retrieves them.

The data from the assessed observing systems are stored in a mixture of institutional, national and international data repositories. Therefore, the amount of financing behind each repository varies substantially, resulting in different levels of functionality in the data search and access services, and in the provision of data permanent identifier (PID). Note that information in Table 6 is based on responses from the INTAROS survey conducted in late 2017 – early 2018. Usually, the services offered by the respective data repositories are under development.

Most of the data repositories did not assign a PID to the datasets but those who did, provided a Digital Object Identifier (DOI) to uniquely identify a dataset. Most repositories offered open access to data, i.e. no user registration required. Not having to register to gain access to a data collection, lowers the barrier for scientists, students and other stakeholders that want to reuse (scientific) data.

Many repositories, often created for single institution or country, require increased resources to develop, maintain, and upgrade the e-infrastructure than international topical repositories or data portals that provide a larger volume of data and services. Among the data repositories utilized by the assessed observing systems, about half are international. In some cases national repositories are connected to or embedded in international repositories.

Only a minority of the assessed observing systems share the same data repository, since many of the international repositories are defined thematically and, therefore, relevant only for a limited number of parameters. On national or institutional levels, the data repositories are generally multi-thematic, addressing a wider range of observed parameters, but they are used by one or few national institutes.

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[4] Data repositories are e-infrastructures that store the data and make them available to users

[5] Data portals are internet-based interfaces that mainly harvest the data from various data repositories and make them accessible to users. Data portals may also store some of the data that they provide.

International thematic repositories provide a large volume of data and services and generally hold the most advances solutions for the efficient usability of the data belonging to the specific theme. On the contrary, national and institutional repositories, with much smaller data volume and resources, can hardly reach and maintain the same level of data organization, and certainly cannot develop specific solutions for all the large variety of stored variables. An effort is required to make the various levels of the data infrastructure organization more efficient.
The European Research Infrastructures ACTRIS, ICOS, EuroARGO, and SIOS have responded to the need of coordinating existing data infrastructures and optimizing the costs of data curation. Their portals provide access to many national/institutional repositories, which, on the other hand, need to have developed standard interfaces to enable the machine-to-machine communication. Such international, topical portals are still few. Two examples are the WMO Global Cryosphere Watch (https://globalcryospherewatch.org/data/data.html) and the Copernicus Marine Environment Monitoring Service (CMEMS) In-situ Component Thematic Assembly Centre (INSTAC) (http://www.marineinsitu.eu/).

These international and discipline-based portals are a convenient solution for those institutions that prefer to store data into their own institutional repositories, to have better control on the data, in particular for data that do not need real- or near-real-time delivery. To connect institutional repositories to international or discipline-based portals, however, considerable resources are required to manage the data infrastructure, as the data need to be machine searchable and readable and to comply with the FAIR principle[6]. These resources are hardly allocated for this purpose, and the result is that most of the data repositories listed in Table 6 do provide data discovery and access services, but do not necessarily comply with the FAIR principles. FAIRness of data requires a close collaboration between the data providers and curators, who must apply standard formats to data and metadata, and the information technology experts, who maintain the data repositories and ensure the accessibility and searchability of the data. This is often lacking, since scientists in many cases have insufficient knowledge on information technology, while data manager experts often lack understanding of data structures and characteristics of scientific data. Standards and tools for metadata and data preparation developed under the H2020 project ENVRI-FAIR are going to be essential also for the institutions and data infrastructures in INTAROS, through a collaboration that optimizes the use of resources.

The data infrastructure used for the satellite products (Table 5) is better organised and more mature than that used for the *in-situ* data (Table 6) in terms of offered services and interoperability. The reason is that the space agencies (ESA, NASA, etc.) have a strong structuring effect on many aspects of data management. There are many institutions developing satellite products, and many of these products are stored in institutional repositories. During the INTAROS project several partners who provide satellite products are adopting protocols for data interoperability, as is the case for the Sea Ice Remote Sensing of the University of Bremen (Germany) and the Arctic Space Centre of the Finnish Meteorological Institute.

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[6] FAIR data are Findable, Accessible, Interoperable, and Reusable

Table 6. List of national/institutional (white background) and international (blue background) data repositories or data portals (green background) from where data collected by the assessed Arctic *in-situ* observing systems can be accessed. The observing systems are listed together with the indication whether the data repositories provide data discovery service, data access service, and permanent data identifier.

