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Synthesis and technical recommendations

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Authors: **Agnieszka Beszczynska-Möller (IOPAN, lead author)**, Andreas Ahlström (GEUS), Roberta Pirazzini (FMI), Francisco Navarro (UPM), Bin Cheng (FMI), Marcel Babin (CNRS-Takuvik), Claudie Marec (CNRS-Takuvik), Mikael Sejr (AU), Marie-Noelle Houssais (CNRS-LOCEAN), Christoph Herbaut (CNRS-LOCEAN), Frank Nilsen (UNIS), Truls Johannessen (UiB-GFI), Nicholas Roden (UiB-GFI), Andreas Rogge (AWI), Ian Allen (NIVA), Angelika Renner (IMR), Geir Ottersen (IMR), Thomas Soltwedel (AWI), Jean-Pierre Gattuso (CNRS-LOV), Andrew King (NIVA), Marie-Helene Forget (CNRS-Takuvik), Pierre Testor (CNRS-LOCEAN), Waldemar Walczowski (IOPAN), Delphine Matthias (CNRS-UIEM), Hanne Sagen (NERSC), Peter Worcester (SIO), Matthew Dzieciuch (SIO), Bruce Howe (WHOI), Mathilde Sorensen (UiB), Peter Voss (GEUS), Matthias Goeckede (MPG), Torsten Sachs (GFZ), Walter Oechel (UNEXE), Donatella Zona (USFD), Florent Domine (CNRS-Takuvik), Michael Tjernström (SU)

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EXECUTIVE SUMMARY

This document, ***Deliverable 3.16 Synthesis and technical recommendations***, provides a summary of sensors, platforms, and observing systems implemented during INTAROS field campaigns and presents technical recommendations based on experience gained from operating these components for collecting in situ observations during the project.

This document is intended to:

- Shortly summarize details of all individual sensors, platforms, and systems developed and deployed during INTAROS for collecting in situ measurements in the cryospheric, ocean, atmospheric and terrestrial domains,
- Provide main recommendations for the technology used in INTAROS with the respect to become a component of a future sustained Arctic observing system,
- Describe main limitations of technology used and recommendations to overcome these limitations to enable including this technology in a future observing system,
- Overview other technical solutions which could better replace or complement technology used during INTAROS to provide similar set of observations for a future observing system,
- Identify and describe cross-cutting technical recommendations based on recommendations for individual systems,
- Summarize main challenges and achievements in implementing in situ observations in WP3,
- Summarize main technical recommendations from WP3 for use in the INTAROS Roadmap for a future integrated Arctic observing system.

INTAROS has collaborated with many other field programs and projects which have contributed to the results in WP3. These programs and projects are listed in Annex A. A summary of platforms and sensors developed and implemented during INTAROS, including main challenges and final outcomes, is provided in Annex B.

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1. Introduction

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

To optimize the fieldwork effort and maintain the integrity of new data, we have built on and effectively extended infrastructure already existing in selected reference sites and distributed observatories. New clusters of sensors have been integrated into a variety of platforms, and several experimental setups have been tested and implemented with the intention of sustained use in a future integrated Arctic observing system (iAOS). New collected measurements have been pre-processed and formatted to provide standardized data sets ready for integration into existing data repositories and registered in the INTAROS data catalogue. Metadata and data formats for observations made with multidisciplinary platforms have been developed in collaboration with data managers in WP1 and WP5. Selected data sets have been exploited in demonstration actions in WP6 and provided for the consultations with stakeholders in WP7.

Different needs and requirements for collecting observations from ice, ocean, atmosphere, and land domains are reflected in the variety of sensors, platforms, and experimental setups implemented in WP3. Detailed descriptions of all observing components, their technical specifications, field deployments, and provided data can be found in the previous deliverables, devoted to (i) the design of system components (deliverables D3.1, D3.2, D3.3, D3.4, and D3.5), (ii) first implementation (deliverables D3.6, D3.7, D3.8, D3.14, and D3.9), and (iii) final implementation of different observing systems and platforms (deliverables D3.10, D3.11, D3.12, D3.13, and D3.15). In these previous reports all activities were described task-wise, reflecting three key sites and two distributed observatories.

In this report we present a short summary of different components of an Arctic observing system operated during INTAROS, focusing on their applications in different domains. Collaboration with other projects and programs is shortly outlined in Section 2. Implementation and operation of different sensors and platforms for cryospheric (Section 3), oceanic (Section 4), and atmospheric and terrestrial (Section 5) measurements is concisely described with main attention paid to the experience gained from numerous INTAROS field campaigns. Specific technical recommendations are provided for individual systems, platforms, or sensors, while considering main challenges and impediments encountered during implementing each specific component.

However, some recommendations are more generic and common across different systems within the same domain or even across all domains. They apply to more general requirements, relevant for a wide range of sensors and platforms and are summarized in Section 6. Additional conclusions on non-technical but logistic and operational challenges are also included.

Finally, Sections 7 provides a summary of new observations implemented during INTAROS and Section 8 presents main technical recommendations as a contribution to the INTAROS Roadmap towards a future integrated Arctic observing system.

2. INTAROS collaboration with other programs and projects

International collaboration with common scientific and logistical work components is crucial for meeting the challenges of the complexity of natural systems, demanding specific tailored observing systems suitable for Arctic conditions (Lee et al., 2019). For the design, development, and implementation of new or extended in situ observing platforms and systems, INTAROS leveraged extensive collaboration with different international and national programs and projects, actively involved in collecting in situ observations in the Arctic and marine or terrestrial field operations.

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

A detailed list of INTAROS collaborating programs and projects, including the scope of activities, is provided in Annex A. Some examples of collaborative efforts under INTAROS WP3 are listed below to give an idea of a wide network of mutual support and joint efforts that was crucial for INTAROS observational activities. For monitoring of the Greenland Ice Sheet, INTAROS collaborated with PROMICE (Programme for monitoring of the Greenland ice sheet) and GC-Net (Greenland Climate Network), while measurements in the Greenland coastal waters were done in collaboration with the GEM (Greenland Ecosystem Monitoring) program. The cooperation between INTAROS and CAATEX as well as A-TWAIN and Nansen Legacy was critical for mooring operations north of Svalbard. In the central Arctic Ocean, INTAROS activities took place in collaboration with the MOSAiC campaign (sea ice and atmosphere), the Equipex IAOOS project (ocean and sea ice), and the ACAS project (atmosphere). In Fram Strait the new ArcFOCE system was implemented in collaboration between INTAROS and the LTER Hausgarten Observatory in FRAM programme. INTAROS measurements of carbonate chemistry in the ocean and GHG on land contributed to ICOS. Seismic measurements in INTAROS were done in collaboration with EPOS-N and GLISN. INTAROS activities in the Sodankylä-Pallas Observatory were supported by the SnowAPP project while INTAROS contribution to the Baffin Bay Observatory was in collaboration with the Amundsen Science and Sentinel North projects. Numerous other national and international projects joined forces with INTAROS to improve in situ observations in the Arctic (see Annex A).

Unexpected development of the COVID-19 pandemic during the last three years of the INTAROS duration resulted in restrictions in mobility, organization of field expeditions, and access to remote places as well as a shortage of qualified manpower. Numerous research cruises or land expeditions were cancelled, and planned field operations had to be postponed, even if it entailed risk of losing valuable instruments and/or collected time series of observations. Only thanks to extensive collaborative network and support provided by other projects and programs, the planned fieldwork activities could be accomplished with possible minimal cutbacks and solutions were found for the complex logistic demands when field operations had to be repeatedly readjusted.

3. Implementation of the observing system – cryosphere component

A major challenge regarding the Arctic icesheets, glaciers and sea ice is the difficulty of obtaining high quality in situ observations in the extremely harsh environment. Due to logistical difficulties, it is often not possible to revisit or replace instruments at geographical positions more than once every few years, ensuring that robustness takes precedence over other factors. Adding new sensors or improving existing systems requires reliable and well-tested solutions that are adapted to the extreme working conditions. For observatories, based on sea ice and drifting in the central Arctic Ocean, no access is possible after deployment. Sustainability and quality of the data return from the ice-based observatories depend on robustness of the measuring sensors, accurate geo-positioning of the observatory, and communication links. Drifting ice-based observatories need to be regularly replaced to maintain the monitoring capacity. The operational performance of in situ cryosphere observatories, either on land or in marine areas, depend on appropriate power supply as well as on a platform design capable to withstand the harsh environment and the accuracy of the geopositioned provided with the data.

3.1. Greenland Ice Sheet observations

Contributors: Andreas Ahlström (GEUS), Roberta Pirazzini (FMI)

Accurate long-term measurements of climate and surface mass balance of the Greenland ice sheet are crucial to assess the surface and near-surface atmospheric conditions, the freshwater runoff from the Greenland ice sheet, and the total mass budget of the ice sheet, including the mass gain from snowfall during the winter season. Different new or improved sensors were added to the existing PROMICE network of automatic weather stations, located on ice in the ablation area of the ice sheet to measure new variables (snow water equivalent, precipitation) or refine existing measurements (high accuracy positioning, tilt and azimuth sensors, better observations of snow albedo over the ice sheet).

3.1.1. Sensors implemented - snow-water equivalent measurements

A novel ruggedized system of SnowFox sensors for measuring snow-water equivalent on the ice sheet margin was added to the AWS network in order to capture meltwater retention mechanisms in the snow and firn on the ice. The new sensor measures how much mass that accumulates as snow during the winter season on the Greenland ice sheet. Five SnowFox instruments were installed at four PROMICE locations. The system shows promises and the SWE measurements fully complement the other instruments to monitor changes in the daily surface mass balance from the PROMICE automatic weather stations. Eventually, the SnowFox will be integrated in the standard station setup and established at all the stations. It has potential to become part of a sustained Arctic observing system.

3.1.2. Technical recommendations - snow-water equivalent measurements

In general, the sensor works, but the system needs a lot of power to measure and record the neutron counts. The SWE measurements will still be kept as a separate system alongside the PROMICE station in order not to jeopardize the core station operation. A combined windmill-solar panel setup has been tested for recharging batteries to avoid data gaps. More and better battery technology with more power for the SWE system is need for optimal use in a future system.

3.1.3. Sensors implemented - high accuracy GNSS positioning

Precise positioning capability of the on-ice sheet network provides calibration for satellite-derived ice velocity maps used to calculate the ice-dynamic mass loss to the ocean and monitor potential feedbacks between meltwater formation and ice dynamics. New dual frequency receiver module (using L1 and L2 bands from GPS and GLONASS) was selected to minimize power consumption so that battery powered operation is possible through the polar night while still providing high accuracy positions. The developed system is also compatible with new receivers capable of receiving Galileo signals (and L5 band) in addition. The system was further optimized to minimize power consumption (using passive antenna, extensive power management). The system was installed on one AWS station.

3.1.4. Technical recommendations - high accuracy GNSS positioning

The main recommendation is to carefully prioritize the requirements when choosing or designing GNSS instruments for use in a sustained Arctic observing system, because design and configuration tradeoffs unusual under different geographic settings may enable otherwise impossible or impractical applications. Current off-the-shelf GNSS products are optimized for highest achievable accuracy or towards small size, low power, and resilience to difficult environments. Both applications rely on rapidly updated real-time positions of rapidly moving receivers. In contrast, remote installations in a sustained Arctic observing system may require only hourly or daily positions from slowly moving receivers with zero-interference and unobstructed view of the sky. In all cases, the main challenge is to operate on battery through the polar night. On the other hand, accuracy and price must be put into perspective when considering e.g. the mechanical stability of stations in the ablation zone of polar glaciers and the overall costs of operating in the Arctic. Once the choice of designing and using instruments specifically optimized for operation in the Arctic, another recommendation is to constantly keep up with the fast pace at which new versions of GNSS receivers come to the market, as full backward compatibility of the newer products is not always guaranteed.

The major limitation of high accuracy GNSS applications in the Arctic is that both public and commercial augmentation services broadcast using geostationary satellites which are low or below the horizon in the Arctic. These services improve the accuracy of the positions calculated autonomously by each receiver in the field, in some cases reducing uncertainties to below 10 cm and making near real time high accuracy monitoring possible without transmitting large amounts of raw data for postprocessing. It would be possible to mitigate this issue by developing a pre-processing algorithm that can be implemented into the firmware of the field units to smooth, downsample and compress the raw GNSS observables enough that they can be transmitted via satellite with acceptable power consumption and airtime fees. Where a stable base receiver can be installed within range of very low power radio link, RTK techniques would provide even higher accuracy without the need of transmitting any raw observables via satellite.

While INTAROS was running, the first low-cost dual frequency GNSS modules came to the market. Their most attractive feature is the significantly lower power consumption, at the expense of a moderately noisier signal. While the price advantage is minor when considering the overall costs of operating in the Arctic, it may become significant for applications where a large number of units would be required, and for units which cannot be safely or economically retrieved. The low power consumption may make it possible to add such receivers to existing stations without need for adding batteries. The higher noise may not be a problem for installations that are not completely stable such as tripod on melting glaciers surfaces.

3.1.5. Sensors implemented - new radiometer tilt and azimuth instrument

Zeroing and calibrating each unit is very important for both the compass and tilt sensors. In the lab, measuring a full calibration curve allows to approximate the accuracy of the dedicated tilt sensor and satisfy the requirements for correction of the PROMICE radiometers. However, the stability over temperature of these calibration curves has not been evaluated. The magnetic compass is susceptible to the effects of nearby magnetic materials, and it is not feasible to recalibrate it after being mounted onto the radiometer or weather station without removing the entire assembly from the station. Furthermore, the steep magnetic field lines at high latitudes limit the accuracy of the azimuth determination. A simple sun azimuth sensor (3 different INTAROS prototype units) has been tested with some success as a replacement the magnetic compass.

3.1.6. Technical recommendations - new radiometer tilt and azimuth instrument

Building a rugged solution for field deployment and avoiding obstruction by snow and riming may be difficult. On the other hand, we do not expect azimuth to change rapidly, so it may still be a viable technique. Another option would be to replace the magnetic compass with GNSS-based attitude determination. This could be made sufficiently accurate but the cost, power consumption and complexity would be much higher. Additionally, because the attitude would be determined from the baseline between two sufficiently separated antennas, any misalignments with the radiometer or deformation of the supporting boom would introduce errors in the measurements.

The market for sufficiently accurate but small and low power magnetic compasses appears to be very limited and lead times from the manufacturers can become a year or longer, so it is highly recommended to maintain a sufficient stock in house and keep an eye on any product change or discontinuation notes from the manufacturer.

3.1.7. Sensors implemented - rain gauges

Rain gauges augmented the in-situ PROMICE stations on the Greenland ice sheet in order to capture the transition of a precipitation regime dominated by snow to one with frequent rain events. Simple tipping-bucket rain gauges to automatic weather stations in six locations, with the technical development directed mainly at obtaining a functional set-up in an extremely hostile environment. As the rain gauges have proved both necessary and adequate, these instruments are now being rolled out for deployment on 40 automatic weather stations currently in use on the Greenland ice sheet and peripheral ice masses in the PROMICE, GC-Net and GlacioBasis monitoring programmes.

3.1.8. Technical recommendations - rain gauges

Observing rainfall on the Greenland ice sheet has rapidly become a high priority as what used to be a rare event, now happens frequently, with important consequences for the surface mass balance. The rain gauges should be simple and robust, rather than large-scale installations. Comparisons on nunataks have shown that the performance of the smaller, simpler rain gauges are adequate. The rain gauges should be coupled to and transmitting data via the AWS, given the urgency of the data for near real-time model comparison and validation. The rain gauges are simple systems and will not provide good data on solid precipitation (snowfall). This limitation cannot be overcome by this type of gauge and snowfall should be measured by other means, e.g. combining sonic ranging devices with up-looking radar or SnowFox instruments measuring the attenuation of cosmic radiation by water molecules. Thus, a final key recommendation is to treat rain and snow as separate parameters, to be measured with different technologies.

3.1.9. Methodology implemented - improved ice sheet albedo measurements

The laboratory facility was developed in FMI to characterize the thermal and angular response of pyranometers (and of whatever other optical device including spectral radiometers). The accuracy and spatial representativeness of the in-situ snow albedo observations (from PROMICE and GC-Net networks) over Greenland ice sheet was enhanced through improved instrument characterization as well as a methodology for correction of in-situ ice sheet albedo measurements. The developed procedures to characterize the thermal and angular response of pyranometers and, thus, increase the accuracy of the solar irradiance and albedo measurements has been applied to some of the CNR1 and CNR4 net-radiometers of the PROMICE network over the Greenland ablation area managed by GEUS. The results showed that, to increase inter-comparability and accuracy of the measurements, it would be beneficial to extend the thermal and angular characterization also to the other pyranometers of the PROMICE and GC-Net networks, the latter covering the Greenland accumulation area and being recently passed under GEUS management. These characterizations will increase the quality and, thus, the value of the data, and will enhance the cost efficiency of the networks without any additional load to the logistics.

3.1.10. Technical recommendations - improved ice sheet albedo measurements

Some of the correction algorithms derived from the instrument characterization cannot yet be applied for near-real time generation of the irradiances and albedo products. Further development steps are needed for the data processing, for which a continuation of the collaboration between FMI and GEUS is desirable.

Pyranometers are a well proven and relatively cheap instruments applied for irradiance and albedo measurements since several decades. Currently there are no other technical solutions that could replace them, as the alternative way to measure shortwave irradiance and albedo is through spectro-radiometers or hyperspectral cameras that are one order of magnitude more expensive, consume more power, are less weather resistant and require more maintenance than pyranometers.

Pyranometers with infrared filters could be installed next to unfiltered pyranometers to separate the visible and infrared radiation. This solution would enhance the spectral resolution of the shortwave irradiance and albedo measurements, for instance enabling the discrimination between the effect of impurities/algae and the effect of snow/ice metamorphism on albedo. Alternatively, cheap spectro-radiometers should be developed, which would measure only the shortest wavelengths of the solar spectrum (avoiding the expensive photodiodes needed for near-infrared radiation) and would be installed in sturdy, weather-proof enclosures.

3.2.Ice thickness measurements with airborne ground-penetrating radar

Contributors: Francisco Navarro (UPM)

3.2.1.Sensors and platforms implemented

The instrument developed during INTAROS is a new version, initially named VIRL8, of the already available ground-penetrating radar VIRL7. The planned main differences were in terms of its internal parameters, in the construction of the control and recording unit (CRU) and in the structure and switch type of the transmitter. The equipment was successfully field-tested taking advantage of the field campaign in Antarctica but the planned full campaign in the north-western Greenland was cancelled due to COVID-19. Consequently, no ice-thickness data collection with this instrument has been possible in Arctic glaciers but the data set from field tests in Antarctic was available to evaluate the improved system. Test flights delivered 200 km of good radar profiles over ice, proving the concept of the new helicopter-borne radar system in the field.

Airborne ground-penetrating radar (GPR), as considered within INTAROS with the aim of estimating solid ice discharge to the ocean, is mostly addressed to ice-thickness measurements, in particular close to the calving fronts of tidewater glaciers or floating ice tongues. An important feature of ` is that, if they are combined (as usually done) with a simultaneous glacier surface topography measurement, their subtraction provides the bed topography. If the bed topography is assumed to not change significantly with time (which is a reasonable assumption in short-to-mid time scales), then once determined a bed topography it is not necessary to measure the ice-thickness again, being sufficient with a new surface topography measurement (which is much less costly) if we aim at monitoring the temporal changes of ice discharge. Consequently, the GPR technology, rather than being applied repeatedly at certain locations for monitoring purposes, should be applied at as many different locations as possible, to provide a comprehensive (and as accurate as possible) knowledge of the subglacial bedrock topography.

3.2.2. Technical recommendations

The sea-terminating glacier fronts are almost always heavily crevassed, and this makes not possible surface-based GPR measurements, which would be much less costly than airborne ones. Therefore, the cost will be an unavoidable limitation of these measurements. On the other hand, the frontal crevasses, especially if water-filled (even if partially), reflect and diffract much of the radar-transmitted energy, preventing it to reach the glacier bed. Consequently, it is most important that the GPR measurements close to the calving fronts be complemented by bathymetric measurements at the fjords where the glaciers end, and as close as possible to the glacier fronts. These bathymetric measurements are often very difficult (impossible at times) due to the presence of ice mélange. But undoubtedly a combination of ice-thickness measurements by airborne GPR close to the calving fronts and bathymetric measurements by depth sounders at the fjords, in the vicinity of the calving fronts, is the ideal setting and therefore should be aimed whenever possible, even if both are costly. Another challenge is the presence of nunataks causing strong lateral reflections of the transmitted radar signal, which mask the bed reflection. As this is physically unavoidable, developing software tools allowing to cancel the effects from these lateral reflections and enhancing the bed reflection is a priority task.

3.3. Sea ice and snow on ice measurements in the Arctic Ocean

Contributors: Bin Cheng (FMI)

3.3.1. Sensors and platforms implemented

During INTAROS, several high-profile international Arctic field campaigns have been carried out. Up to 38 SIMBA (snow and ice mass balance apparatus) buoys have been deployed in different regions in the Arctic Ocean and drifted along with the ice floes. Additionally, one SIMBA buoy was deployed in the coastal land fast sea ice zone in the Young Sound, east Greenland. The average working time of SIMBA buoy is about one year depending on the in-situ environment and configurations of data acquisition frequency. All the SIMBA buoys deployed during INTAROS period have been terminated. Most of them worked quite well and provided valid observations data for scientific research. Among all deployed SIMBAs, only few of them failed not long after deployment, mainly due to the malfunction of thermistor strings, probably caused by ice deformation. The SIMBA thermistor string-based ice mass balance buoy would be suitable to become a component of a future sustained Arctic observing system. SIMBA is a simple, innovated and cost-cutting designed apparatus. In addition, SIMBA requires a simple deployment procedure and has the capacity to be recovered and reused multiple times These characteristics ensure a large number of deployments compared with the sophisticated and expensive observation instrument.

3.3.2. Technical recommendations

For a sustainable and remote operation system, the cost for data transmission and capacity of battery are bottlenecks. In a short term, there is not much we can do to overcome those issues technically, except to optimize them by smart management (remote configuration to save power, GSM data transmission for SIMBA operation near the Arctic coastal area). However, in a long run, we expect the cost for data transmission can be reduced drastically and capacity of battery can be greatly enlarged. So, SIMBA can be more robust and provide more data.

The spatial variations of snow and sea ice in the Arctic Ocean are large. A cluster-type of SIMBA deployments in regional domain could provide valuable in-situ data to extract better information on snow and ice temporal and spatial variations. The consortium-based deployment of SIMBA could be another recommendation to boost utilization of SIMBA. For individual research organization, the SIMBA can be deployed upon research projects. However, if a consortium composed by several research organizations who have the capacity to deploy SIMBA, it is then easier to build up a consortium-based SIMBA network.

The USA CRREL IMB (ice mass balance buoy) and CRREL SIMB (seasonal ice mass balance buoy) as well as China, PRIC Unmanned Ice Station (UIS) are alternatives instrument for snow and ice mass balance observations. In terms of sophistication, those are better devices, but those are also more expensive and less likely to be deployed with a massive number.

The manual processing of SIMBA data is still largely used by individuals for research papers. A unified data processing technique to reliably and accurately determine sea ice thickness and snow depth from this kind of data is still missing. Several SIMBA algorithms have been developed (Zuo et al., 2018, Liao et al, 2018, Cheng et al, 2020) and worked well in cold condition. However, during summer melting season, the robustness of the algorithms reduced significantly. Further improvement of SIMBA algorithm in terms of fully utilize SIMBA-ET and SIMBA-HT data is underway. Currently ongoing work is focused on a procedure to identify ice-ocean interface applying neural networks (NEN), wavelet analyses (WAA) and Kalman filter (KAF). The procedure seems work well largely (Liao et al., 2021, under preparation). In a long run, however, the SIMBA algorithm should be applied particularly for the operational analyses of SIMBA data in real time.

3.4. Fixed station and UAV-based radiation measurements in the central Arctic

Contributors: Roberta Pirazzini (FMI)

3.4.1. Sensors implemented - fixed radiation station

The FMI broadband radiation station was installed on the main ice floe during the MOSAiC experiment (November 2019 - November 2020) The station included upward and downward facing pyranometers and pyrgeometers to measure the surface shortwave and longwave radiative budgets, as well as an upward facing SPN1 sunshine pyranometer to measure the diffuse global radiation.

3.4.2. Technical recommendations - fixed radiation station

In situ sea ice surface radiation budget is traditionally measured with fixed, surface-based stations powered with batteries, solar panels, or the ship generator. The two-source power supply system (a battery-based circuit associated to the power cables connected to the ship generator) developed for our FMI station proved successful in the challenging task of providing continuous power supply during the one-year-long MOSAiC campaign. It is therefore a recommended solution for future sea ice campaigns.

3.4.3. Sensors and platforms implemented - UAV-based measurements

During MOSAiC leg 5 the drone SPECTRA equipped with broadband and spectral radiometers was operated in synergy with a smaller drone (Mavic 2 Pro) equipped with camera to perform photography mapping of the area measured by the SPECTRA drone. a photography mapping of the target area from an altitude of 40/50 m was performed with Mavic 2 Pro. The Mavic 2 Pro drone was guided along a serpentine pattern to reach a high overlap (ideally about 80%) between the photos and, thus, enable the derivation of the 3D surface topography through image processing. The SPECTRA drone was mostly guided along repeated transects at 5 m, 10 m, and 30 m elevations. Vertical profiles of albedo with SPECTRA hovering for 1-2 minutes at 5 m, 10 m, and 30 m were repeatedly carried out at specific locations over flags or buoys. Altogether, 17 flights were carried out with SPECTRA in 8 days, corresponding to ~5 flight hours, and 35 flights with Mavic 2 Pro in 18 days, corresponding to ~11.5 flight hours.

3.4.4. Technical recommendations - UAV-based measurements

Drones proved to be a very powerful and promising tool to measure albedo at various horizontal scales, which is a critical necessity in case of heterogenous surfaces such as the sea ice. Despite the many challenges met when operating close to the North Pole in freezing conditions, drones were often used when atmospheric conditions did not allow any helicopter measurements. Hence, drones enable to dramatically lower the cost and increase the temporal frequency of aerial radiation measurements compared to measurements performed via helicopters. Further development of the drone’s navigation system to enable safe and automatic piloting also close to the North Pole (where the magnetic orientation is jeopardized) would be greatly beneficial.

To improve the quality of the albedo measurements, in the next version of drone the current pyranometer will be replaced with one having faster response time (e.g. the KIPP and Zonen PR1) and the spectro-radiometers with a single, better performing spectro-radiometer, equipped with two optical fibres oriented upward and downward. This configuration requires a different drone matrix, with a single gimbal for horizontal alignment of the sensors instead of the current two gimbals and would also include a camera synchronized with the optical sensors. In addition to solar irradiance and albedo, the new set-up would allow measurements of the anisotropic reflectance distribution factor, a key parameter for the interpretation of satellite radiances measured over snow and ice surfaces.

3.5. Measurements of sea ice properties in the Baffin Bay

Contributors: Marcel Babin, Claudie Marec (CNRS-Takuvik)

3.5.1. Sensors and platforms implemented

In addition to the classical optical properties on the water column measured under the sea ice (radiance, irradiance, absorption, backscattering, chlorophyll-a, nutrients), Takuvik has developed three sensors to measure, within the sea-ice, the spatial variability of the inherent optical properties (IOPs - absorption and backscattering), the radiative field and the nitrate concentration. For IOP measurements, the diffuse reflectance method used to measure the IOPs of human tissues was adapted to sea-ice. To assess the radiative field, a custom radiance camera was designed and assembled to improve the radiometric quality of the measurements, reduce the size (and therefore the footprint) and allow better control over the acquisition parameters. Takuvik also developed an improved method to measure nitrate using a custom-made liquid waveguide capillary cell spectrophotometer and designed a 12V battery-powered instrument ideal for in situ observations. The nitrate concentration was estimated using an UV spectroscopic approach, with a custom-made liquid waveguide capillary cell (LWCC) spectrophotometer. The sensors developed at Takuvik will be integrated to a sea-ice endoscope in development at Université Laval. This endoscope will optimize the acquisition of data in situ over a wide range of sea-ice geometries.

3.5.2. Technical recommendations

Regarding the technological challenges, for the nitrate sensor, the main limitation is the measurements of nitrates within the brine channels, rather than the nitrate within the sea-ice as a whole. An approach that is under evaluation is the use of the 'sackhole' approach, where a hole is produced using a sea-ice corer, to a specific depth and brine leaks in the hole and pumped for measurements.

The integration of all sensors into the sea-ice endoscope and the development of the sea-ice endoscope itself also prove to be technologically challenging, to match all the requirements for in situ observations and to physically integrate the different new sensors.

The sea-ice sensors developed at CNRS-Takuvik, once integrated to the sea-ice endoscope, will provide a suite of in situ bio-optical measurements within sea ice. This efficient platform will be easy to transport and to deploy in various coastal environments where sea ice may take various forms (landfast ice, multiyear ice, ridges, etc.). The data that will be gathered from this platform will greatly improve the modelling of the sea-ice itself as well as the light field of the underneath water column.

4. Implementation of the observing system – ocean component

INTAROS aimed in development of a robust prototype of autonomous and scalable multidisciplinary observation system for ocean physics (including sea ice motion and thickness), biogeochemistry, biology, pollution, and earth processes. Novel instrumentation was tested and implemented to obtain more comprehensive datasets that can in time address questions as the rate of Atlantification of the Arctic Ocean, changes in sea ice condition, uptake and advection of anthropogenic carbon, rate of change in ocean acidification, changes in biology and ecosystems, uptake and advection of contaminants and finally changes in seismic activity that can potentially lead to geohazards. New ocean observations were collected in the costal Greenland, north of Svalbard, in Fram Strait, and in the Greenland and Svalbard fjords. Besides challenging operations and logistics, the main limiting factors for autonomous ocean observing systems in the Arctic regions are the battery capacity for the sensors, limited and challenging data recovery and delivery from underwater platforms, and a lack of geo-positioning of observations from mobile underwater platforms in ice-covered regions.

4.1.Physical and biogeochemical environment of coastal Greenland

Contributors: Mikael Sejr (AU)

4.1.1.Sensors and platforms implemented

The main objective was to extend to spatial coverage of moorings maintained by the ongoing Greenland Ecosystem Monitoring (GEM) programme in order to resolve local impacts of Ice Sheet runoff on environmental conditions in the fjord. Two standard instruments were used both produced by RBR but fitted with slightly different sensor packages. Instruments were deployed in August and retrieved the following year and instruments logged data at two sites nearly continuously from August 2018 to August 2021.

The instrument and sensor package generally functioned well and with two interchangeable sets of instruments the system is now fully integrated in the monitoring programme. Only one parameter could not be quantified. Due to extensive sedimentation observed in some years the PAR sensor was partly covered upon retrieval. The fouling of sensors on moored instruments is well described problem, and now a wiper for daily cleaning of sensor surfaces is available. There are however some challenges regarding battery life for the extended deployments and low temperatures, but the plan is to start testing the Wiper instruments in summer 2022.

4.1.2.Technical recommendations

In the regions with extensive sedimentation, daily cleaning of sensor surfaces requires using wipers is recommended. This in turn implies using batteries with higher capacity/better battery life to ensure comparable operating periods as for standard instruments.

Another consideration for continuous monitoring programs is related to calibration intervals of instruments. In the GEM programme, all CTDs (moored and profiling) are going through annual service and calibration. However, with 8 instruments and more than 25 sensors deployed annually, the accumulated costs including shipping instruments back and forth from the remote location is considerable. We are therefore testing if it could be sufficient to calibrated moored instrument every second year. Service and calibration intervals are a relevant concern for all observation systems, but the cost can be significant for larger programs and prompts considerations about how to optimize spending within a limited budget.

4.2.Physical ocean environment north of Svalbard

Contributors: Agnieszka Beszczynska-Möller (IOPAN), Marie-Noelle Houssais (CNRS-LOCEAN), Christoph Herbaut (CNRS-LOCEAN)

4.2.1.Sensors and platforms implemented

Three to five deep oceanographic moorings dedicated to measurements of physical ocean properties and sea ice in the key region of Atlantic water inflow to the Arctic Ocean were deployed in 2017-2020 north of Svalbard. Moorings were installed, mostly for one-year long deployments, along two mooring lines: INTAROS line at 22°E and A-TWAIN line at 31°E. All moorings were subsurface structures (except one that was a bottom frame) with a top at the approx. 30-50 m depth to avoid damage by sea ice. All moorings were equipped with a wide range of oceanographic sensors, measuring sea pressure, temperature, conductivity (salinity) and ocean currents at the fixed depths (point measurements) and in the water column (profiling devices). Oceanographic moorings carried the McLane Moored Profilers (MMP) for measuring temperature and salinity profiles in the entire water column (except the surface layer of about 50 m), different types of point pressure, temperature and salinity sensors (SeaBird SBE37, RBR Concerto3) distributed along the mooring length, point temperature sensors (SBE53, RBR Solo and Duet), and different types of upward- and/or downward-looking ADCPs for ocean current measurements (TRDI LR-ADCP, TRDI QM-ADCP, Nortek Signature 55). Additionally, the upward-looking ADCPs (Nortek Signature 250) measured drift and draft of sea ice. Moorings were mostly deployed and recovered in the ice-covered waters from icebreakers equipped for mooring operations (the Norwegian Coast Guard icebreaker KV Svalbard, the Norwegian research icebreaker Kronprins Haakon).