Data repository/Portal	**Observing systems (#count)**	**Data discovery service**	**Data access service**	**PID offered**
ACTRIS Data Centre	ACTRIS **(#1)**	Yes	Yes	Not yet
CORIOLIS (France) and FNMOC (USA) Global Data Centres	Argo-Poland, NorArgo **(#2)**	Yes	Yes	Yes
Distributed repositories[1]	Fluxnet, Tower network for atmospheric trace gas mixing-ratio monitoring/ Station in USA, PEEX **(#3)**	Varies among repositories	Varies among repositories	Yes (for some data)
EBAS	ACTRIS, Global Atmosphere Watch (GAW)-Aerosol (Regional/Global) **(#3)**	Yes	Yes	No
FMI Arctic Space Centre	Sodankylä Supersite, Tower network for atmospheric trace gas mixing-ratio monitoring/Sodankylä **(#2)**	Yes	Yes	No
GFZ + AWI institutional repository	Airborne obs. of surface-atmosphere fluxes **(#1)**	No	No (but data are accessible upon request)	No
Glacier Thickness Database (GlaThiDa)	GlaThiDa **(#1)**	Yes	Yes	Yes
Greenland Ecosystem Monitoring Database	Greenland Ecosystem Monitoring Program **(#1)**	No	Yes	Yes (for some data)
ICOS Carbon Portal	ICOS **(#1)**	Yes	Yes	Yes
IGPAN institutional repository	Hornsund Polish Station **(#1)**	No	No	No
Incorporated Research Institution for Seismology (IRIS)	GLISN **(#1)**	Yes	Yes	Yes (for some data)
Permanent Service for Mean Sea Level (PSMSL)	Global Sea Level Observing System (GLOSS) - Greenland **(#1)**	Yes	Yes	No
IOPAN institutional repository	AREX summer survey,A-TWAIN Poland **(#2)**	No	No	No
The Bolin Centre for Climate Research data base	Arctic Summer Cloud Ocean Study (ASCOS), Arctic Clouds during Summer Experiment (ACSE) **(#2)**	Yes	Yes	No
NIVA institutional repository	NIVA Barents Sea Ferry Box **(#1)**	Yes	Yes	No
Norwegian Marine Data Centre (NMDC)	IMR fixed hydrographic sections, IMR SI_Arctic vessel mounted ADCP system, R/V Håkon Mosby, IMR Barents Sea winter survey, IMR-VNIRO Ecosystem Survey, Fram Strait Multipurpose acoustic system, IMR Barents Sea Opening mooring **(#7)**	Yes	Yes	Yes
NOAA National Centres for Environmental Information (NCEI) – former National Climate Data Center (NCDC)	Radiosounding network, GRUAN, US stations of the Tower network for atmospheric trace gas mixing-ratio monitoring **(#3)**	Yes	Yes	No
Norwegian Polar Data Centre (NPDC), connected to NMDC	N-ICE2015, Sea State 2015, A-TWAIN **(#3).**	Yes	Yes	Yes
PANGAEA	Polarstern cruises **(#2)**	Yes	Yes	Yes
Polar Science Center, Univ. Washington, USA	International Arctic Buoy Programme (IABP) **(#1)**	Yes	Yes	No
PROMICE	PROMICE **(#1)**	Yes	Yes	No
Global Land Ice Measurements from Space initiative (GLIMS) – Randolph Glacier Inventory (RGI)	RGI **(#1)**	No	Yes	Yes
University of Bergen institutional repository (Norway)[2]	Norwegian National Seismic Network (NNSN)[3] **(#1)**	Yes	Yes	Yes
UNIS institutional repository[4]	UNIS ocean observing system **(#1)**	Yes	Yes	No
Word Glacier Monitoring Service (WGMS)-Fluctuation of Glacier (FoG) Database	WGMS- FoG (Fluctuations of Glaciers) **(#1)**	Yes	Yes	No (open access)
WMO Global Runoff Data Centre (GRDC)	Arctic-HYCOS **(#1)**	No	Yes	No

[1] “Distributed repositories” are used by those international observing systems that do not have a unique and dedicated data repository. Data from the different stations/platforms of one system are stored in different repositories, which may provide different services and have very different levels of organization: in the least mature cases, data are stored in a personal repository such as hard-disk, computer, or notebook. Most commonly, data are stored in national or institutional repositories. .

[2] The seismic data stored into the University of Bergen institutional repository will soon become available through the EPOS-Norway portal.

[3] The NNSN is part of the European Plate Observatory System (EPOS), a European Research Infrastructure

[4] The UNIS institutional repository will be soon embedded into the Svalbard Integrated Arctic Earth Observing System (SIOS)

6. General conclusions

This assessment shows that the funding model is a critical factor for successful implementation of observation systems in the Arctic. When funding for an observing system is made available in a concerted action, all the way from the *infrastructure investment* over *staffing* to *data handling*, through *international agreement* and *national commitment*, best results will be achieved. Not only does this lead to sustained observing, it also leads to well characterized, easy to access and easy to use data. Critical to this success is that the international agreement goes beyond the existence of the system; it also deals with the scope and details in the system. Examples of such efforts in the atmosphere are the European Research Infrastructures, such as ICOS and ACTRIS. This pattern is clear; infrastructure programs like GRUAN, ACTRIS and ICOS safeguard sustainability, quality control and data availability. It is also worth noting that these observing systems are not Arctic-specific, and that the number of observing sites in the Arctic is very small; currently, only a handful. Therefore, there is an urgent need to expand on this, which depend on the willingness of the member countries to invest in Arctic components of the infrastructure.

Observing systems that fall under national meteorological services through WMO agreements, are somewhat similar. However, the quality of these observations is typically lower, or at least more uneven, and less well safeguarded and characterized. This is likely due to national budget constraints together with less rigorous international constraints. Dedicated monitoring networks often have lower scores for sustainability and struggle with securing of sustained funding. Many of these systems were originally set up for science rather than operations and after having been run for a substantial time still struggle with budget constraints within national agencies. For atmospheric observations, many such systems were deployed for some other purpose but could with small efforts be useful also for atmospheric services, e.g. as data assimilated into numerical models.

Most national and international research projects today have a contractual obligation to make their data openly available. Unfortunately, the present situation of getting more credit for scientific publications than for making data available, combined with a lack of funding for the data handling, compels scientists to prioritize journal papers over data publishing. Therefore, there is further need for research-targeted systems to make collected data openly available through mature data infrastructures, using standard formats for metadata and data, and with associated documentation to support re-use.

6.1. Marine Arctic

6.1.1 Atmospheric observations

Atmospheric observations over the Arctic Ocean need special consideration and possibly a new paradigm. In the marine Arctic there are very few *in-situ* near-surface observations, no stationary observation stations and essentially no in-situ observations of atmospheric vertical structure. The only type of observations with a very good coverage are satellite observations; however, the INTAROS assessments showed that the quality of the satellite observations over the Arctic is often insufficient for climate monitoring and environmental forecasting, while the performance of numerical environmental models in the Arctic is also inadequate. Using satellite information alone for studies of atmospheric processes is difficult and should always be performed with great care – or not at all.

The available atmospheric observations from the Arctic Ocean with the highest quality come from ship-borne scientific expeditions; however, these always score very low on data management issues in addition to, by definition, not being sustainable and are too sparse in time and space. Additionally, there is a strong seasonal bias to summer or early autumn, when ice conditions favor navigation. Moreover, while there are scientific expeditions to the Arctic Ocean every year, only a few perform atmospheric observations, many have uncertain data quality management and do typically not share the data. The operational soundings performed on IB *Polarstern* are an exception and may serve as a role model for other Arctic logistics providers.