4.2.2.Technical recommendations

In view of the harsh Arctic environment in the remote locations with difficult access and costly logistics, autonomous ocean platforms and autonomous sensors for data collection are highly recommended for a future observing system. Moorings deployed during INTAROS comprised a mixture of matured technology and newly available instrumentation. In general, well-proved sensors provided data as expected with battery capacity being the limiting factor for the length of time series.

Sensors and instruments implemented on the moorings north of Svalbard for measurements of physical variables represented the well-proved and robust technologies that worked with no significant failure during all year-long deployments in 2017-2020. Robustness is a key requirement for any long-term observing component of a sustained Arctic system, in particular for moored platforms which can be turned around only once a year (or even in longer intervals up to 2-3 years). While new technical solutions are indispensable for improving and extending the capabilities of an observing system, they should be extensively tested until reaching a high TLR and proved reliability before operational implementation as a component of the long-term observatory.

To ensure the continuous temporal coverage and coherence of sustained observations, the core set of sensors and platforms should be available at least in duplicate to allow for necessary calibrations and repairs between long-term deployments (this seems to be an obvious requirement, but it is not always the case due to limited availability of spare instruments). Additionally, development of the backup data storage system for instruments located at one mooring could be advantageous in the case of an instrument total failure (including data loss). Developing the acoustic or optical data transfer from self-recording moored instruments could in future enable easier data recovery from a vessel or even an autonomous mobile platform (as surface vehicle, underwater glider, or AUV/ROV) without a need to recover the entire mooring.

The surface access is limited for moorings operated in the ice-infested waters where no instruments are placed in the surface/subsurface layer (of a few tens of meters) because of the high risk of damage or losing the equipment from ice collision. Acoustic profilers (as used in INTAROS) provide ocean current measurements up to a few/several meters from the surface but are limited by a physical principle of measurement. Moreover, they cannot deliver temperature and salinity measurements in the surface layer that are of key importance for studying the ocean-sea ice-atmosphere interactions. Several technical solutions have been tested in polar areas for surface access from fixed moorings but none of them reached the maturity level allowing its implementation for long-term observations in a sustained system. Therefore, there is a critical need for a dedicated effort to take advantage of currently emerging new technologies (miniaturized sensors/profilers, new ice-resistant materials, remote methods, etc.) for collecting the upper ocean measurements despite the ice presence.

The lack of surface float (buoyancy element) also results in the significant pull-down of a mooring when deployed in the strong current regime (as in the case of moorings north of Svalbard). It can be partially remedied by a mooring design that takes mooring dynamics into account but in future better streamlined (less drag) mooring components, in particular flotation and large instruments, should be considered.

A lesson learned from mooring operations in the ice calls attention to appropriate recovery aids, including acoustic transponders, Argo or Iridium beacons, and avalanche beacons which can be critical in finding the mooring (or its components) when surfacing under or in the ice.

Endurance time of all moored self-recording instruments and sensors is mostly limited by battery capacity. For one-year-long deployments and using the optimized sampling rate, all implemented instruments were able to deliver the full data record while is the case of longer deployments (not intentional but due to ship unavailability or ice conditions hindering the mooring recovery) measurements usually stopped prematurely. There is a significant progress in power usage of newer sensors but in general battery lifetime in cold arctic waters is decreased (as compared to other regions) and instruments with higher energy consumption (e.g., active acoustic profilers) have limited endurance.

Since an access to ship time on ice-capable vessels equipped for mooring operations in ice-covered waters is very limited and often based on collaborations with and using opportunities of other programs and project, moorings should be designed, build and prepared in such a way that any trained mooring technician (with no specific knowledge of a specific mooring) should be able to recover and deploy it even if the mooring owner/operator cannot participate in a cruise. This highlights a need for collaboration and coordination of efforts related to complex field operations in the marginal ice zone and ice-covered waters.

In a future sustained observing system where fixed moorings with multidisciplinary instrumentation should play an important role, the main challenges include development of more robust sensors for long-term deployments, availability of more efficient power supplies and possibility of remote data retrieval. For some sensors (mostly biogeochemical), sensor stability and calibration also pose a challenge.

Combined systems with moorings and autonomous vehicles such as underwater gliders are particularly useful to describe and monitor the three-dimensional Arctic Ocean. The two components, moorings and gliders, should be harmonized to best support a multi-purpose, multi-disciplinary future OS. Combining glider surveys with underwater moorings, ice-tethered platforms and remote sensing capacities will be key to substantially advance the observational capacity in the ice-covered Arctic Ocean. In addition to their potential to fill observational gaps between sparsely distributed moorings or drifting buoys/floats, gliders can also act as messengers by retrieving underwater mooring data and possibly allowing NRT transmission in low ice concentration conditions.

Establishing an international collaborative forum gathering the necessary expertise in all relevant disciplines (physics, acoustics, electronics, ocean sciences, internet technologies, robotics, etc.), also building on a joint coordination of data management, would be a significant advance towards an AOS relying on a robust autonomous component.

4.3.Ocean bottom pressure north of Svalbard

Contributors: Frank Nilsen (UNIS)

4.3.1.Sensors and platforms implemented

Two Bottom Pressure Recorders (BPR) were deployed north of Svalbard in 2018-2019, one SBE26 at 500m and one WRL Seaguard at 850m. BPR were deployed at the bottom of oceanographic moorings, carrying other instruments. The BPRs are currently not re-deployed, however, we hope to redeploy since the concept and scientific outcome from such measurements are proven to be valuable (Nilsen et al., 2021).

4.3.2.Technical recommendations

Due to technical issues with the SBE26 sensor, it has not been possible to calculate the geostrophic current time series as planned. Hence, the observatory set up is vulnerable since we are dependent on two sensors working together and operating in pairs. But there are large benefits and opportunities when this technology work. It could be a safer setup if one used two BPR's on the same bottom anchor/frame, i.e. in the same position, in case one of them did not record as we experienced during the INTAROS fieldwork. BPR's are low-cost instruments that can easily be added to bottom anchors/frames.

4.4.Biogeochemical ocean environment north of Svalbard

4.4.1.Sensors implemented - pCO2 and pH sensors

Contributors: Truls Johannessen (UiB-GFI), Nicholas Roden (UiB-GFI)

Biogeochemical sensors were implemented on two INTAROS moorings deployed north of Svalbard. The first mooring BGC1, deployed in 2018-2019, was devoted to ocean biogeochemical and biological observations (and accompanied by a separate nearby mooring for physical measurements) and measured pCO2 and nitrate over a yearlong deployment. SAMI-CO2 instruments measured pCO2 at three separate depths using sensor technology based on a colorimetric pH indicator contained in a gas permeable membrane. The instruments were calibrated by the manufacturer before deployment to the expected annual range in temperature and pCO2 for the region. SUNA V2 instruments measured nitrate concentrations at two depths on the mooring by using an ultraviolet spectrophotometer. The second mooring NERSC-4 deployed in 2019-2020 in the deep Nansen Basin carried three SAMI-CO2 sensors measuring pCO2 for the entire mooring deployment at three depths. SAMI-pH sensors were also deployed at each of these depths, measuring pH using a similar colorimetric method as the CO2 sensors.

It was determined that pre-deployment factory calibrations, particularly for SAMI instruments, could not be relied upon for their entire deployment period. Post-deployment calibrations were done on functioning SAMI sensors however this is only useful if drift within each sensor is a linear function of time. Duplicated CO2 sensors on the BGC11 mooring indicated that this assumption could not be reliably made.

4.4.2. Technical recommendations - pCO2 and pH sensors

Our recommendation is that the SAMI sensors (both pH and pCO2) *could* be used in an Arctic observing system, but with some caveats and limitations. The accuracy of the measurements they produced and the stability of the sensors over extended deployment periods did not align with the performance parameters stated by the manufacturer. These discrepancies might be related to the difficulties of deploying reagent-based instruments in polar environments and operating in such demanding conditions. The remainder of this section, while not a comprehensive Best Practice, will outline the limitations of these sensors and steps that should be taken to maximize their reliability in an Arctic observing system.

Before extended deployments, SAMI instruments should be calibrated and refurbished by the manufacturer. Care should be taken to prevent the reagents inside the SAMIs from freezing when being transported and deployed. When using multiple SAMI-CO2s or SAMI-pHs, we recommend validating each sensor against its matching counterpart(s) in seawater shortly before deployment to ensure that the sensors are functioning as expected. Validation samples should also be collected during this procedure. Our experience with duplicated SAMI-CO2 sensors showed that sensor drift was unacceptable after 3-4 months. Attempts to apply a post-retrieval calibration were made by comparing the SAMI-CO2 measurements to a second independent platform (i.e. a lab-based General Oceanics pCO2 system). This however, showed that sensor drift was non-linear and therefore unable to be corrected without the availability of mid-deployment validation samples. Given the remote nature of many Arctic mooring sites, frequent visits to a mooring location are expensive and for the most part, impractical. Furthermore, rapidly changing sea ice conditions or operational constraints can prevent accurately co-located validation samples from being taken in the first place. Therefore, we recommend the inclusion of a co-located automatic water sampler on the mooring rig for each SAMI instrument. This will help reduce the uncertainties regarding the timing and magnitude of sensor drift and aid in post-deployment calibration of sensor data.

Further consideration should also be given to CO2 sensors based on infrared absorption spectrometry (e.g. CONTROS HydroC CO2) and pH sensors based on the solid state ISFET technology (e.g. Sea-Bird SeaFET V2). While it is likely these sensors would still have the same mid-deployment validation requirements as the reagent-based sensors, their solid-state nature may make them more practical for Arctic operations and deployment. Ultimately though, the accuracy and reliability of the sensors must be balanced against their cost and the type of scientific enquiries that hope to be addressed.

4.4.3. Sensors and platform implemented - Octopus system with UVP6

Contributors: Andreas Rogge (AWI)

The horizontally free-moving sensor pack (Octopus system), hosting the latest prototype of the camera system Underwater Vision Profiler 6 (UVP 6; Hydroptic) has been developed and implemented for biogeochemical and biological (visual imaging) measurements on the INTAROS BGC1 mooring north of Svalbard. The instrument harbors an intelligent camera, which automatically identifies and counts particles within a defined sample volume (0.65 L) and cuts and stores them as separated vignettes. The constructed mooring frame featured a fin and was thereby fully rotational and tiltable so that a pointing of the camera into the current was ensured. The sensor package also included a SUNA nitrate sensor (SeaBird), as well as an Ecotriplet fluorometer (SeaBird) for chlorophyll and cDOM to measure environmental conditions, such as nutrient supply and the bloom situation. An additional fluorescence channel for particle backscatter within the Ecotriplet further allowed quality control for the small particle fraction measured by the UVP6.

All system components have worked reliably during one-year long deployment and the system was robust enough to survive recovery of the mooring from under the ice in difficult ice conditions encountered in 2019. The drawback of the first deployment of a prototype instrument was not optimal sensor setup (resulting in too long exposure time, blurry images etc.) but the collected data serve well as a proof of the principle for deployments of the UVP6 system on long-term moorings. After improvements of the weaknesses identified during the INTAROS (i.e. low light beam intensity coupled to long exposure times) the system has the potential to produce unique data also in areas of seasonally high current velocities, such as North of Svalbard, in the framework of a future sustained Arctic observing system

4.4.4. Technical recommendations - Octopus system with UVP6

For the UVP6 camera the reduction of exposure time and stronger light beam will optimize sharpness of images and particle size measurements in regions of high current velocities. Biofouling was not observed but implementation of copper housings should be considered for deployments in euphotic areas with reduced sea ice coverage. Acquisition of dense/untransparent particulate material only is optimal for quantification of crustaceans and dense marine snow. Recognition of transparent particles and organisms may require illumination with other wave lengths or phase contrast, but also staining technologies. Validation of big image data sets in the future will require advanced machine learning algorithms.

Long-term UVP6 particle quantification should be complemented with punctual high- resolution profiling UVP5 measurements to assess spatial particle distributions as well. Future light weight UVP6 high frequency versions will also enable direct deployments on moored profiling CTDs allowing long term acquisition of spatial distributions. Real-time output of particle data (number per size class) is possible already with the actual sensor setup and can be used for satellite transmission i.e. using the ARGO-network in future deployments. Bidirectional transmission should be considered to monitor sensor operation and prevent data loss. For the rotatable and tiltable sensor frame the ensured correct acquisition angle is a key feature. Special care should be taken regarding weight reduction and galvanic currents to ease handling on board and reduce corrosion.

4.4.5. Sensors implemented - passive samplers for organic contaminants

Contributors: Ian Allen (NIVA)

Silicone rubber passive sampling devices were deployed on three moorings north of Svalbard (on two at three depth levels and on one at two depths) for one-year long collection period 2018-2019. One of the moorings remained in water for two years due to COVID-19 related restrictions. Sampling cages were designed for easy handling of the samplers and to minimize the potential for contamination during deployment and retrieval operations. Passive samplers were mounted into solvent-rinsed cages and each cage held up to 10 silicone rubber sheets. Recovered samplers were analyzed for polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), organochlorinated pesticide residues such as

DDT, HCHs and hexachlorobenzene, polybrominated diphenyl ethers (PBDEs) and selected UV filter including UV-328 which is candidate substance for the Stockholm Convention list.

4.4.6. Technical recommendations - passive samplers for organic contaminants

The use of the passive sampling devices with specifically designed exposure cages, and sensitive instrumental analysis for the measurement of trace-level non-polar organic contaminants in polar waters was successful. The system was robust for deployments of 1 or 2 years and considering the state the equipment was in after 2 years under water, it could have stayed longer. The system in place allowed us to estimate dissolved contaminant concentrations at depths in water as low as 1500m below the surface.

The procedures put in place to deploy and retrieve the samplers to minimizing possible contamination during manipulation of the samplers (on deck of the ship) were also successful. The build in calibration system ("PRCs") provided robust estimates of sampler uptake rates even after a two-year deployment. The platform that the designed exposure cages provide can easily be used to host other types of devices to target other types of contaminants. Different types of devices could easily be accommodated for in the sampling cages to increase the breadth of chemicals to be monitored. It could for example include compounds such the more mobile but still persistent perfluoro chemicals (PFAS).

4.4.7. Sensors implemented - combined ADCP/echosounder

Contributors: Angelika Renner (IMR), Geir Ottersen (IMR)

To add biological observing capability to the observing system north of Svalbard, a Nortek Signature 100 combined ADCP/echosounder was selected for deployment alongside the existing A-TWAIN mooring array. The instrument was tested successfully during a short-term deployment in January/February 2019, and then deployed for 2019-2020. Due to memory card defect, no data were recorded during the first deployment. Another instrument was deployed in the same place in 2020 and recovered in November 2021, providing full data set.

4.4.8. Technical recommendations - combined ADCP/echosounder

The Nortek Signature100 combined ADCP/echosounder is a relatively new instrument enabling concurrent, co-located observations of ocean currents and zooplankton/small fish. It delivers valuable time series information on the marine ecosystem which currently are lacking in most of the Arctic Ocean. They therefore should be incorporated in future observing systems. However, experience with these instruments is limited, making full exploitation of the dataset difficult. A community effort for development of deployment and processing routines is underway and should be continued and communicated.

Limited experience prevents full usage of the instrument. This can be overcome by open exchange of deployment and setup routines and protocols, processing approaches, and open publication of processing routines in the user community. Derivation of biological parameters like abundance or biomass of organisms is currently hampered by lack of calibration routines for the echosounder component of the instrument. These vary from conventional ship-mounted echosounders and therefore need to be developed. It is highly recommended to do this as the additional information would greatly enhance the value of the observations. The physical setup of the ADCP/echosounder requires free view from the echosounder beam and thus set limitations for mooring design. Alternative design should be developed (including resulting alternative processing approaches) that enable deployment of the instrument "in line" instead of requiring a separate mooring or limiting mooring height.

The combination of ADCP and echosounder in one instrument provides a great opportunity for co-located and concurrent observations of physical and biological parameters. Currently available alternative solutions require separate instruments and thus (i) a more complex mooring setup, and (ii) further processing steps with larger error margins to combine the records. It is therefore recommended to improve the usage of the combined ADCP/echosounder for future observing systems.

4.5.Deep ocean biogeochemistry and biology in Fram Strait

Contributors: Thomas Soltwedel (AWI)

4.5.1.System implemented - ArcFOCE system for ocean acidification

Ocean acidification is a global threat to the world's oceans, particularly to those in colder regions like the Arctic Ocean (AO). In situ experiments in key regions of the AO are needed to see how Arctic marine organisms are adapted now, and how they might respond to climate change induced ocean acidification in the future. Therefore, the arcFOCE (arctic Free Ocean Carbon Enrichment) system has been designed and developed as an autonomous experimental platform (based on a free-falling system, i.e. a bottom lander) that can be deployed repeatedly, over different periods of time, in different locations and at different water depths - so the system is very flexible in its use. The first long-term experiment of the system was conducted in 2018- 2019 in approx. 1500 m water depth at the LTER observatory HAUSGARTEN in the eastern Fram Strait. By the end of the experiment, the ROV PHOCA was used to take sediment samples inside and outside (as controls) of the mesocosm. The bottom-lander was subsequently recovered to check the performance of the individual components of the arcFOCE system during the long-term experiment.

4.5.2.Technical recommendations

Designed as an autonomous system, energy supply is the major 'bottleneck'. Any energy supply must be taken along on each mission and the energy consumption ultimately determines the maximum length of the experiment. For nearshore applications, e.g. in fjords, a cable connection with a shore station can eliminate these limitations. Long-term stability is still an issue with most currently available pH sensors needed to control the experiments.

By now, the sampling of sediments and inhabiting small benthic organisms (i.e. bacteria, meiofauna) for further studies to the end of the acidification experiment in deep waters is carried out by (cost-intensive) Remotely Operated Vehicles (ROVs); the availability of a ROV is essential for targeted sampling inside the experimental mesocosms of the recent arcFOCE version.

Generally, there is no conceptual alternative to individual in-situ experiments in key regions of the AO to study effects of ocean acidification on marine organisms. For arcFOCE experiments in deep-water/offshore regions, more efficient upcoming energy sources may reduce current constraints (i.e. trade-offs in the duration of the experiment) in the future. Sensor stability issues might be solved by repeated in-situ calibrations during the long-term experiment. Technical modifications of the arcFOCE system should be considered for deep-water experiments (out of reach for divers) to avoid the sampling of sediments and inhabiting small benthic organisms with a ROV to the end of the acidification experiment.

4.6.Carbon system in the Svalbard fjord

Contributors: Jean-Pierre Gattuso (CNRS-LOV)

4.6.1.Sensors and platforms implemented

Carbon system data were collected at the COSYNA-AWIPEV underwater observatory in the Kongsfjorden Arctic fjord system on the west coast of Spitsbergen. The INTAROS seafet pH sensor and Contros pCO2 sensor were set-up at the AWIPEV observatory which comprises a land based

FerryBox system equipped with a set of sensors. The FerryBox system receives water from an underwater pump station at 11 m water depth. At this pump station, a remotely controlled profiling sensor carrier is fitted with another set of sensors. The profiling unit performs a vertical cast every day from 11 m to 0 m water depth. pCO2 was measured continuously and data logged every minute. pH (volts) was measured continuously, and data logged every minute. Volts were converted to pH on the total scale (pHT). Seawater was sampled at approximately monthly frequency for pH measurements in the Ferrybox and in the field, at 11 m with a Niskin bottle to calibrate the pH sensors. pCO2 and pH were available throughout the year and well distributed across months, including winter months. A unique high-frequency time-series of parameters of the carbonate chemistry was collected in 2017-2021. Overall performance of the seafet pH sensors and Contros pCO2 sensors was good. Both would be key components of a future sustained Arctic observing system.

4.6.2. Technical recommendations

A key limitation of any instrument measuring a variable of the carbonate system is the maintenance and calibration. Our task as part of INTAROS was made easy by the fact that the instruments were deployed in a coastal location easily accessible. Two sets of pH sensors and Contros pCO2 sensors were available. Hence, sensors could be swapped every year and sent for calibration. The coastal location also enabled to take discrete samples for calibration. A major difficulty towards the end of the project was the change in the rules to manipulate mercuric chloride, a chemical that is used to preserve discrete samples pending analysis.

It is strongly recommended to have duplicate sensors, so that when one is in operation, the other one is sent to maintenance. Discrete samples have also proven essential. If logistic conditions allow, the minimum frequency should be weekly.

The extreme conditions prevailing at the site of measurement incurred incidents such as interrupted supply of seawater in the FerryBox due to frozen pipes (due to pump stop) or damages resulting from icebergs pounding on the field instruments. Resolution of these incidents sometimes took weeks to months until temperature warmed, making de-icing possible. It is very difficult to prevent such incidents without having permanent staff closely overseeing the project. Pump issues could be remedied with more efficient automated switching and more redundancy. Protection concepts must be developed and improved to safeguard individual components of the monitoring system against the fundamentally harsh environmental conditions including the threat of drifting ice floes.

4.7. Ocean biogeochemistry and pollution from ships of opportunity

Contributors: Andrew King (NIVA)

4.7.1. Sensors and platforms implemented

Three different types of new sampler/sensors were developed and implemented on the Barents Sea Opening FerryBox system that operates between Tromsø, Norway and Longyearbyen, Svalbard on the container ship M/S Norbjørn. The three instruments include a microplastics sampler, a combined deployment of spectrophotometric sensors for measuring pH and CO3 ion, and an integrated sphere absorption meter sensor for measuring optical properties of seawater including dissolved organic matter and phytoplankton chlorophyll a, and taxon-specific pigments. A microplastics sampler was constructed and developed for automated operation alongside a FerryBox sensor system and concentration of microplastics was collected during field campaigns in spring and summer 2019 in the Barents Sea Opening. pH/CO3 system which was field-tested and refined in 2018-2020 and deployed on the Barents Sea Opening FerryBox in 2020 and 2021. The CO3 ion system was installed on the Barents Sea Opening FerryBox in April 2021, but the system is not fully operational due to pump and flow issues. Collected data include fCO2 (µatm), pH (total scale), and CO3 ion (µmol kg-1) for a transect from Tromsø-Longyearbyen. An integrated sphere absorption meter sensor for measuring spectral absorbance (360-750 nm) was adapted to the Barents Sea FerryBox system by developing it for flow-through operations. The system was installed on the Barents Sea Opening FerryBox in 2021, but a failure in one of the source LEDs required the instrument to be sent back to the manufacturer for repair. The instrument has returned from the manufacturer and ready for re-installation and operation in August 2021.

4.7.2. Technical recommendations

The Arctic can be a difficult place to access and conduct field work year-round. Any future sustained Arctic observing system will greatly benefit from a coordinated and well-trained operations team that can install, maintain, and repair multiple observing platform and sensor technologies, ideally during the same trips. While it is possible for each team to send its own personnel, this is inefficient with regards to cost, time, and logistics. This was made even more apparent when COVID-19 restricted travel and access to observing platforms

Marine biogeochemical and biological sensors still heavily rely on ground-truthing with in situ samples. These ground-truthing samples should be collected and analyzed using traditional and accepted techniques as a way of validating sensor data. Because fieldwork is limited in the Arctic, and at times not possible (e.g., during the winter when ice limits access), the acquisition and use of ground-truthing samples can be challenging. Furthermore, sensor-based observations give us a snapshot (synoptic) view. While this is important to gather information related to trends or variability in environmental variables, we generally lack a mechanistic understanding of what the ramifications of those changes mean for an ecosystem. Thus, the integration of experimental and modeling approaches with an observing system must be implemented in order to better understand and manage ecosystems.

For the ocean sphere, the variability in technical solutions as used in INTAROS is important to have redundant and complementary components of the observing system. This approach allows us to capitalize on aspects that any particular platform/sensor excels in, and this will reduce observing gaps (in space or time).

4.8. Physical and biogeochemical ocean observations from mobile platforms

4.8.1. Sensors and platforms implemented – Argo floats

Contributors: Marie-Helene Forget, Claudie Marec, Marcel Babin (CNRS-Takuvik)

The scientific objective is to study seasonal variations in phytoplankton biomass as controlled by sea ice dynamics, vertical mixing, light, and nutrients. BGC Argo floats (manufactured by NKE) are specialized profilers, equipped with sensors capable of sampling essential ocean variables. The biogeochemical parameters were collected all year long between over profiles between 0 and 1000m are salinity, temperature, dissolved oxygen, nitrates, chlorophyll a concentration, CDOM, particle abundance, and radiometry at 3 wavelengths and PAR. These autonomous platforms enable data collection during winter when scientific campaigns are limited due to ice cover. BGC Argo floats are a reliable component of a future sustained Arctic observing system.

We can also highlight that we gained experience in recovering floats before their end of life and had them refurbished for new deployments. This is an important component for a sustained Arctic observation system, which needs to be budgeted and logistically coordinated with the different ships navigating in Arctic waters.

4.8.2. Technical recommendations – Argo floats

A main limitation in the use of BGC Argo floats navigating in ice-covered ocean is the lack of position for the data in wintertime because the platform cannot surface for geo-localization. Routes are therefore calculated by interpolation. Under-ice positioning of Argo floats (or autonomous platforms more generally) remains a challenge and requires technological improvements.

Over the period of the project, we learned that the first generation of deployed floats was lacking in flexibility for the integration of new sensors, which led us to upgrade the platforms with new motherboards. These upgraded BGC Argo floats (model CTS5-Usea by NKE) were deployed in 2021 in Baffin Bay.

Moreover, commonly used radiometry sensor (OCR4) proved to be not sensitive enough to measure very low light levels under ice, conditions encountered by the floats in late winter and early spring. Takuvik worked with Biospherical Scientific Instruments on the design of a highly sensitive radiometer (MPE) that was added to the initial payload for the 2021 deployments. These new sensors will provide original irradiance data, which is essential to compute the specific phytoplankton growth rates and to improve the under-ice light models.

4.8.3. Sensors and platforms implemented - gliders

Contributors: Marie-Noelle Houssais, Christoph Herbaut, Pierre Testor (CNRS-LOCEAN)

Regular gliders missions have been carried out in eastern Fram Strait since the beginning of the project during four successive summers (2017 to 2019). The duration of each mission was planned for approximately two months and the gliders would repeat every year, as far as possible, approximately similar sections across the West Spitsbergen Current (endurance glider lines). All gliders were equipped with sensor payload allowing to monitor physical (conductivity, temperature, pressure, dissolved oxygen) and optical (chl a fluorescence, CDOM fluorescence, turbidity, or backscattering) properties of the water column.

State-of-the-art gliders are versatile vehicles considering (1) their navigational capabilities can be adapted to complex environments with moderate architecture modification and (2) they can host complex scientific payload with multiple sensors. Assuming that remaining technological challenges will be addressed, the benefit of integrating a fleet of gliders in a future OS is obvious for a variety of applications including (i) monitoring of ocean properties along endurance lines, (ii) fine-scale (mesoscale and sub-mesoscale) description of the ocean in dedicated ocean areas via, e.g., sections across the Arctic Boundary Current, retrieval of vertical motion in regions of water mass transformation, mapping of preferred locations for shelf-slope exchanges around the arctic basins, (iii) new information on physical-biological-chemical interaction combining measurements by a set of multiple sensors. Specific payloads of particular interest are currently available or being developed which include optical water characteristics (PAR) sensor, fluorescence puck like sensors, passive acoustic monitoring payloads with several types of hydrophones, velocimetry payload with ADCP and turbulence sensors, zooplankton payload with UVP6 plus EK80 WBT mini echosounder.

4.8.4. Technical recommendations - gliders

Glider navigation in icy conditions: when the proportion of open water is insufficient to allow for regular surfacing of the glider for GNSS positioning and communication with land, other technologies must be deployed. Acoustic positioning based on a network of underwater sound sources is the most promising approach and has been successfully tested in some regions of the Arctic, including Fram Strait, but it remains very challenging. This approach should be generalized to a multi-purpose, multi-scale underwater acoustic network allowing under ice positioning of underwater vehicles and providing support to communication. Ice avoidance during glider profiling is also needed, which can be done either by upward looking echo sounding or implementation of existing under ice detection algorithm using CTD measurements by the glider.

Glider power autonomy: with a more complex glider payload due to implementing different new sensors, a suitable glider architecture must be installed to optimize the management of the limited power available. Navigation in the vicinity of the pole: close to the magnetic pole (large inclination and declination values) an improved compass for dead reckoning navigation is needed.

Extension of glider payload: miniaturization of new sensors is always a technical challenge, yet an important issue to continuously enlarge the scope of the collected information.

4.8.5. Sensors and platforms implemented – ice-tethered platform

Contributors: Agnieszka Beszczynska-Möller, Waldemar Walczowski (IOPAN)

The INTAROS IAOOS-Equipex ice-tethered platform was deployed in 2018 in the Amundsen basin close to the North Pole (as a part of the North Pole drift ice station) during the Swedish icebreaker Oden cruise ARCTIC2018 in the central Arctic Ocean as a part of the North Pole drift ice station. The ice-based platform deployed under INTAROS was equipped with three separate sensor packages, dedicated to atmospheric, ocean and sea ice measurements. The instrument package for atmospheric consisted of microlidar and weather mast, ocean measurements were collected with a CTDO profiler and a SIMBA-type instrument was used for sea ice measurements. The IAOOS platform drifted southward with Transpolar Drift and delivered the full data set for over 4 weeks after deployment, but transmission stopped afterwards, the most likely due to the damage by a polar bear.

4.8.6. Technical recommendations - ice-tethered platform

The lifetime of the IAOOS platform was unexpectedly short and a technical failure due to mechanical damage by a polar bear was the most likely cause. This sort of accidents cannot be unfortunately foreseen and has been for long time one of most common dangers to the equipment drifting for long time on sea ice in remote areas.

Future efforts should include development of better protection of the on-ice components of the platform against polar bears and other physical damage (improving robustness of the outer shell, deterrent system against polar bears). A duplication of a communication (positioning and data transfer) system would be advantageous, taken that the power supply is provided independently for both systems (main and backup).

More generally, the heavily instrumented multidisciplinary ice-tethered platforms provide a benefit of concurrent collection of different data types (ocean, atmospheric, sea ice, sometimes also biogeochemical data) but they are also increasingly expensive. Taking into account the potential high risk of ice-tethered deployments in the central Arctic, a future observing system should be perhaps composed of a higher number of simpler, more robust, lower cost ice-tethered platforms measuring a basic suite of ocean key physical variables with better coverage (and therefore limited data loss if a single platform is lost) and a smaller number of experimental, multiparameter platforms with a more sophisticated (and costly) backup systems for data retrieval. Development of a future ice-tethered platform that will be robust, affordable, and operable by different groups and can be more widely used in the Arctic Ocean requires a dedicated long-term effort.

4.9. Acoustic environment of Greenland and Svalbard fjords

Contributors: Delphine Matthias (CNRS-UIEM)

4.9.1. Sensors and platforms implemented

Multi-disciplinary acoustic system similar to earlier system in the Young Sound was implemented in Kongsfjorden to study the Arctic coastal ecosystems in two contrasted fjords by merging physical oceanography and marine biology and using the passive acoustics non-invasive technique to characterize both physical (dynamics of sea ice and icebergs, waves-ice interactions) and biological compartments (behavior of organisms at different trophic levels). Long-term recordings (over 14500 hours) were collected with autonomous recorders deployed at the entry of the Kongsfjorden, with the purpose of assessing the soundscape of this Arctic fjord. The main focus was on antropophony (mainly from shipping activities) and biophony (marine mammals occurrence, biological activity within the kelp forest).

4.9.2. Technical recommendations

The main recommendation is to continue the underwater soundscapes monitoring with passive acoustic recorders of Arctic fjords visited by touristic vessels is essential to watch the changes of biological and physical sound sources in relation with vessel noise.

The instrumentation used for the INTAROS project consisted of autonomous passive acoustic recorders with limited battery autonomy. Using the new generation of passive acoustic recorders would overcome this limitation and would allow to get 1 year of continuous acoustic data with only 2 instruments per monitored site.