It is clear that, for the atmosphere over the Arctic Ocean, a longer-term observing system must rest on satellite data combined with data assimilation into numerical models of the environment; so-called reanalysis. Due to the polar orbiting satellites, satellite-based atmospheric data are more abundant over the Arctic than over the globe. However, their quality is low due to low sun angle when the sun is above the horizon, and loss of visible wavelengths in the dark season as well as the low contrast between cloud and snow/ice. Generally, retrieval algorithms do not account for the specific features of the Arctic troposphere.

In observing-system design the concept of comprehensive, baseline and reference system is often used. In an analogy with this traditional concept the campaign observations will have to serve as the “reference system”, satellite data will serve as the “baseline system” while the model analyses contribute the “comprehensive system”, providing information both on unobserved processes and variables, and importing observed information from beyond the Arctic, thereby providing the linkage to lower latitudes. Today, neither satellite data, models nor their data assimilation are adequate to fulfil useful criteria and improving this remains major development effort. This includes upkeep of older and development of new of satellite sensors in combination with more frequent field campaigns providing ground truth especially for vertical profiling. More routine observations by ships of opportunity would also be extremely useful as well as development of low-cost autonomous observation stations also for features like atmospheric vertical structure.

6.1.2 Ocean and sea-ice observations

The assessment shows that the in situ ocean and sea ice observing systems have a high sustainability when they are funded by national programmes over several decades. The most pronounced programmes are the Norwegian-Russian hydrography, ecosystem and fisheries monitoring programme in the Barents, Greenland and Norwegian seas, and the German FRAM programme with the Hausgarten seafloor observatory, mooring arrays and hydrography sections in the Fram Strait. The latter is also supported by the Norwegian Polar Institute’s monitoring programme. The International Arctic Buoy Program, the Greenland Ecosystem Monitoring Programme and the tide gauge network around the Arctic are also examples of systems that have been operated since the 1990s.

Ship-based observations are an essential part of ocean and sea ice observing system in the Arctic. Data collection from ships is done through regular monitoring programmes as well as through research cruises. In the Arctic ice-covered areas, all the ship-based observations are taken from icebreakers during research expeditions. Most of these expeditions take place in the summer-autumn season, when year-round observing systems (moorings and ice buoys) are deployed and recovered.

The lack of multidisciplinary (physical, biogeochemical and biological) data from the Arctic Ocean calls for development and implementation of complex, heavily-instrumented observing platforms, collecting autonomous observations of multiple variables collocated in space and time. The deployment and operation of a network of such platforms can be done by coordination between the ice-going vessel that are present in the Arctic every year. Development of observing systems should also target relatively small, low-cost, long-endurance and mobile autonomous platforms that could be deployed during research expeditions and from ships of opportunity, in particular in the rarely accessed regions.

European infrastructure programmes such as ICOS, EuroARGO and EPOS can potentially provide sustainable in situ observations in the Arctic, provided that member states prioritize Arctic observations. Common for these infrastructure programmes is that they have well-established organizational and financial systems, but are not yet operating observing systems in the ice-covered areas.

Observations from polar orbiting satellites is the only method by which consistent data can be obtained regularly for the whole pan-Arctic region. After decades of development of observing methods for different sea and ocean variables, there are now operational observing systems organized through the Copernicus Marine Environmental Monitoring Service (CMEMS). These services provide regular data products as well as forecasting products for both sea ice and open ocean variables. Satellite passive microwave observations of sea ice extent represent the longest and most mature system for sea ice monitoring, covering more than 40 years of uninterrupted daily observations. In the last decade also ice thickness is retrieved from satellite altimeters. In open ocean areas, satellite observing systems for seas surface wind, waves and temperature as well as sea level and ocean colour have been developed and provide regularly data products that are distributed through the CMEMS services.

6.2. Terrestrial Arctic

Atmospheric observations over Arctic land suffer from partly from lack of spatial coverage and uneven data quality. INTAROS results shows that while a better spatial cover would be beneficial, especially for monitoring of trace gases and aerosols, over large areas and at least for the sounding and surface observation network GOS networks, an improvement of the quality of observation and more reference stations would be more important than increasing the network density.

Land surface observing requires a balance between space-borne and in-situ observing systems. The land surface is very heterogeneous and it is difficult to cover sufficiently with in-situ observations, but the available satellite observations require development to enhance the quality of the information. In this respect, supersites are crucial in providing co-located measurements of a large number of terrestrial and atmospheric variables, that together enable the testing and development of model and algorithms for satellite retrievals and for the assimilation of the satellite data into operational models. There are perhaps less than 20 supersites in the Arctic (mainly belonging to the IASOA, GEM and SIOS networks), most of which were not included in this assessment because INTAROS partners are not directly involved in the measurements (particularly for sites in Canada, Alaska, Svalbard, and Russia).

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 from Global Cryosphere Watch will serve to this purpose, if national institutes that manage the observation infrastructures commit to follow the recommendations and adhere to the measurement, data management and metadata protocols.

In-situ observations of glacier and ice sheet mass balance in the Arctic are crucial to validate regional climate models and satellite-derived data products, yet have issues with sustainability. Observational networks on glaciers and ice sheets are notoriously difficult to maintain and often entails costly logistical support. Most such efforts have started out as research projects, expanded and maintained, sometimes over decades, by time-limited project funding. Such programmes need to make the transition to governmental funding through other sources than process/project research. Similarly, the in-situ land-ice monitoring datasets acquired need to reach a higher level of maturity in terms of data access and uncertainty characterization.

Most of the land-based and ice-based stations have low maturity in metadata and data uncertainty handling. Especially for those stations that have long data records, an effort should be made by the managing institutions to improve these aspects and hence the usability of the data, enhancing the cost-effectiveness of the infrastructures.