The other solution is the installation of cabled observatory to get real time data, or adding acoustics to the existing ones (i.e. FerryBox in Ny-Alesund) but this means doing monitoring close to research facilities / ports and with less biological interests (ex: less marine mammal presence inside Ny-Alesund harbor than close to Kongsfjordneset point).

4.10. Seismic observations in Fram Strait

Contributors: Mathilde Sorensen (UiB), Peter Voss (GEUS)

4.10.1. Sensors and platforms implemented

During INTAROS, three ocean bottom seismograph (OBS) monitoring campaigns have been completed. The first two deployments were along the Arctic part of the mid-Atlantic ridge. During the first campaign in 2017-2018 6 LOBSTER systems were deployed with ROV at the Loki’s Castle hydrothermal vent field and subsequently 3 NAMMU systems were deployed in 2018-2019 west of Svalbard. Finally in 2019-2020, three NAMMU OBS systems were deployed in the southern and central parts of Storfjorden. During last two campaigns the OBS systems were prepared on board the ship and dropped to the sea floor (free-falling) at pre-defined locations. The OBS experiments carried out during INTAROS have clearly demonstrated the added value of seismological monitoring on the ocean bottom in detection and analysis of earthquakes in the offshore regions. Two approaches have been tested for OBS deployment: the traditional “free-fall” release with “pop-up” recovery and the more controlled deployment and recovery with an ROV.

4.10.2. Technical recommendations

Our main recommendation for the use of OBS (Ocean Bottom Seismometer) units in the Arctic is to include ROVs (remote operated vehicle) in the deployment and recovery of OBSes in cases where there is a high risk that the instrument is trapped under sea ice. In ice free waters, standard deployment and pop-up recovery has proven to be sufficient to obtain high data quality. However, as there is a certain risk of the instrument not responding to the release signal (e.g. due to technical failure or the instrument being trapped in sediments), it is strongly recommended to develop contingency plans for recovering OBS units with ROV when needed.

The main limitation in using ROV for OBS deployment and recovery is the additional cost. The use of ROV will require more ship time. Furthermore, an ROV is expensive compared to the OBS units, it is required that the ROV can be operated from the vessel used in the operation (limiting the number of potentially available vessels), and skilled staff is needed to operate the ROV. The deployment and recovery will also be more time consuming, especially for deployments at large water depths.

Two major limitations in seismological monitoring with OBS are the limited deployment period, usually of about 1 year, due to limitations in battery power, as well as the lack of real-time data since data only becomes available after recovery of the instrument. Operational use of seismological data requires that data is available in real-time as fast response is needed in many cases.

The OBS units operate autonomously but having OBS units cabled to management facilities allows for manual operation and real-time data exchange, better data QC and high data recovery level. In addition, data from cabled OBS units will provide important real-time information on hazardous events such as large earthquake, landslides, and tsunamis. The DAS (distributed acoustic sensing) is another technology that has the potential of providing important information on hazardous events, since the DAS systems, connected to land facilities, can give real-time information on changes in the strain at the sea floor. However, DAS technology has, to our knowledge, not been tested in the offshore arctic environment yet. Floating seismometers (MERMAIDs) is another technology that should be explored in the Arctic environment.

4.11. Pan-Arctic acoustic network with multidisciplinary moorings (CAATEX)

Contributions: Hanne Sagen (NERSC), Matthew Dzieciuch (SIO), Espen Storheim (NERSC), Peter Worcester (SIO), Bruce Howe (University of Hawaii)

CAATEX- Coordinated Arctic Acoustic Thermometry Experiment is a joint U.S.-Norwegian acoustic thermometry experiment across the Arctic basin. The CAATEX experiment was designed to be comparable to previous trans-Arctic propagation experiments, the 1994 Trans Arctic Propagation (TAP) experiment and the ACOUS experiment in 1999. The purpose is to capture the change in acoustic propagation of low-frequency sound across the Arctic basin due to changes in ocean stratification, mean ocean temperature and sea ice conditions. The goal is to explore the fundamental limits to exploit the acoustic remote sensing capabilities to characterize the large-scale properties of the Arctic Ocean in combination with point measurements of oceanographic parameters.

Two acoustic sources transmitted low-frequency (35 Hz) sound, one source transmitted from Nansen Basin in the Eastern Arctic, and a second source transmitted from the Beaufort Sea in the Western Arctic. All six moorings were equipped with 25-40 hydrophone vertical arrays, oceanographic instruments for salinity and temperature measurements, an upward-looking sonar to measure the ice thickness, and pressure gauges to measure the ocean bottom pressure. The deployed array of acoustic moorings deviated significantly from the originally planned array primarily due to a Russian short notice missile exercise at the North Pole, but also because of rough ice conditions in the North pole region. This rapid turnaround of plans demonstrated the importance of having flexibility and capability during the execution of the field operation to implement a secondary plan The moorings successfully recorded transmissions every 36 hours during a yearlong deployment from fall 2019 to fall 2020.

CAATEX is funded by the US Office of Naval Research and the Research Council of Norway. The deployment of the CAATEX system were supported by the US ice breaker USCG Healy and the Norwegian Coastguard ice breaker KV Svalbard. Through support from the Norwegian Coast Guard to CAATEX we were able to recover all acoustic moorings in 2020, as well as provide support to the INTAROS mooring recovery activities despite the CoVId19 situation.

4.11.1. Sensors and platforms implemented

Besides acoustic sources, an essential component of the acoustic system is the receiver technology (D-STAR – Distributed Simple Tomographic Acoustic Receiver). The D-STAR has been developed over two decades to provide high accuracy time keeping using a dual clock system and accurate monitoring of the mooring motion. The D-STAR receiver can host up to 99 hydrophone modules distributed over a 1000 m long mooring wire. Each hydrophone module is controlled by the D-STAR through inductive modem, and accurately positioned by a Long Base Line navigation system. The LBL navigation system is comprised by a pinger integrated with the STAR and 4 transponders surrounding the mooring at the sea floor. The D-STAR technology has been successfully used in in several Arctic and sub- Arctic environments suggesting a TRL level 9. In previous experiments (e.g. EU-DAMOCLES, EU-ACOBAR, RCN- UNDER-ICE and ONR-CANAPE) the STAR technology has been integrated with sweeper sources produced by Teledyne Webb Research.

During CAATEX two low frequency C-BASS source from GeoSpectrum Technologies Inc. were integrated with the STAR receiver technology. Each C-BASS source produced a 15-second-long M-sequence signal at 35 Hz with 8 Hz bandwidth every 3rd day. The transmissions were successfully received up to 2600 km away from the source throughout the experiment. The integrated source and receiver system reached TRL 7 within CAATEX.

CAATEX has developed a design of multidisciplinary moorings that can be deployed and recovered in deep (4000 m depth) and ice-covered regions of the central Arctic, as well as procedures for safe deployment and recovery. The mooring design includes acoustic locators for positioning of the top of the mooring during and after release of the mooring, avalanche beacons for locating top of moorings if trapped under ice, and XEOS locators for location of the surface steel sphere after getting to surface. For safe recovery it is crucial that the mooring is designed to stay vertical in the water column after release. All moorings with the instruments were recovered, and only around 5 out of 375 instruments failed to provide data. This shows that the overall multidisciplinary mooring system used in CAATEX has a TRL >7.

4.11.2. Technical recommendations

There is a strong need for coordination of efforts in development of standards and best practices for implementation of multipurpose acoustic networks, as well as development of geo-positioning procedures in gliders and floats making use of nested acoustic networks. This will enable the ARGO program to extend their network to cover the fully or seasonally ice-covered Arctic Ocean, and this will have a large impact on the data availability from the ice-covered regions of the Arctic Ocean.

Moorings in ice covered regions are excellent for collecting time series of measurements of a multitude of ocean data. However, the mooring must be recovered for data download. Today's power supply capabilities require recovery of the moorings at least every second year (depending on sampling frequency and processing activities). It is therefore expensive and demanding to sustain the mooring network. It is essential to increase the operation period of the mooring network as this will reduce the risk for failures during turnaround operations, reduce the costs significantly, and reduce the environmental impact of operations. To be cost efficient in the maintenance of mooring networks it is important to coordinate so that the network becomes multipurpose serving several disciplines and stakeholders.

Our recommendation is furthermore to support technology development to fill the major gaps in the data livery chain from underwater observing systems in ice covered regions. This includes:

- Accurate positioning of fixed moorings and drifting observatories making use of new satellites-based GPS system for the Arctic.
- Adapt technologies and methods for accurate geo-positioning of autonomous underwater platforms (e.g. floats and gliders) through use of a basin wide acoustic network in combination with regional to local acoustic networks.
- Investigate alternative power supplies such as fuel cells to increase the mooring deployment time and thereby reduce the environmental impact of operations.
- Develop efficient internal transmission of data from distributed instruments along a vertical mooring to a data hub to ease data recovery.

Develop technologies enabling data download without recovery of the mooring for example using ROVs equipped with optical data transmission technology that can harvest data from hubs located within the mooring.

4.11.3. Recommendations for future ocean observing system

The CAATEX experiment represents a successful forerunner of a basin wide multipurpose acoustic network for acoustic thermometry, underwater GPS system, and passive acoustics in integration with oceanographic point measurements at the positions forming the network. In CAATEX, two low frequency acoustic sources at two different mooring locations allowed for thermometry between these moorings and four additional receiver moorings. However, a minimum of three acoustic sources are needed in a multipurpose acoustic network for UW-GPS functionality. Regional to local scale multipurpose acoustic networks have been developed for different environmental conditions using a wide range of mid frequencies (200-300 Hz) in the Fram Strait, Beaufort Sea, and Labrador Sea. We recommend a nested and sustained acoustic network to be developed for the Arctic. The system should be composed of 1) a network of low frequency sources (e.g., CAATEX) to cover the central Arctic and 2) regional networks of mid frequency sources in key regions such as North of Svalbard, Fram Strait, and Beaufort Sea. Future acoustic mooring networks should be developed to be multidisciplinary and serving both navigation and observing.

Development of an integrated High Arctic Ocean Observation System including nested multipurpose acoustic networks need sustained international collaboration, coordination, and funding. We recommend establishing a formalized collaboration between ice-ocean research infrastructures involved in Arctic Ocean Observing (e.g., mooring network operators, the Arctic Buoy Program and Argo program).

The ultimate limiting infrastructure services in sustained long-term ocean observing deep in the ocean and below an ice-covered ocean is the provision of power, and communication. Submarine cable systems providing power and communications can facilitate sustained real-time observations and support to a UW-GPS system. This is technologically feasible, but dedicated science cable systems are expensive and would have few direct users in the Arctic outside of the research community.

In the Smart Cable approach (Howe et al. 2019), sensors are embedded in the repeaters of commercial telecom cables, ultimately to achieve global scale coverage for example CAM, a 3700 km ring linking Lisbon, Azores, and Madeira with 50 SMART repeaters will be installed in 2025. Selected sensors include bottom temperature, pressure, accelerometers, and optionally hydrophones. The basic cable route is specified by telecom connectivity requirements. The incremental SMART cost is about 10 percent of the total cost. The Arctic Express proposed cable system will connect Japan to Europe via Alaska, the Canadian Northwest Passage and the Labrador Sea, with a SMART option. The submarine cable industry is on the cusp of offering telecom-rated branch units that can support "nodes" that then can enable cable connected moorings, AUV docking, and instrumentation, albeit requiring remotely operated vehicle (ROV) support. For instance, Arctic Express could support moored multi-purpose acoustic moorings in the western Arctic, reaching (acoustically) through the central Arctic to the European side. Requirements for both SMART repeaters and nodes (combining telecom and sensing) are being formalized within the framework of International Telecommunications Union (ITU) Study Group 15/Q8 G.SMART Recommendation.

We recommend working with all related stakeholders to incorporate SMART repeaters and nodes into planned and future Arctic cable systems. Further, development of cable connected vertical moorings with instruments in the water column (e.g., similar to US NSF OOI RCA cabled vertical moorings), specifically for multi-purpose acoustics, with power and communications distributed along the mooring, should be pursued.

5. Implementation of the observing system – atmospheric and terrestrial components

5.1. Automated collection of air samples for GHG in the Arctic

Contributors: Matthias Goeckede (MPG)

5.1.1. Sensors and platforms implemented

A flask sampler that can be used for the automated collection of air samples under standardized conditions at remote Arctic sites was installed and operated at Station North on Greenland which is part of the ICOS atmospheric monitoring program. Two drawers were reserved for the samples have a combined holding capacity up to 12 flasks at a time while one drawer was reserved for pumps, computers, etc. The sampler facilitated multiple modes for filling flasks. The flask sampler, which has started its operation in September 2019 and has continuously provided data since, has been integrated into the Station North facilities to enhance its status within the European ICOS observation network. Flasks were analyzed at MPI-BGC in Jena for the concentrations of CH_4, CO_2, CO, N_2O, H_2, and SF_6. As additional parameters, the ratios of O_2/N_2, Ar/N_2, and the stable isotope signals $d^{13}C$-CO_2, $d^{18}O$-CO_2, $d^{13}C$-CH_4, and d^2H-CH_4 were sampled. The analysis of time-integrated signals of trace gas mixing ratios and stable isotopes from five different source regions demonstrates that this novel that long-term integrated sampling of trace gas signatures was capable of capturing individual fingerprints in air mass composition, depending on the source region.

5.1.2. Technical recommendations

The automated flask sampler employed by MPG for sampling at remote Station North on Greenland has fulfilled all requirements for a continued operation in the Arctic. This type of instrument is highly suited for long-term operation at remote Arctic sites, as long as regular instrument checks by reliable, non-technical personnel can be assured. The flask data (i) can be used as a reference for quality-checking the continuous greenhouse gas observations, (ii) allow to monitor additional trace gas species not covered in the continuous program, and (iii) can be used also for monitoring ^{14}C-CO_2, and therefore better constrain fossil fuel emissions contributing to the mixing ratio signals. Therefore, it holds the potential to substantially improve our insights into Arctic carbon cycle processes at larger scales, provided a network of such devices would be established across the Arctic.

While not being a technological limitation, the operation of the sampler obviously relies on reliable personnel on site to regularly monitor the performance, and swap flasks in the available bays at regular intervals. Our own experiences with the operation on Station North were excellent in this context, however. Analysis of the collected air samples relies on a working logistics to retrieve filled flasks from the sampling site, export them to the laboratory facility, and allow to ship empty, conditioned flasks the other way. Both 'limitations' listed above are an inherent feature of the observational approach, and we do not see any ways to overcome them with upgraded observational devices.

We are not aware of alternative products that may produce atmospheric flask data of a higher quality. For some of the parameters that can be sampled using flasks collecting atmospheric air samples, but which are not covered in standard continuous atmospheric monitoring programs yet, new generations of greenhouse gas analyzers have recently emerged. These include e.g. the Picarro G2201-i for $\delta^{13}C$ of CH_4 and CO_2. However, such analyzers can only provide a subset of the parameters which can be provided by analysis of the flask samples and come at a quite high price tag.

5.2. Aircraft-derived vertical atmospheric profiles in Alaska and Canada

Contributors: Torsten Sachs (GFZ)

5.2.1. Sensors and platforms implemented

Aircraft-derived vertical atmospheric profile data on temperature, humidity, CH_4 and partially CO_2 from multiple past airborne campaigns covering the Alaskan North Slope and the Mackenzie River Delta, Canada were contributed to assist in characterizing atmospheric transport and mixing processes. These observations are campaign-based by nature and in our case project-/proposal-based, and thus do not constitute an operational observing system in the sense of continuous or regularly scheduled observations.

5.2.2. Technical recommendations

This system has been operational since before INTAROS, thus there are no specific challenges identified during the project. However, it should be noted that a sensor warm-up phase of up to 45 minutes was needed for the gas analyzer. Occasionally sensors could be pre-heated by ground power, but this was not always available.

5.3. Eddy covariance measurements of CO2 and CH4 emissions in Alaska

Contributors: Walter Oechel (UNEXE)

5.3.1. Sensors and platforms implemented

The first annual balance of both CH_4 and CO_2 fluxes in a total of five sites spanning a 300 km transect across the North Slope of Alaska as well as an estimation of the regional CH_4 emissions based on aircraft observations. Ecosystem scale of CO_2 and CH_4 fluxes were measured using the eddy covariance (EC) method with three EC towers in Barrow and one in Ivotuk. A new heated sonic anemometer was installed in Barrow, Alaska, during summer 2019. The goal was to collect continuous CO_2 and CH_4

fluxes during the entire year, with a particular focus on the fall and winter, which are the most uncertain times of the year in terms of both CO_2 and CH_4 emissions.

5.3.2. Technical recommendations

For the first implemented sonic anemometer (CSI_CSAT3BH), the heating system was not appropriate to completely de-ice the sonic anemometer during the fall and winter, which resulted in large data losses, particularly during spring 2020 when we were not able to access the sites. Two new A METEK sonic anemometers were thus acquired to replace the previous instrument.

The new Class-A Metek sonic anemometer showed to have a very reliable de-icing system, which proved to be able to de-ice the sonic anemometer even in extremely harsh conditions in winter. We suggest eddy covariance towers that aim to collect data year-round to adopt the use of the Class-A Metek, and select a de-icing system based on quality flags instead of air temperature, in order to minimize the activation time of the heating. Reducing the activation time will reduce the amount of time in which the heating could affect the quality of the measurements, and the power consumption.

Unfortunately, the heating system of the CSAT-3BH proved not to de-ice the anemometer during the winter. Multiple tests we did in the field showed that the heating of the sonic was not enough to de-ice the instruments to continue the data collection during the winter. The new Class-A Metek sonic anemometer proved to have an appropriate de-icing system, but main limitation to the adoption of the Class-A Metek sonic anemometer is the power availability in the more remote site that rely on solar panels or wind turbines, and do not have grid power. Without enough power, the heating of the Class-A Metek sonic anemometer might not be able to function properly. We suggest upgrading the power in the sites where year-round measurements are required to properly operate the heating system, as the Class-A Metek has the best de-icing systems for Arctic conditions.

The manual removal of the snow from the sonic could help reducing the power needed to de-ice these anemometers. However, a manual removal would require access to the sites, which might not be possible in the most remote sites during the winter. Remote monitoring of the operation of the sonic anemometer, and of the conditions at the research site could help evaluate the conditions under which the de-icing system works properly and help to plan the visit to maintain the sites and target these maintenance visits reducing the cost to monitor the site. The site PI should decide if the winter measurements are critical to meet the project objectives, and if this is the case a proper de-icing is required to extend the greenhouse gas flux measurements during the cold period.

5.4. Profiles of soil temperature and soil gas concentrations in Alaska

Contributors: Donatella Zona (USFD)

5.4.1. Sensors and platforms implemented

Two high spatial and temporal resolution temperature profiles at the Alaskan sites Atqasuk (US-Atq) and Ivotuk (US-Ivo) were installed in summer 2016 to better characterize the soil freezing and the persistence of unfrozen soils during the cold period. A third system was installed at the US-Bes site near Utqiaġvik during summer 2018. These profiles included thermocouples every 5 cm from 25 cm above the surface to 90 cm below the surface at US-Ivo and US-Atq and 75 cm below the surface at US-Bes.

5.4.2. Technical recommendations

High resolution soil temperature profiles are critical to properly model the soil thawing and freezing processes. To be included into an Arctic observing system these measurements should be standardized across sites, so that the same depths are measured across different ecosystems. The data collection should also be standardized so that the rate of data recording is the same. Moreover, water table and thaw depth should be collected in each of the sites where these high-resolution temperature profiles are installed, to validate the ability of this system to also capture the water level across different soil type and validate, and the development of the active layer depth.

The main challenge we experienced was the data loss during the winter given the harsh arctic conditions. To be able to collect measurements year-round access to the site is critical to assure a reliable power to the datalogger, and access to the sites to replace broken sensors. Establishing a remote monitoring system that could detect malfunctioning in any of the sensors or datalogger, could also improve the data cover.

Waterproof encasement should be installed to protect the datalogger, at least 1 meter above the ground to limit water damage during snow melt, the thermocouples should be protected using aluminum conduits to reduce the risk of damage by wild animals, particularly attracted by these cables during the winter.

Access to the site and remote monitoring of this system could majorly help to successfully collect measurements particularly during the winter, when it is more likely for the instruments to be damaged.

5.5. Monitoring of snow and vegetation properties in Canada

Contributors: Florent Domine (CNRS-Takuvik)

5.5.1. Sensors and platforms implemented

Climate-relevant variables were monitored in the atmosphere, snow, and soil at four sites in the Canadian High Arctic along a latitudinal gradient between 55 and 83°N. Besides climate monitoring, the purpose was to gain data allowing process understanding, in particular regarding the impact of warming-induced vegetation growth on snow properties, the permafrost thermal regime, and soil carbon stocks. Time series of air temperature, relative humidity, wind speed and radiation are obtained at 4 locations. Furthermore, snow height, thermal conductivity and temperature are monitored at 11 sites at these 4 locations, differing in vegetation type. These variables are monitored at several heights in the snowpack. Soil temperature and volume water content at 5 depths in the active layer are monitored at 16 sites at these 4 locations. Soil thermal conductivity is monitored at 6 sites at our 4 locations. CO2 fluxes are monitored at one site in Northern Quebec using eddy covariance. Soil carbon stocks have been quantified at 3 of our 4 locations, for different vegetation covers.

5.5.2. Technical recommendations

Radiometric data are important components of energy budgets. Frequent recalibration of instruments is essential. At least once every 5 years, ideally every 3 years. Regarding instruments in remote areas, the limitation is access for maintenance. Not much can be done to improve the situation.

Obtaining radiation data in the Arctic is difficult because winter frosting compromises data and providing heating is a problem for remote instruments in the polar night. The compromise was to heat and ventilate the radiometer for five minutes every hour and take a measurement then. However, the five minutes of hourly heating was often insufficient during the polar night and much longer heating times would be requires but this is really an issue regarding power supplies. Since solar panels do not work during the polar night and measurement site is not windy enough for windmill, other options to provide more power supply must be explored.

An important aspect is data retrieval. During the pandemic, access to some sites was not possible and data was lost. Being able to automatically transmit data would be useful, but this adds significant costs.

5.6.Ground-based system for optical and microwave remote sensing of snow

Contributors: Roberta Pirazzini (FMI)

5.6.1.Sensors and platforms implemented - microwave remote sensing

The SodScat scatterometer is a custom-built prototype of a ground-based radar suitable for operation in Arctic conditions, designed and built by Harp Technologies Ltd. (Finland) with FMI funding. During the INTAROS project, efforts were focused on upgrading the system to an operational status by means of acquiring a 3-axis pointing device, displacement rail, and developing software for remote operation of the instrument (pointing device and rail acquired using FMI internal funding). A protocol for radiometric calibration and SAR image reconstruction using time-domain back-projection was developed, enabling the fast processing of science-quality data. An integral part of the activity was also the definition of best practices for instrument operation and maintenance in Arctic conditions. The instrument and the developed data processing chain are recommended for cal/val sites for microwave - based snow and soil products. The data will be usable for operational cal/cal of SAR satellite sensors as well as for the development of forward models and retrieval methods of geophysical variables using SAR.

5.6.2.Technical recommendations - microwave remote sensing

The developed radar system was custom-built around a commercial network analyser. For an operational device, inherent radar signal processing electronics and software would be more optimal to reduce physical size and power consumption of the instrument. The ground-based system also is limited to observing the immediate vicinity of the installation tower, and spatial representativeness is limited to the field of view. While SAR processing allows to separate some spatial variability in the target properties, the close field setting also generates some challenges to data interpretation (the obtained images are more skewed by local observation geometry, when compared to e.g. typical spaceborne SAR images made from orbit). This could be mitigated by higher physical installation; however, this may impose additional transmit power requirements.

In INTAROS a ground-based SAR system was developed to enable operational measurement of radar signatures of natural targets at plot scale, enabling to study e.g. the seasonal and diurnal variability at high temporal resolution. The custom-built radar enabled free choice of frequency band in the operational range, full polarization capabilities, and SAR image reconstruction, being as such suitable for scientific use. A network of cheaper, non-imaging (but e.g. scanning) radar systems, constrained to specific frequencies of existing or planned space-borne SAR systems, might supply similar information at reduced cost but with better spatial representativeness for satellite cal/val purposes and e.g. retrieval algorithm development for specific frequencies and systems.

5.6.3.Sensors and platforms implemented - optical remote sensing

The developed SVC-FMI spectro-albedometer, with the weather-proof enclosure, internal heating, and ventilation of the domes to prevent frost formation has proven to withstand harsh winter conditions in the terrestrial Arctic and can be applied for continuous measurements with minimal maintenance effort. The developed instrument is therefore a viable solution for unattended measurements of the full spectrum of incoming irradiance and surface albedo. These measurements are very much needed for the development of algorithms to retrieve snow properties from satellite optical sensors, and for the monitoring and modelling of the surface snow and sea ice albedo. This instrument is a robust and economically convenient solution compared to the traditional manually operated instruments.

5.6.4. Technical recommendations - optical remote sensing

As all ground-based sensors, the instrument has a limited field of view (few tens of square meters), and therefore cannot provide albedo measurements representative of the satellite footprint in case of surfaces with heterogeneous albedo. For cal/val applications, it should be associated to an assessment of its spatial representativeness and, in case of surface albedo heterogeneity, to drone-based albedo measurements over the scales sampled by satellites.

5.7. Atmospheric observations in the central Arctic Ocean

Contributors: Michael Tjernström (SU)

5.7.1. Sensors and platforms implemented

Atmospheric observations in the central Arctic Ocean are few, and information on the vertical structure of the atmosphere and on clouds are extremely rare, essentially limited to a few icebreaker-based expeditions. An atmospheric observatory ("supersite") to be run on an icebreaker unattended or with a minimum staff was designed to allow deployment on all expeditions with that vessel. The system consists of several linked parts including (i) an advanced weather station (measuring standard meteorological variables, incoming radiation, surface temperature, precipitation, visibility, and cloud-base geometry scenes and lidar backscatter intensity), (ii) a system for vertical soundings of temperature, atmospheric water vapor, winds and pressure on free-flying helium balloons, (iii) a surface turbulence flux station with instruments for eddy-covariance, and (iv) a set of surface-based remote sensing instruments (a cloud radar and a scanning multi-frequency microwave radiometer). The semiautomated atmospheric system developed for and implemented on the Swedish icebreaker Oden was first deployed in 2018, while a partial unattended deployment was carried out in 2019 on the so-called Ryder expedition, to the Ryder fjord and glacier on northwest Greenland. The whole system was deployed again in July-September 2021on the IB Oden during Synoptic Arctic Survey in the central Arctic Ocean. The planned deployments should continue in 2022 with the ArcOp22 ocean-floor drilling expedition. In 2023 there are two expeditions planned; ARTofMelt, to explore the onset of the summer melt and the multidisciplinary EUROASIAN Arctic C4 expedition to the Siberian shelf break to explore the Arctic carbon cycle. In 2024 a multidisciplinary expedition to north Greenland fjords (GEOEO) is planned.

5.7.2. Technical recommendations

All ship-borne expeditions venturing into the Arctic for any reason should always be required to carry instruments for and do atmospheric observations. This should be made a mandatory requirement for platform operators. The exact conditions for expeditions will of course determine the capacity for observation programs and hence to extent and quality of the observations. Ideally, vertical soundings should be carried out and the results transmitted in near real time on WMO's GTS network. Realizing this may become prohibitively labor intensive, there are now instruments available that can provide some of this information without much manual interference and this option should become a minimum.

Some instrument systems require manual labor; this is realistically the case especially for atmospheric sounding systems. Although automized systems are available, they come at a high cost. Also, environmental issues still remain for some observing systems, requiring manual interference, such as the propensity for some instruments to accumulate ice or frost in many weather conditions, requiring manual interference to keep them operational. Improved instrument systems to ensure they do not ice up and to automize the communication of observations. Also, profiling remote sensing instruments, such as surface-based microwave radiometers and ceilometer lidars, should be deployed to facilitate vertical profiling for missions where manpower for such observations is limited.

Statements from the Arctic Ministerials have repeatedly promised improved collaboration on observations. Requiring all platforms entering the Arctic to carry out a minimum of atmospheric observations would be one way to ensure that this actually happens in reality.

6. Cross-cutting technical recommendations

6.1. Multidisciplinary platforms with complementary measurements

Multipurpose use of autonomous observing platforms and infrastructure is a key requirement for a future observing system. Complementary multidisciplinary measurements not only increase value of collected information but optimize usage of observing infrastructure. Multipurpose platforms enable more efficient field work logistics, increase sensors redundancy to limit data loss, provide possibility of additional inter-calibration between sensors, and reduce environmental impact of observing infrastructure.

6.2. Development of more efficient energy sources

One common requirement reported across all observing systems is development of more efficient energy sources (batteries), adapted for extended operation in low temperature conditions. Power supply is a critical factor not only for duration and temporal resolution of measurements but also for auxiliary systems (e.g. heating required for deicing of atmospheric sensors) improving quality and year-round coverage of observations. Development of the next generation of high-performance and high-capacity batteries with a tolerance for a wide range of temperatures would enable longer autonomous operation of an observing system with the reduced need for maintenance and possibility to add auxiliary components, increasing safe data return.

6.3. Simple, low-cost sensors for massive deployments

For a future observing system, many recommendations call for development or refining of small, relatively simple, robust, low-power, and cost-efficient sensors that could be deployed in larger numbers to improve spatial coverage and data return from key areas. Relatively low unit cost provides the potential to scale to large numbers, both for achieving large scope and for creating robust systems that are resilient to instrument losses. Low-cost systems can provide a flexible observing capability that can be readily reconfigured in response to changing needs and objectives. Lastly, relatively light logistical requirements and low-cost help make sustained operation over many-year timescales more tractable. Duplication of instruments in critical locations or measurement points would be more feasible with low-cost sensors, ensuring lower risk of data losses and gaps.

6.4. Reliable, broadband, and cost-efficient satellite communication

There is a lack of satellite communications in the Arctic in terms of geographic coverage, bandwidth, quality of service and affordability. As of end of 2021 four polar (or near polar) orbit LEO communications satellites with Arctic coverage are operational: Argos (France/US), IridiumNEXT (US), Kepler (Canada), and Gonets (Russia). Current possibilities of satellite data transfer and bi-directional communication for observing infrastructure in the remote Arctic areas are limited to the former two systems with Argos providing low data rate (additionally used for tracking, sensor alert, and surface beacon monitoring) and IridiumNEXT providing narrow- and mid-band telemetry services. The broadband service (up to 704 kbps) is available with Iridium Certus platform, however required hardware (modems, antennas) is not yet optimal for small and power-limited autonomous platforms.

Kepler will offer truly broadband services to support larger data applications (>100 Mbps) with many potential applications in a future Arctic observing system if required hardware (antennas and terminals) is available and robust. As provider specifically targeting IoT, Kepler can specifically provide dedicated services for autonomous observing assets and unmanned systems. New mega constellations of LEO satellites will be available in future and two of them, OneWeb (UK) and Starlink (SpaceX, US) have already started deploying satellites. Both systems will provide coverage in Arctic regions but expected data rates is still difficult to estimate. Other important features will have to be considered, e.g. usability on moving vessel or surface vehicle, power consumption, data volumes, physical size of terminal and antenna, service cost, etc.

For autonomous observing systems and platforms operating in the high Arctic, reliable satellite communication is highly needed for data telemetry to provide NRT data for operational use and secure data return from instruments operated in harsh Arctic conditions (for some systems as e.g. ice-based platforms, this is the only way to receive measured data since they are not retrieved). In addition to data transfer, bi-directional satellite communication is required to monitor the status of an observing platform, adjust set up and measurement schedule of its sensors and supporting systems, and optimize maintenance needs.

Considering currently ongoing or near-future extensions of satellite systems with polar coverage, main recommendations with respect to a future Arctic observing system should include development of required hardware (modems, antennas, terminals), suitable for implementations on autonomous platforms of different size and power limitations, and capable to operate in the harsh Arctic conditions. Optimal, tailored to specific observing systems, and cost-efficient data services should be negotiated with future service providers to maximize accessibility of satellite communication to Arctic observers.

6.5.Multipurpose acoustic networks

Mobile ocean platforms operating in the ice-covered areas, cannot access satellite services (GPS and Iridium), and must instead rely on acoustic networks for underwater geopositioning (UW-GPS) and data telemetry. Platforms as Argo floats and gliders could benefit from acoustic signals provided by underwater sources to obtain position when surface access is hampered by sea ice. For subsurface moorings under the ice, acoustic data telemetry would enable the near-real time (NRT) data retrieval and increase data return. Acoustic infrastructure might thus be required to maximize the utility of autonomous approaches. Acoustic networks augmented with hydrophones and oceanographic instruments could provide a scalable multipurpose ocean observing system including UW-GPS, acoustic thermometry along fixed sections, passive acoustics, and oceanographic point measurements.