One of the weakest aspects of terrestrial satellite products is the lack of uncertainty characterization. Satellite remote sensing is the only viable method to gain complete coverage of land snow and ice in the Arctic, but satellite products rely heavily on relatively sparse *in-situ* monitoring effort for validation, calibration, and uncertainty characterization. Understanding land ice contribution to sea level rise, the changes in seasonal snow and permafrost conditions, there is a need for both deploying dedicated satellite missions and to strengthen and sustain the *in-situ* component that these missions depend on. This is also essential for the expected increase in real-time applications of satellite products, such as the assimilation of satellite data into operational models. For these applications, it is essential to ensure in-situ observations and field campaigns that would enable the validation and uncertainty quantification of the satellite data soon after the start of the satellite mission.

6.3. Community-based monitoring

A review of community-based environment monitoring (CBM) programs in the Arctic was also made in deliverables under WP4. CBM programs can complement scientist-led observing programmes. CBM is characterized by:

1) utilizing different and often simple methodologies with low costs;
2) engaging the experience of indigenous knowledge holders and other long-term residents with substantial environmental knowledge (Tengö et al. 2019), and;
3) by enabling an increase in sample size or density, area and time (Danielsen et al. 2018).

At least in some disciplines, scientists have started to incorporate CBM programmes and CBM tools into their work because they have found that their science has improved (e.g., Mercer et al. 2010; Eerkes-Medrano et al. 2017). Further work is required to identify the gaps in existing Arctic data delivery chains that CBM programs might plug into (Eicken et al. in review). Monitoring conducted by and anchored in communities is likely to gain in importance where scientist-based monitoring is sparse, and for environmental attributes where remote sensing cannot provide credible data (Danielsen et al. in review). The spread of smart-phone technology and online portals will further enhance the importance and usefulness of this approach (Johnson et al. in review).

7. Recommendations

The assessment of the present Arctic observation capacity is based on the observing systems analysed by the INTAROS partners as part of the Work Package 2, with focus on in situ systems. Many existing Arctic observing systems, especially outside Europe, were not included, and the assessment is therefore biased towards the European Arctic. The assessment builds on established methodology developed and used in other projects. The methodology made it possible to extract the key features and gaps in observing capacity and sustainability that are common to the whole Arctic.

Based on these, a list of key recommendations can be drawn for sustainable Arctic observing systems for the application areas addressed in the assessment (Fig. 1):

1. Observing systems are most sustainable when they are part of monitoring programmes with long-term funding from national, international or regional organisations such as Arctic Monitoring and Assessment Programme under Arctic Council, EU infrastructure programmes or the Copernicus programme. The in situ component of the observing systems is based national and international research projects with short-term funding and has therefore low sustainability. The in situ component need an improved funding model to be sustainable.

2. There is an urgent need to improve the coordination between the operational monitoring systems and the research-funded observations. Collaboration between national meteorological, oceanographic and other operational agencies and Arctic research programmes should increase.

3. Existing infrastructures should be better utilized to achieve more cost-effective Arctic in situ observing across multiple disciplines. The infrastructures consist of observation stations including supersites, ships and icebreakers, drifting platforms, underwater installations and aircraft. Icebreakers can be used to increase atmospheric, ice-ocean and seafloor observations in most of the ice-covered Arctic Ocean. Also commercial vessels can be used to enhance the data collection, especially for standard atmosphere/sea ice/ocean observations; many of these can be automatized.

4. The largest gaps in the observing systems are found in the marine ice-covered parts of the Arctic, where deployment of new autonomous observing platforms is of high priority. The platforms should provide long-term monitoring of physical, biogeochemical and biological variables. This requires development of new sensors and robust and cost-effective platforms as well as ice-going vessels for deployment and maintenance of autonomous platforms and for observations that need involvement of personnel.

5. Terrestrial in situ observing systems should focus on upgrading and enhancing existing stations, including improvement of instrument technologies and development of new autonomous instruments. Arctic supersites, which are stations with extensive multidisciplinary measurement capacity should be enhanced. Supersite observations are critical to provide high-quality ground truth data for validation of a number of satellite

products as well as for numerical models and forecasting systems, such as those under the Copernicus services.

6. While there are significant investments in satellite observing systems, through Copernicus and other satellite programmes, this assessment shows that the quality of some satellite data is not adequate. Moreover, there is also a lack of uncertainty characterization of satellite data, which restricts their usefulness in data assimilation. Satellite data cannot be fully exploited without appropriate in situ observations, while data assimilation and reanalysis need improvements for a better utilization of satellite products. In the marine Arctic, satellite observations, ship-based scientific observations, data assimilation and model reanalysis must be considered as integrated parts of the system, where each has an important role. This is equivalent to "baseline", "reference" and "comprehensive" networks, respectively, in the hierarchy of observing systems suggested by the H2020 GAIA-CLIM project (see D2.11). This will require substantial and coordinated improvements in all three areas; satellite and in situ observing, data assimilation and numerical models.

7. The generally low scores on data handling from in situ field programs remain a problem, given some of the recommendations above. The assessment concludes that this is a consequence of how these programs are funded and is intimately linked program sustainability and the funding model for scientific projects. Although almost all research funders today require data to be openly available, this has not improved the situation. If some of the organisational recommendations in this report is implemented, improving the sustainability of the observations, this will likely improve this issue. However, the research funding models must also be amended so that the extra cost of publishing high-quality data is covered. It is also necessary to improve collaboration between the data providers and the managers of data repositories and the data curators. Closer connections between scientists developing the observing systems and stakeholders outside the science community will ensure that the observations can support societal needs.

8. Arctic observing systems also include Community-Based Monitoring (CBM) systems established by local communities in a bottom-up process. Assessment of CBM systems is done in the documents from WP4.