6.6.Collaboration on field logistics and operational challenges

Most of field operations and activities during INTAROS have been hindered to different extent by limitations resulting from the COVID-19 regulations. Field trips and research cruises have been cancelled or delayed, access to many in situ locations has been limited or shut down, travels have been difficult or impossible, and availability of trained technical professionals and scientists with experience in field work was severely diminished due to pandemic.

Numerous field operations in INTAROS, being mooring deployments or recoveries, or maintenance of terrestrial infrastructure were possible only through excellent collaboration between different groups and institutions, providing services also for others even if these additional activities were not planned in advance and did not belong to a main campaign or cruise. Collaboration on *in situ* operations and field logistics should be highly supported, encouraged and valued. It is recommended to develop relevant frameworks to enable shared burden, alignment, and optimization of field operations.

The experience gained during INTAROS shows that the high quality, detailed technical documentation (best practice documents) should be developed and disseminated for all individual components of the system. This will increase interoperability of different components of an observing system, improve safety during field operations, and make it possible to obtain support from independent technical professionals and scientists. Availability of open technical trainings and dedicated manuals/best practice documents on different sensors and methodology of field operations would highly benefit all Arctic observing community and increase efficiency of maintaining a future sustained observing system.

7. Summary of WP3 challenges and achievements in implementing in situ observations

INTAROS WP3 focused on developing and implementing innovative solutions and new technologies to fill selected gaps in the existing Arctic observing systems. Figure 7.1 provides an overview of *in situ* observations collected during INTAROS field campaigns in different regions of the Arctic.

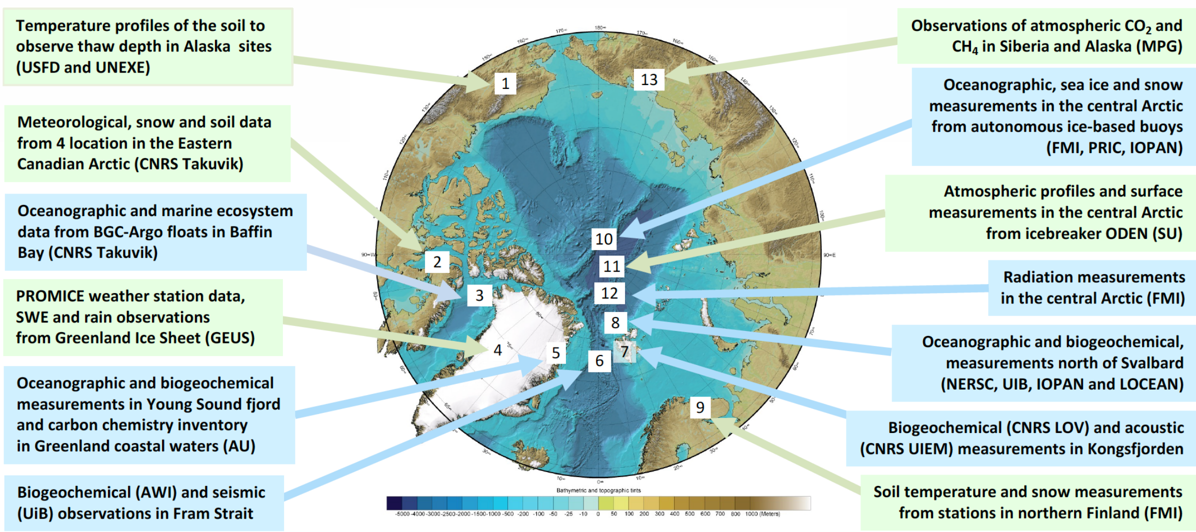

Fig. 7.1 Spatial distribution of observing system, networks and platforms providing *in situ* observations during INTAROS field campaigns in 2017-2021. Blue boxes and arrows indicate measurements collected in ocean and sea ice domains while green boxes depict atmospheric and terrestrial observations.

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

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

The main achievements of INTAROS WP3 in enhancing *in situ* observations in the Arctic can be summarized as follows.

New in situ observations were collected across all Arctic domains: ocean, sea ice, atmosphere and land and delivered (or will be soon delivered after final processing) to open data repositories.

Observations of new variables (snow water equivalent, precipitation) or refined existing measurements (high accuracy positioning, tilt and azimuth sensors, better observations of snow albedo) were collected on the Greenland Ice Sheet. In the central Arctic Ocean new observations of sea ice and snow on ice were gathered from drifting ice-based buoys. New radiation observations were provided from fixed stations on sea ice and airborne measurements with UAVs over the ice.

New time series of physical (temperature, salinity, currents) and biogeochemical (dissolved oxygen, nitrates, pCO2 and pH, turbidity, PAR) ocean variables, biological observations (acoustic and visual imaging), sea ice measurements and inorganic contaminants samples were collected on ocean moorings in Young Sound on Greenland and in the Nansen Basin north of Svalbard. New measurements of carbonate chemistry were collected continuously in the Svalbard fjord (Kongsfjorden) and along repeated transects in open ocean (between Norway and Svalbard) from ships of opportunity, the latter also providing microplastic samples and observations of seawater optical properties. Ocean acidification and its impact on ecosystem were observed in Fram Strait with dedicated experimental bottom system.

Physical and biogeochemical ocean observations were also collected with mobile platforms: Argo floats in Baffin Bay, underwater gliders in Fram Strait, and ice-tethered platform in the central Arctic Ocean. Acoustic observations and underwater soundscape monitoring were implemented in Kongsfjorden, Svalbard and seismic measurements were collected in Fram Strait.

Measurements of greenhouse gases and stable isotope signals were collected on Station North in Greenland. Eddy covariance measurements of CO2 and CH4 emissions were collected in Barrow, Alaska as well as profiles of soil temperature and soil gas concentrations. Snow and vegetation properties were monitored in the Canadian High Arctic as well as atmospheric and soil variables. Ground-based optical and microwave remote sensing of snow and soil was implemented in the northern Finland. Atmospheric measurements including meteorological variables, precipitation, radiative fluxes, winds, aerosols, clouds, and vertical soundings were collected from an icebreaker in the central Arctic Ocean and in Greenland fjords.

New instruments or platforms were added to existing observing systems to extend time series of observed key variables or add new measurements of previously missing variables.

A novel ruggedized system of SnowFox sensors for measuring snow-water equivalent on the Greenland Ice Sheet was added to the PROMICE AWS network. New radiometer tilt and azimuth instruments were added for correction of the PROMICE radiometers and new rain gauges augmented the in-situ PROMICE stations on the Greenland ice sheet. Nearly 40 SIMBA buoys for sea ice measurements and one IAOOS platform were deployed in the central Arctic, enhancing the existing network of ice-based platform. Fixed radiation measurement station was added to on-ice observing network during the MOSAiC campaign. New instruments for measuring physical and biogeochemical variables were added to ocean moorings in the Young Sound fjord, enhancing Greenland monitoring network. In Kongsfjorden on Svalbard new pH sensors for carbonate chemistry were added to the real-time observing system and new instruments were implemented for passive acoustic monitoring of the fjord environment.

Numerous up-to-date instruments for autonomous measurements of temperature, salinity, ocean currents, bottom pressure, and sea ice drift and draft were implemented on new ocean moorings deployed north of Svalbard, significantly enhancing existing moored array. Additionally, new sensors for BGC measurements (DO, pH, pCO2, nitrate sensors) and biological observations (acoustic imaging) were installed on new dedicated moorings. For one year (2018-2019), the six CAATEX moorings and the INTAROS mooring array provided a basin wide observing system from north of Svalbard to the Beaufort Sea with altogether more than 400 instruments for physical ocean and sea ice measurements. New endurance glider lines were established in Fram Strait by vehicles equipped with a rich sensor payload for physical and BGC measurements. Bottom-moored OBS instruments deployed in Fram Strait extended the EPOS network for earthquake monitoring.

High spatial and temporal resolution temperature profiles with high-resolution thermocouples were installed at three key sites in the Barrow cluster on Alaska, extending the existing network for GHG monitoring in the Arctic.

New sensors and improved technologies were developed or adapted to polar conditions for long-term use in a sustained Arctic observing system.

New laboratory facility to characterize the thermal and angular response of pyranometer (and other optical sensors) was established to improve snow albedo observations. New version of an airborne ground-penetrating radar was developed for ice thickness measurements on Greenland and Svalbard. A cluster of drones was adapted for use from sea ice for albedo measurements in the central Arctic Ocean.

In Baffin Bay INTAROS contributed to development of new sensors to measure the spatial variability of the inherent optical properties, the radiative field, and the nitrate concentration within the sea-ice. Additional contribution to the Baffin Bay observatory supported deployments of the BGC Argo floats adapted to work under the sea ice (ProIce floats).

A novel integrated sensor pack (Octopus system) with camera system (UVP6) and a suite of BGC sensors was developed and deployed for biogeochemical and biological (visual imaging) measurements on the mooring north of Svalbard. New passive samplers for organic contaminants were built and deployed on three moorings north of Svalbard. A suite of new sensors (microplastics sampler, a pack of spectrophotometric sensors for pH and CO3 ion, and an integrated sphere absorption meter sensor) was developed for FerryBox measurements from a ship of opportunity. A novel autonomous bottom system for in situ experiments to study ocean acidification (arcFOCE) was developed and implemented in Fram Strait.

For terrestrial measurements, a new automated system for collection of air samples for monitoring of greenhouse gases in the Arctic was developed and implemented on Station North on Greenland. New heating system was designed, tested, and implemented to enable year-round measurements with sonic anemometers on eddy-covariance towers.

The semiautonomous observing system for atmospheric measurements was developed and implemented on IB Oden, including a combination of an advanced weather station, a system for vertical soundings on free-flying helium balloons, a surface turbulence flux station with instruments for eddy-covariance, and a set of remote sensing instruments (a cloud radar and a microwave radiometer).

New data processing algorithms and delivery chains were developed for collected data.

New or improved processing algorithms were developed and tested for a variety of instruments providing in situ measurements in INTAROS, often in connection with newly developed sensors or adapting the existing instrumentation for use in the Arctic environment (e.g. processing algorithms for data from SIMBA buoys, improved characterization of responses for radiation sensors, improved data processing for acoustic doppler profilers for ocean currents and sea ice measurements). Improved or new data delivery chains were established for most data collected in WP3, from raw data retrieval to a submission of processed data into open repositories. The WP3 data sets were already (or will be soon when final processing is completed) submitted to the relevant open data bases and registered in the INTAROS data catalogue.

Standardized data formats conform to requirements of modern databases and FAIR principles were developed for different types of observational data.

INTAROS data collected in WP3 and delivered to existing repositories of established observing networks (e.g. PROMICE, GEM, EPOS, ICOS) were processed and formatted according to given standards. For new WP3 data without existing standards (e.g. times series from instruments on ocean moorings), appropriate standardized NetCDF data formats including comprehensive metadata were developed in accordance to recommended conventions (CF, ACDD, OceanSites, CMEMS).

Requirements and technical recommendations for a future observing system were elaborated based on first-hand experience in implementing in situ measurements during numerous INTAROS field campaigns.

Detailed technical recommendations were elaborated for all observing systems and platforms implemented under INTAROS. Overarching cross-cutting recommendations relevant to all systems in different domains (ocean, ice, atmosphere, land) were identified to serve as guidelines in development of a future sustained Arctic observing system. Major technical developments were highlighted that are critical for a transition from short-term observations to a sustained long-term integrated system.

Majority of observing platforms, networks, and reference sites where INTAROS contributed to enhancement of existing measurements or establishing new observations will be operated beyond INTAROS with the long-term perspective to become important components of a future sustained integrated Arctic observing system.

New technical solutions, platforms and sensor setups developed and implemented under INTAROS will be continued beyond the project as a part of existing observatories and key sites in different Arctic regions. New or improved sensors implemented on the Greenland Ice Sheet and in Greenland waters will contribute to the PROMICE network and Greenland Environmental Monitoring programme (GEM). Ocean and sea ice observations implemented by INTAROS north of Svalbard will be partially carried on under the newly established Atlantic Distributed Biological Observatory (ADBO). Further development and operational implementation of the arcFOCE system will be pursued as a part of the FRAM observing infrastructure and long-term monitoring in the LTER Hausgarten. Building on INTAROS and CAATEX developments, in situ ocean and sea ice observations in the central Arctic will be continued and significally extended under the following EU HE project HiAOOS (High Arctic Ocean Observing System).

8. Summary of WP3 technical recommendations for future iAOS

A multitude of different sensors, platforms, and systems deployed and installed for collecting in situ measurements at key sites and in distributed observatories during INTAROS provided a vast experience in operating these assents. Furthermore, INTAROS leveraged from extensive collaboration with other field programs such as MOSAiC and CAATEX, clearly demonstrating the benefits of collaboration in development and operation of an integrated Arctic Observing System (see Section 2). Based on the experience gained during the project field work, numerous specific technical recommendations were elaborated for individual systems, described in detail in Sections 3-5. However, among these specified recommendations, several cut across different systems employed within one domain (ocean, cryosphere, atmosphere, and land) or even across observing systems in different domains.

These cross-disciplinary recommendations are summarized below:

1. Facilitate a transition from short-term thematic/regional observatories towards a sustained observing system by integrating the existing fragmentary networks and enhancing them with new instrumentation to improve present-time measurements and add new observed variables.
2. Support and strengthen implementation of multipurpose observing systems, enabling multidisciplinary observations and providing additional services for different platforms and systems (e.g. acoustic geo-positioning or data telemetry in the ocean).
3. Promote development of relatively simple, low-cost, and low-power sensors for measuring essential ocean, atmospheric, and terrestrial variables that could be deployed in larger quantities to improve spatial scales and representativeness of observations and mitigate data gaps.
4. Accelerate a development of robust and reliable sensors for biogeochemistry and biology to be routinely used for ocean observations in the Arctic environment.
5. Encourage development and wider implementation of autonomous systems for atmospheric measurements over land, sea ice and ocean, including radiative fluxes, winds, aerosols, and clouds.
6. Improve technical solution for adaptation of standard sensors for operating in the Arctic conditions, e.g. solutions for deicing of atmospheric and terrestrial instruments or innovative power supplies for surface instruments operating during polar night (no solar panels, failing windmills).
7. Encourage and promote development of new generation of power sources with high capacity, high performance, and improved tolerance for low temperatures, possible also rechargeable, to enable longer and more efficient autonomous measurements in the Arctic.
8. Facilitate availability of reliable, broadband, and cost-efficient services for satellite data transmission and development of robust, low-power hardware for data transfer, in particular with respect to new satellite communication systems coming in near future.
9. Promote using ships of opportunity for autonomous collecting ocean, sea ice, and atmospheric observations in the Arctic Ocean.
10. Encourage and support development of publicly available best practice documentation for operating different *in situ* systems in the Arctic and open technical trainings available to professionals from different disciplines involved in Arctic observing.
11. Promote further development of common data standards for the new measurements collected.

Based on the broad experience reported in this document by the partners operating observing assets as a part of INTAROS, the most critical technical prerequisites for a sustained pan-Arctic network can be identified from recommendations shared by all operators. The pivotal technical developments for building a future sustained Arctic observing system should be focused on providing: (i) standard sensors ruggedized for Arctic conditions and new, low-cost and low-power sensors, (ii) autonomous observing systems, capable of long-term operations in changing Arctic conditions (e.g. with less sea ice cover or on melting permafrost), (iii) new generation of improved power supplies, and (iv) reliable, high bandwidth, and cost-effective services and hardware for satellite data transfer. Collocated multidisciplinary measurements should be implemented within different components of an observing system (wherever technically and logistically feasible) as they strongly benefit from above developments. Several of the technical recommendations are already addressed within EU Research and Innovation Programmes (e.g. under calls on more efficient batteries) and new technologies to be delivered in future as the outcomes of these projects should be adapted for and implemented in a future Arctic observing system.

9. Main conclusions

INTAROS WP3 focused on developing and implementing innovative solutions and new technologies to fill selected gaps in the existing Arctic observing systems. Novel instruments, platforms and sampling methods were integrated with mature components of existing observatories to enhance collection of in situ data in three reference sites (Coastal Greenland, North of Svalbard, Fram Strait and Svalbard fjords) and two distributed observatories (for ocean and sea ice, and for land and atmosphere).