In addition to the recommendations from the INTAROS assessment, there is a number of recent studies addressing the need for improving Arctic observing systems. For marine observing systems, there is an urgent need for ice-borne in situ observing systems that can provide near-realtime, open access data to improve weather and ice forecasting in the Arctic (Smith et al., 2019; Lee et a., 2019, Vihma et al., 2019). The value of sustained in situ Arctic Ocean observation for sea-ice predictions in the Barents Sea was recently demonstrated by Bushuk et al (2019). In the Arctic Boreal Zone (ABZ) new satellite observations are needed for snow and ice albedo, snow water equivalent, permafrost, vegetation, and fire monitoring, and lidar for greenhouse gas concentration (Duncan et al. (2019). These recommendations are in line with the results of a previous assessment of the need for polar satellite observations (Polar View, 2016).

The synthesis of the INTAROS gap analysis and the recommendations presented in this report will be used in defining strategies to enhance and optimize the Arctic observing system. The report is therefore a milestone in development of the Roadmap for a sustainable Arctic Observing System, which is major goal of INTAROS. The work of INTAROS is in line with other initiatives to develop roadmaps for Arctic observing systems, such as described in publications by Smith et al. (2019); Lee et al. (2019); SAON Road Map Task Force (2019); and EU-Polarnet D2.6, (2019). These documents provide foundation for investing in Arctic observing systems to support different Societal Benefit Areas, including scientific and operational requirements. Roadmaps for Arctic observing systems need to consider the technological readiness, logistical feasibility, costs and priorities of the variables to be included in the systems. Organisation and structuring of the systems across scientific disciplines and between governance bodies in the Arctic is an open question, although SAON is envisaged to be an umbrella connecting the different systems.

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Appendix A: Non exhaustive list of Arctic *in-situ* observing systems and satellite products that were not included in the assessment

Community based observing systems are not considered in this assessment

A1 Multidisciplinary

IN-SITU

- Circumpolar Biodiversity Monitoring Programme (CBMP)
- Environment Canada
- North Pole drifting stations (AARI, RU)

A2 Atmosphere

IN-SITU

- Several atmospheric composition variables (incl. ozone profiles, trace gas concentrations, atmospheric chemistry); key systems related are also lacking (e.g. EMEP, TRAGNET, AERONET)
- Data from individual measurement campaigns are often difficult to find; many of those were likely not included
- ARM, NOAA and some other long-term so-called “super-sites” observation stations (e.g. Barrow, Oliktok Pint, Eureka, Alert, Pearl, Summit Station etc.), many belonging to the IASOA
- Long Term Ecological Research (LTER) Network (4 stations in Alaska)
- Atmospheric data from the International Arctic Buoy Program and from other non-IABP buoy systems
- The current assessment of GHG observation systems excludes flux chamber sites. Due to very heterogeneous characteristics in spatial and temporal observational coverage and also in the applied methodology, composing a comprehensive assessment of existing flux chamber experiments is a big challenge. An attempt to generate a first overview is currently underway at http://cosima.nceas.ucsb.edu/carbon-flux-sites/.

A3 Marine physics

IN-SITU

- Ocean Network of Canada
- NABOS system (US/international)
- iAOOS Equipex (France)
- Fram Strait Arctic Outflow Observatory (Norway)
- Tides Norway
- NOAA Fisheries (Alaska)
- AOOS (Alaska Ocean Observing System)
- Pacific Distributed Biological Observatory
- Argo Canada
- Tides Canada
- Tides Russia

- Several other systems in the Western Arctic maintained by US and Canada

A4 Sea ice

IN-SITU:

- Snow and Ice Mass BAlance (SIMBA) buoy network

SATELLITE:

- NSIDC is the most important portal. This system is by far too complex and comprehensive to be assessed in our deliverable.
- JAXA portal
- SICCI sea ice concentrations provided by met.no.
- Sea ice concentration data products from MIRS at https://www.ospo.noaa.gov/Products/atmosphere/mirs/seaice.html
- Snow Melt Onset Over Arctic Sea Ice from SMMR and SSM/I-SSMIS Brightness Temperatures

A5 Marine Biogeochemistry

IN-SITU:

- Data from gliders, floats and ships.
- Repeated oceanographic expeditions conducting full oceanographic section for ocean physics, biogeochemistry (including the carbon cycle) and biology on hot spots where out of the scope because of the modest funding available in INTAROS.

SATELLITE:

A6 Hydrology

IN-SITU:

- The data availability of each national hydrological service was not assessed in full detail. The assessed Arctic-HYCOS data provides a sub-set of all available stations, selected to represent river flow to the ocean and Arctic hydrological regimes as good as possible.

SATELLITE:

- Satellite altimetry missions providing water levels of inland waters (e.g. ESA Sentinel 3)

A7 Glaciology

IN-SITU:

- GlacioBasis and Remote Sensing sub-programmes of the Greenland Ecosystem Monitoring programme
- The Camp Century Climate Monitoring Programme
- NASA’s airborne IceBridge programme, measuring ice elevation and ice thickness
- Summit Station on the Greenland Ice Sheet
- K-transect mass balance programme on the Greenland Ice Sheet (only indirectly through UPM’s WGMS assessment)

- Canadian mass balance programmes (only indirectly through UPM's WGMS assessment)
- Alaskan mass balance programmes (only indirectly through UPM's WGMS assessment)

SATELLITE:

- Near-real time melt maps of Greenland derived from gridded brightness temperatures from the Defense Meteorological Satellite Program (DMSP) Special Sensor Microwave Imager/Sounder (SSMIS) passive microwave radiometer.
- MODIS

A8 Terrestrial snow

IN-SITU:

- Snow data assimilation system (SNODAS) products (limited to NA) from NSIDC
- Blended data products (e.g. SSM/T and MODIS snow cover) from NSIDC
- Campaign datasets from NSIDC (e.g. CLPX)
- Snow status (wet/dry) observations in general
- Snow precipitation measurement networks in general
- Snow Telemetry (SNOTEL) sites in Alaska, operated by operated by the Natural Resources Conservation Service (NRCS) of the United States Department of Agriculture in the Western United States.

SATELLITE:

- NASA SMAP soil F/T from NSIDC
- MEASURES Global record of Daily Landscape freeze/thaw status from NSIDC
- MODIS Terra/Acqua snow cover, snow extent, surface albedo

A9 Seismology

IN-SITU:

- Short term temporary deployments.
- U.S Geological Survey

Appendix B: Details results and recommendations for specific variables

B1 Ocean and sea ice

Key strengths:

1. Large Arctic Ocean in-situ observation community
2. Mature data storage systems for remote sensing data (? see 3)
3. Sensor technologies with high readiness level for physical parameters
4. Platforms for collections of *in-situ* observations in open ocean with generally high readiness level
5. A few long-term observatories, providing time series of essential physical ocean variables in key locations that can be relatively easily enhanced to include new parameters (e.g. biogeochemical variables)
6. Satellite products of sea ice concentration have coverage and resolution on goal level defined by OSCAR requirements.

Key gaps:

1. The majority of measurements collected through short term funding which makes it difficult to sustain consistent long-term observations.
2. Low spatial coverage by autonomous ice-based platforms in the central Arctic Ocean
3. Few fixed *in-situ* data collection system (bottom anchored moorings and tide gauges), in particular in the central Arctic Ocean.
4. Autonomous sensors to measure biological and biogeochemical parameters in the Arctic are lacking.
5. Sparse biogeochemical and biological observations due to 4.
6. Sparse observations in the deep ocean (particular under sea ice)
7. Lack of near-real-time in-situ observations from subsurface fixed and mobile platforms.
8. Lack of standard metadata and data formats for certain categories of data.

Main recommendations:

1. Ensure development of multipurpose and diversified observing systems in the Arctic including Lagrangian platforms and fixed observatories.
2. Avoid redundant observing efforts through improved and continued coordination at the Pan-Arctic level and a requirement-driven design of ocean and sea ice observing system
3. Facilitate the development of small size, cost effective, robust and easily deployable mobile platforms for autonomous ocean and sea ice observations in the central Arctic.
4. Continue and increase the frequency of research cruises in the central Arctic and provide recommendation for a minimum set of ocean and atmospheric measurements collected during each cruise. Provide systems for autonomous measurements and easy-to-handle in-situ platforms to be used/deployed from ships of opportunity.
5. Facilitate sustained funding to enhance the spatial coverage of fixed ocean measurements in key locations, for monitoring variability of the Arctic Ocean environment over different temporal scales.
6. Facilitate funding needed to provide UW-GPS infrastructure for under-ice operations of gliders and Argo floats as well as acoustic thermometry. Develop robust technical solutions for gliders and Argo floats capable of under-ice positioning.
7. Develop and implement technical solutions for data transfer from subsurface and under-ice observing platforms via a surface link, to enable satellite communication and delivery of near-real-time observations.
8. When developing and implementing the observing system, secure funding needed to develop/adapt standards and tools for metadata and data preparation.

9. Facilitate competence building in data management for scientists and technicians.

B2 Marine biogeochemistry

Key strengths:

1. We do have promising approaches on how to build up a comprehensive monitoring system for the arctic within all domains.

Key gaps:

1. Lack of data to build up comprehensive and robust climatologies or baseline by which changes in the Arctic biogeochemical cycles can be clearly documented. Particular lack date in the interface between land, river and ocean that becomes a more critical issue under global warming scenarios.

Main recommendations:

1. Establish a comprehensive network of station measuring biogeochemical variables in the atmosphere, ocean and land. Focus on the "essential ocean variables" http://www.goosocean.org/index.php?option=com_content&view=article&id=14&Itemid=114 for the ocean and add some more particularly focusing on the sea ice ocean interaction

B3 Sea ice

Key strengths:

1. Five satellite sea-ice based data products, two drift products (D2.1, Tab. 13)
2. Sea ice satellite products generally well validated and stored, access easy (D2.1 Tab. 16)

Key gaps:

1. Few in-situ observations of sea ice available for validation of satellite products and continuous quality control
2. D2.1 and 2.2 describe many observation repositories and data products in detail, however the accessibility has not been assessed actively. I am aware that actively checking this would be much work which probably we cannot achieve within INTAROS.
3. Sea ice satellite data generally no automated quality control, frequently quality flags missing, uncertainty quantification weak
4. Comparison of satellite data products for the same geophysical quantity currently distributed over several tables. Makes inter-comparison of different data products for the same quantity cumbersome. Mainly applies to sea ice concentrations (5 products).
5. Threshold requirements are not met by several geophysical parameters, for example "Sea ice drift" (spatial resolution: 62 resp. 31 km instead of 25 km), "Thickness of thin sea ice" (spatial resolution: 30 km instead of 25), "Mean dynamic topography" (timeliness 360 days instead of 3 days)
6. Uncertainty only given for 2 out of 13 products (T. 17). Required in case of quantitative usage such as in assimilation.

Main recommendations:

1. Have more *in-situ* observations of sea ice for validation of satellite products and continuous quality control
2. For the five sea ice concentration products, a more detailed comparison should be done, combining spatial resolution and coverage (T 14), temporal coverage and resolution (T15), uncertainty characterization (T16, 17) into one table for easy overview.
3. Remark:
   D2.1 and D2.2 both already contain sections Recommendations (Sections 3 and 5, resp.). These should not be ignored.

4. Explicit uncertainty values should become a standard in future data products. This is already the case for the SICCI sea ice concentrations distributed by met Norway.

B4 Atmosphere

Key strengths:

1. Several key long-term atmospheric basic data sets are well-organized in data repositories and are available and accessible via WMO-linked platforms.
2. Well established long-term and ongoing data exist for some key composition variables (e.g. ozone)
3. The longest continuous data series on aerosol number is also >30 years and is still maintained
4. Recent efforts made in research infrastructures aimed at improving observation harmonization, calibration, data collection and back-up (e.g. ACTRIS or ICOS) show promise for the future.
5. Many data sets initially intended for other purposes also acquire atmospheric data. These data are in principle openly accessible, and therefore available to the atmospheric community.
6. Polar orbiting satellites orbit geometry means a lot of satellite data in the Arctic

Key gaps:

1. Severe lack of in-situ observation data north of the continents (i.e. Arctic Ocean), especially for the atmospheric vertical structure which is essentially non-existing
2. Inadequate accuracy for many satellite derived products, especially vertical structure and winter clouds
3. For several specific variables (mainly aerosols), measurement methodology is not uniform throughout the network and the measurement uncertainties are poorly quantified or not known
4. Spatial coverage of atmospheric composition measurements is insufficient, both vertical and horizontal
5. Most observation campaigns focus on summer seasons, sever lack of of winter data
6. For many datasets, there is a too long delay between the data collection and appearance in a database
7. Lack of observations on Arctic clouds: Currently 2 ACTRIS stations with detailed cloud properties within the AMAP area that are continuously operated, several less detailed measurements using ceilometers which are not fully exploited at the moment

Main recommendations:

1. Continue with efforts building harmonization and better quality assurance of aerosol/GHG/cloud data
2. Improving spatial coverage of aerosol observations at least in vertical and over the sea areas
3. Full exploitation of potential cloud observations from the Arctic
4. Better use of ships of opportunity for atmospheric observations in the Arctic Ocean, especially for the atmospheric vertical structure
5. Improving the temporal coverage of all composition data in order to better cover the winter season
6. Assure the continuation of the currently existing long-term measurements
7. Improve on the quality of some of the Russian sounding stations; improve traceability of WMO-related observations
8. Automatization of data collection and archiving, as moving towards (near) real time data to provide better/new products and services for the Arctic

9. For the Arctic Ocean, the only perceivable long-term solution is satellite observations in combination with very few in-situ observations; this requires both better satellite products, better in-situ data and better numerical models

B5 Greenhouse gas (GHG) monitoring

Key strengths

- Networks of tall towers and eddy covariance stations provides continuous, well-calibrated observations of atmospheric GHG mixing ratios and fluxes, covering hundreds of locations across the Arctic
- Very large field of view (footprint) of tall towers, extending over several 1000s of km per site, covering the largest fraction of key biomes in the Arctic, including different types of tundra, wetlands, lakes, and also forest ecosystems at the southern margins
- Tall tower network provides basic information for constraining large-scale, medium to coarse resolution greenhouse gas exchange fluxes at pan-Arctic scales, while eddy-covariance towers delivers flux exchange information at ecosystem scale (100-1000m) ith tall towers established in most parts of the Arctic, most regions in Canada, Europe, and Western Russia; also the Arctic Ocean receive good overall data coverage
- Continuous flux measurements from eddy-covariance towers available at high temporal resolution (30 min) throughout the year is possible, although often not achieved

Key gaps

- Several Arctic regions receive only limited data coverage, owing to sparse infrastructure; logistical constraints (site access, power supply) and harsh environmental conditions, leads to many eddy-covariance sites not operating year-round. Examples include the Russian Far East, Western Alaska, and the Eastern Canadian Provinces.
- In some regions, seasonal shifts in prevailing wind conditions result in varying data coverage for tall tower measurements of GHG mixing ratios over the course of the year. Such areas where footprint coverage gaps exist seasonally mainly include parts of Western Russia and Central Siberia
- While virtually all EC-sites provide flux exchange rates of CO2 and energy (latent and sensible heat) many non-CO2 gases have substantially weaker data coverage: only about half of the sites capture CH4 fluxes and other gases are rarely included.
- Not all listed EC-sites are currently active, although datasets from previous years are available.
- EC-sites have limited footprint and even considering all available sites and the pronounced variability in Arctic ecosystem, the existing network cannot provide information on the entire Arctic domain; this also makes the representativeness of the observed flux time series sometimes difficult to assess. In particular Siberia, but also some regions within North America, are not well represented

Main recommendations

- Investments in observational infrastructure in any of the areas with (seasonally) limited data coverage listed above are recommended to increase the overall performance of the pan-Arctic atmospheric network for greenhouse gas monitoring.
- With growing insights that wintertime fluxes play an important role for the Arctic carbon and energy budgets, an investment in winter-proofing existing eddy-covariance observation sites is highly recommended
- Since the methane budget plays a decisive role in the net carbon budget, an upgrade of existing eddy-covariance observation sites with gas analyzers for CH4 would substantially enhance the network performance.

- The establishment of new observation sites to cover critical gaps in network coverage especially in parts of Siberia and some areas in North America, concerning both the eddy covariance and tall tower networks, is highly recommended.
- Further detailed footprint analyses would help reducing the uncertainty related to small scale variability in the tower footprints

B6 Hydrology

Key strengths

- The Arctic-HYCOS project.

  This is an active project including National Hydrological Services from the Arctic council member states, with the aim to improve and sustain observational capacity, committed to provide hydrological data from operational monitoring networks of river fresh-water flow to the Arctic Ocean.

  Work is ongoing to improve the system with regard to metadata and data management gaps identified in INTAROS and to include more hydrological observations where available

  Arctic-HYCOS observation station network currently represents about 60% of the area draining into the Arctic Ocean and the non-gauged missing areas are well represented by the existing observations except for Greenland and high latitude islands in Canadian and Russian Arctic. The mean length of Arctic-HYCOS time-series is around 50 years, and for some stations > 100 years.

- Other observation systems assessed by INTAROS relevant for hydrology, are for instance: Pan-arctic in-situ and remote sensing-based observation systems for snow water equivalent, and glacier and Ice sheet observation systems

Key gaps

- River discharge data is estimated from water level observations, but in most cases neither the water level nor the transformation functions and parameters are given with the discharge data, reducing the re-usability, especially with improved possibility inland water levels from satellite altimetry.
- The largest spatial gaps in the Arctic-HYCOS network is found in 1) Greenland, 2) in high latitude coastal river basins such as the tundra area of Canada, Alaska, and Russian Federation that are not draining to one of the larger Arctic rivers, and 3) in Svalbard, Iceland, and Scandinavia. However, flow-to-ocean from rivers in Scandinavia and Iceland would be well represented if available observations were included from river basins smaller than the 5000 km^2 threshold. This threshold is used to qualify a station for the Arctic-HYCOS flow-to-ocean sub-network.
- The temporal coverage is very good, but latency may be up to 2 years for data to be updated in the central GRDC repository, although near-real-time preliminary data is provided from some countries
- Critical gaps in the Arctic-HYCOS river discharge data with respect to I and R in FAIR principle: Data from the central repository at GRDC, as well as from many of the national databases, are not provided in an Interoperable way and uncertainty information is not provided, uncertainty or errors in metadata, and supporting documentation is either lacking or has variable quality from the different providers.

Main recommendations

- Continue the pan-arctic Arctic-HYCOS collaboration to provide river discharge data!
- Improve the timeliness of the quality controlled data, and strive to provide real-time or near real-time preliminary data from all countries.

- Consider extending the “flow-to-ocean” station network to improve the spatial coverage as much as possible with stations available in the existing national networks.
- Include more observations and model estimates from Greenland in the Arctic-HYCOS network.
- Provide the original water level observations and not only the derived river discharge data
- Include some uncertainty information.
- Improve supporting documentation.
- Improve metadata on station location and delineation of the upstream drainage basins.

B7 Glaciology

Key strengths:

1. Satellite remote sensing has intensified over the recent decade, providing key data products like ice velocities, albedo, elevation change and mass changes at a high spatiotemporal resolution
2. Existing long-term monitoring systems (instrumentation) on and next to the Greenland Ice Sheet margin, including PROMICE and GNET (to be taken over by Denmark)
3. A worldwide glacier inventory (RGI)

Key gaps:

1. Lack of sustainable glacier mass balance time series from the Russian Arctic, Greenland and High Arctic Canada
2. Lack of sustainable snow accumulation observations from the Greenland ice sheet interior
3. In-situ SWE and rain observations from the ice sheet margin
4. Improved in-situ radiation measurements for satellite validation
5. Improved in-situ ice velocity observations for satellite validation
6. Glacier thickness data from more high Arctic glaciers needed to assess ice volume

Main recommendations:

1. Continue K-transect mass balance time series on the Greenland Ice Sheet (>25 yrs about to be stopped in 2020)
2. Continue GC-Network stations on the Greenland Ice Sheet (>20 yrs about to be stopped in 2021)
3. Improved in-situ instrumentation to provide data for validation of satellite data products, including radiation, SWE, rain and ice velocity
4. Initiation of glacier mass balance programmes in the Russian High Arctic, Greenland and the Canadian High Arctic
5. Airborne missions to measure glacier and ice sheet thickness in the Arctic (the NASA IceBridge mission is about to be stopped)

B8 Terrestrial cryosphere observing systems

Key strength:

1. Some basic snow parameters (snow depth, density and temperature profile) are measured also in terrestrial networks focusing on GHG, atmospheric fluxes, or ecosystem (e.g. Fluxnet, PEEX, GEM). These data are in principle openly accessible, and therefore available to the cryosphere community.
2. Some basic snow parameters related to e.g. soil freezing, can be deduced from soil permittivity profiles, frost tube networks and soil temperature profiles.
3. Historical datasets on e.g. Snow Water Equivalent from the former Soviet Union, Canada and Scandinavia have recently been assembled which provide a basis for satellite data product validation

Key gaps:

1. Observation networks are too sparse, and spatial coverage of key variables (snow depth, snow density, snow albedo) is inadequate for satellite validation and environmental monitoring
2. The measurements of some key snow variables (snow density, snow water equivalent) are still mostly manual and time consuming. Specialized parameters such as snow profiles including snow microstructure are very rare and non-continuous even for well-equipped sites
3. The management of in-situ snow data has very low maturity, not enabling data to fulfill the FAIR principle
4. Current satellite SWE products are generally unable to meet the requirements for product accuracy and spatial resolution. High degree of inconsistency between model-derived datasets and observations.
5. Microwave-based satellite snow products are provided at a spatial resolution of 25 km which in insufficient for most users, in particular in NWP and hydrology. Also latency exceeds NWP requirements

Main recommendations:

1. Given the large variability in snow cover conditions across multiple spatial scales, distributed snow depth and SWE measurements within the footprint area of SYNOP stations, Arctic eddy covariance towers, and satellite sensors (in cal/val sites), would be needed.
2. Automatic instrumentation should be adopted instead of manual ones, especially when cheap and practical solutions are available; this allows for Increased distribution covering areas and glaciers of different characteristics for better representation of regional snow conditions.
3. Some properties presently measured for research applications should be acquired also by operational networks, particularly when they are collected with automatic instruments.
4. Development and use of internationally agreed measurement protocols for each of the applied measurement techniques are strongly encouraged
5. Research is needed to develop methods to retrieve snow properties from the synergy of optical and microwave satellite observations to compensate for the limitations caused by only visible or only microwave satellite observations.

B9 Seismology

Key strengths

1. A broad international corporation on data exchange, international recognized standards and protocols for data exchange. Well established data centers for parametric and waveform data. Long-term, continuous monitoring in many land areas.

Key gaps

1. Lack of monitoring in the Arctic Ocean, sparse monitoring and real time data exchange in the remote regions surrounding the Arctic Ocean.

Main recommendations

1. Committed allocation of experienced resources to process and analyze seismological data of Arctic origin at national level.
2. National and international support to land-based seismological monitoring in remote Arctic areas.
3. International dedication to undertake permanent seismological monitoring on the Arctic Ocean sea floor at 5-10 evenly distributed locations.

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