- New in situ observations were collected across all Arctic domains: ocean, sea ice, atmosphere and land and delivered (or will be soon delivered after final processing) to open data repositories.
- New instruments or platforms were added to existing observing systems to extend time series of observed key variables (e.g. key physical ocean variables or standard atmospheric measurements) or add new measurements of previously missing variables (e.g. BGC variables in the ocean, SWE and rain measurements on GIS, sea ice measurements, GHG year-round sampling, ship-borne atmospheric measurements in the central Arctic, and many others).
- New sensors and improved technologies were developed or adapted to polar conditions for long-term use in a sustained Arctic observing system (e.g. the arcFOCE experimental system for observing an impact of ocean acidification on Arctic biota).
- Major challenges and shortcomings of implemented platforms, sensors and observing methodologies were identified, mainly related to robustness of available technology under harsh Arctic conditions, high sensor/platform costs, limited power supply for autonomous platforms, limited access to critical services (GPS positioning, satellite data transfer), and complex and costly field logistics. Future solutions (short- and long-term) were proposed in each case based on experience gained during INTAROS field deployments.
- New data processing algorithms and delivery chains were developed for collected data. Standardized data formats conform to requirements of modern databases and FAIR principles were established and implemented for different types of observational data.
- Specific requirements and technical recommendations for individual platforms, sensors, and methods to be used in a future observing system were elaborated based on first-hand experience in implementing of *in situ* measurements during numerous INTAROS field campaigns.
- Cross-cutting recommendations were distilled from a variety of detailed improvement suggestions for individual systems. They were mainly focused on using multidisciplinary platforms, development of simple, low-cost, and low-power standard sensors to be deployed in larger quantities, improvements of autonomous sensors and samplers for biogeochemistry, biology, and atmospheric measurements, accelerated development of high-capacity power sources and cost-efficient broadband services for satellite data transmission, and a wide implementation of common data standards and best practices.
- Majority of observing platforms, networks, and reference sites where INTAROS contributed to enhancement of existing measurements or establishing new observations will be operated beyond INTAROS with the long-term perspective to become important components of a future sustained integrated Arctic observing system.

10. Annex A. Collaborating field programs and projects

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

Program or project	Domain	Scope of collaboration
CAATEX (Coordinated Arctic Acoustic Thermometry Experiment) *Norway, US*	Ocean	CAATEX contributed to deep water mooring design and operation. It provided ship time for INTAROS for mooring operations, in situ measurements, deployment of ice buoys, and drone operations. INTAROS contributed to CAATEX field operations, standardization of data processing, formatting, and delivery of oceanographic data. Joint activities on defining practices and recommendations for further technological development of regional to pan-Arctic Ocean observing systems.
MOSAiC (Multidisciplinary drifting Observatory for the Study of Arctic Climate) *International*	Sea ice, ocean, atmosphere	MOSAiC provided space and infrastructure on Polarstern and access to interdisciplinary data for the participating partners. INTAROS contributed to radiation measurements and SIMBA buoy deployment during the MOSAiC field campaign.
A-TWAIN (Long-term variability and trends in the Atlantic Water inflow region) / Nansen Legacy *Norway*	Ocean	A-TWAIN/Nansen Legacy provided ship time for INTAROS mooring operations and support during the field operations. A-TWAIN also provided mooring infrastructure for two INTAROS instruments (ADCP/echosounder and ADCP/ice) Collaboration on instrumentation, data processing, and scientific use of observations.
PROMICE (Programme for monitoring of the Greenland ice sheet) *Denmark and Greenland*	Ice sheet, atmosphere	PROMICE sharing field logistics and infrastructure with INTAROS. INTAROS contribution to development and implementation of new or improved components of the PROMICE observing system (SnowFox instruments, rain gauges, GNSS positioning, tilt and azimuth sensors).
GC-Net (Greenland Climate Network) *Denmark and Greenland*	Ice sheet, atmosphere	GC-Net contributed field logistics and infrastructure with INTAROS. INTAROS contributed to development and implementation of new or improved components of the GC-Net instrumentation (SnowFox instruments, rain gauges, GNSS positioning, tilt and azimuth sensors).
GEM (Greenland Ecosystem Monitoring) *Denmark and Greenland*	Ocean	GEM provided field logistics and infrastructure to mooring operations. INTAROS contributed to ship-borne carbonate system measurements in coastal waters and added new mooring and instruments to moored observatory in Young Sound.
LTER Hausgarten Observatory in FRAM (FRontiers in Arctic marine Monitoring) *Germany*	Ocean	INTAROS contributed to development and implementation of a new platform (ArcFOCE) in the FRAM observing system. FRAM provided ship time, field logistics and infrastructure for the new INTAROS platform.
Equipex IAOOS (Ice-Atmosphere-Arctic Ocean Observing System) *France*	Ocean, sea ice	Equipex IAOOS provided know-how, logistics, infrastructure and technician support for development and deployment of the IAOOS ice-based platform contributed by INTAROS for ocean, sea ice, and atmospheric measurements.
COSYNA-AWIPEV Underwater Observatory *France, Germany*	Ocean	INTAROS contributed to implementation of new sensors (pH sensors) as components of the observing system for continuous measurements of carbonate system variables. COSYNA-AWIPEV observatory provided infrastructure and logistics for new sensors.

EPOS-N (European Plate Observing System - Norway) *Norway*	Natural hazards, ocean	INTAROS contributed to EPOS-N with deployments of new OBS systems for earthquake monitoring. EPOS-N provided instruments and data management infrastructure for the OBS data.
GLISN (Greenland Ice Sheet Monitoring Network) *International*	Natural hazards, land and ice sheet	The GLISN project has established a real-time sensor array of 33 stations to enhance and upgrade the performance of the scarce existing Greenland seismic infrastructure for detecting, locating, and characterizing glacial earthquakes and other cryo-seismic phenomena, and contribute to our understanding of Ice Sheet dynamics.
DanSeis *Denmark*	Natural hazard, sea floor	Danish national research infrastructure providing access to cutting edge seismic research equipment to scientists from research institutions in Denmark and worldwide.
ICOS (Integrated Carbon Observation System) Atmospheric Monitoring Program *International*	Atmosphere	INTAROS contributed to development and implementation of autonomous system for GHG sampling and to enhancement of Station North facilities as the European ICOS observation network for GHG. Station North provided infrastructure for new sampling platform.
FMI Sodankylä-Pallas Observatory (cal/val site for the NASA SMAP and ESA SMOS missions) *Finland*	Atmosphere land	INTAROS contributed to development and implementation of ground-based sensors for microwave and optical remote sensing of snow. Sodankylä-Pallas Observatory provided field logistics and infrastructure for new instruments.
SnowAPP (Modelling of the Snow microphysical-radiative interaction and its APPlications) *Finland*	Land	SnowAPP provided part of the resources to process the observations and develop the observation routines of the SVC spectro-albedometer and the full-polarized SodScat radar.
ACAS (Arctic Climate Across Scales) funded by the Knut and Alice Wallenberg Foundation *Sweden*	Atmosphere	INTAROS contributed to implementation of semiautonomous system for atmospheric measurements on IB Oden that was developed and established by ACAS.
Year of Polar Prediction (YOPP), program by the WMO-initiative Polar Prediction Project (PPP) *International*	Atmosphere	INTAROS provided near-real-time Arctic observations on the WMO Global Telecommunication System during the Arctic Ocean 2018 and Synoptic Arctic Survey 2022 expeditions, both on the Swedish icebreaker Oden, as well as participated in the YOPP outreach program with popular science articles in the ECMWF and PPP Newsletters.
DINGLAC, project funded by Agencia Estatal de Investigación-Spanish Polar Programme *Spain*	Ice sheet, glacier	DINGLAC project co-funded the ground-penetrating radar developments performed under INTAROS by the UPM team.
Norwegian Ocean Acidification monitoring project, funded by the Norwegian Environment Agency *Norway*	Ocean	Norwegian Environment Agency project on monitoring ocean acidification and INTAROS have collaborated and both contributed to the carbonate system observations in the Barents Sea Opening.
INTAROS_SVALBARD (2018-2021), funded by French Polar Institute (IPEV) *France*	Ocean	INTAROS-SVALBARD provided support for glider rental and logistics in Svalbard for the endurance glider lines operated under INTAROS.

APT (Accelation of permafrost thaw), funded by the BNP-Paribas Foundation *France*	Land	APT co-funded instruments and field work for multi-disciplinary monitoring of snow and vegetation properties in the Canadian High Arctic.
ESCAPE-Arctic (Ecosystems – Snow – ClimAte – Permafrost feedbacks) funded by French Polar Institute (IPEV) *France*	Land	ESCAPE co-funded instruments and field work for multi-disciplinary monitoring of snow and vegetation properties in the Canadian High Arctic.
PCSP (Polar Continental Shelf Program) *Canada*	Land	PCSP provided logistical support for field work related to multi-disciplinary monitoring of snow and vegetation properties in the Canadian High Arctic.
Amundsen Science *Canada*	Ocean	Amundsen Science manages all the scientific operations aboard the icebreaker NGCC Amundsen. Through a collaboration, Amundsen Science contributed ship time and berths for the deployment of BGC-Argo floats over the entire INTAROS time frame.
Baffin Bay Observatory *France, Canada*	Ocean, sea ice	Shared field logistics and infrastructure with INTAROS. INTAROS contribution to implementation of under-ice BGC Argo floats and new sensors for sea ice properties.
Sentinel North *Canada*	Ocean	Sentinel North supported the BGC-Argo float work through post-doctoral fellowships as well as ship-time for the deployment of the floats in 2021. INTAROS contributed to operating the BGC-Argo floats and data analysis.
FACE-IT (The future of Arctic coastal ecosystems – Identifying transitions in fjord systems and adjacent coastal areas) *International*	Ocean	FACE-IT contributed to analysis of time series data and design of perturbation experiment in mesocosms in Kongsfjorden observatory. INTAROS contributed with new sensors and measurements to carbonate system observations from Kongsfjorden.

11. Annex B. Summary of platforms and sensors in INTAROS

Domain	Ice sheet	Sensor/platform	SnowFox for SWE
Partner	GEUS		
Action	Snow-water equivalent on the ice sheet		
Objective	To reduce uncertainty in meltwater output to the ocean		
Field deployment	Summer 2018 - 5 instruments at four locations on the Greenland ice sheet		
Challenges	Insufficient power supply during winter/snow burial		
Final results	Data on snow water equivalent (SWE) successfully retrieved from SnowFox instruments and processed from four sites co-located with PROMICE weather stations, power supply issues were identified, and mitigation measures taken. The demonstrated SWE measurement will be rolled out for additional PROMICE weather stations over the coming years and data made openly available through the PROMICE database.		

Domain	Ice sheet	Sensor/platform	GNSS unit
Partner	GEUS		
Action	Precise positioning of ice sheet stations		
Objective	Assembling new type of GNSS unit with antenna and communication/control to calibrate satellite-derived ice velocity maps and numerical weather prediction		
Field deployment	Summer 2019 (test unit)		
Challenges	Complications in the communication between parts of the assembly caused delays in field deployment, limiting test deployment to one site in 2019		
Final results	High-precision vertical and horizontal positional data was successfully retrieved from the new GNSS unit, capable of recording e.g. ice ablation by accurately recording changes in elevation. The deployment successfully tested a range of possible issues and a modified version of the device already implemented in experimental landslide monitoring. The GNSS unit will be rolled out on further ice sheet and glacier weather stations over the coming years and data made openly accessible to enhance the value of existing AWS data products significantly.		

Domain	Ice sheet	Sensor/platform	Tilt and azimuth sensors
Partner	GEUS		
Action	New radiometer tilt and azimuth instrument for improved radiation correction		
Objective	Assembling new type of tilt/azimuth unit with communication and control to correct the radiation measurements with improved tilt and new azimuth data, because automatic weather stations on ice cannot provide a stable level orientation of the radiometers		
Field deployment	Summer 2019 (test unit)		
Challenges	Problems with powering and interfacing to the ADIS16209 resulting in occasional lock-ups during testing, as well as difficulties implementing the planned serial communication using the SDI-12 protocol. First field deployment 2019-2020 resulted in corrupted flashcard and thus no data.		
Final results	A rugged, precise, and low-power tilt and azimuth sensor was developed and tested in the lab. First field deployment yielded a corrupted flashcard, possibly from sudden power loss during data writing, emphasizing the vulnerability of this data storage method. A second deployment is ongoing.		

Domain	Ice sheet	Sensor/platform	Rain gauges
Partner	GEUS		
Action	Rain gauges on ice sheet stations		
Objective	To observe rain events and their magnitude on the ice sheet		
Field deployment	Rain gauges deployed during and prior to the INTAROS effort from 2016 and onwards. The rain gauges to be deployed on all relevant AWS on or near the Greenland ice sheet		
Challenges	The undercatch correction is substantial and needs field validation		
Final results	Corrected rain datasets from the ice sheet have been successfully retrieved and compared to results from regional climate models and reanalysis products. Rain gauges are now being implemented as a new observation on PROMICE, GC-Net and GEM monitoring weather stations on ice in Greenland		

Domain	**Sea ice and ocean**	**Sensor/platform**	**Camera system and moored CTD sensors**
Partner	AU		
Action	Snow cover on sea ice		
Objective	To study the impact of freshening on the marine ecosystem		
Field deployment	Aug 2018 – Aug 2019		
Challenges	A new camera system to monitor conditions above the instrument in the inner fjord, deployed in August 2018 was found broken in August 2019. It appears to have been damaged by musk oxen. The system was serviced and replaced and is hopefully taking daily images for the 2019-2020 season		
Final results	Two years of CTD data so far successfully retrieved from the marine instruments deployed in Aug 2018 and again in 2019, with a third year expected by Aug 2021. It is planned to continue this monitoring as a part of the GEM programme.		

Domain	**Ice sheet**	**Sensor/platform**	**Calibration laboratory for albedo sensors**
Partner	FMI		
Action	Entirely new laboratory facility constructed for instrument characterization of in-situ ice sheet albedo measurements		
Objective	To obtain improved validation of satellite albedo products		
Field deployment	N/A (calibration of instruments before field deployment)		
Challenges	The cooling system of the temperature-controlled chamber broke and the consequent need of total replacement of many components caused a one-year delay in the characterization work		
Final results	Laboratory instrumentation and procedures to characterize the thermal and angular response of pyranometers, to increase the accuracy of the solar irradiance and albedo measurements has successfully been applied to CNR1 and CNR4 net-radiometers of the PROMICE network. The method is expected to be applied to similar radiometers of the PROMICE, GC-Net and GEM monitoring networks in the future		

Domain	**Ice sheet**	**Sensor/platform**	**Ice-penetrating radar system**
Partner	UPM		
Action	Improvement of ice-penetrating radar system		
Objective	To generate ice thickness data over ice-sheet outlet glaciers		
Field deployment	January 2019, testing the system (Livingston Island, Antarctica)		
Challenges	Initially planned fieldwork in Greenland in spring 2019. However, due to logistic reasons, this campaign could not be accomplished. It has been necessary to re-use some modules from the existing radar in the development of the new system VIRL8		
Final results	Test flights delivered 200 km of good radar profiles over ice, proving the concept of the new helicopter-borne radar system in the field. The processed radar profiles have successfully yielded bedrock returns in usually difficult glaciological settings near glacier fronts, although partly disrupted by occurrence of meltwater and reflections off nearby nunataks		

Domain	**Ocean**	**Sensor/platform**	**Pro-ice BGC Argo floats**
Partner	CNRS-Takuvik		
Action	Improvement of under-ice monitoring		
Objective	To observe spring bloom and bio-optical/-geochemical properties		
Field deployment	Pro-ice BGC Argo floats deployed: five in Spring 2016 (with four in Baffin Bay), seven in Summer 2017, two in Summer 2018, two in Summer 2019.		
Challenges	Although the Pro-ice floats are adapted to ice-infested waters, the experiment remains a real challenge. The real reason for the loss of some floats, at the beginning of the experiment remains unexplained, but we could diagnostic a mismanagement of the grounding in the firmware that leads to three losses at least (issue has been fixed).		
Final results	More than 1900 profiles have been acquired so far with unprecedented sets of data with series measured under ice during wintertime. Takuvik intends to continue measuring sea-ice properties in Qikiqtarjuaq and other coastal ecosystems in Baffin Bay. The sensors developed at Takuvik will be integrated to a sea-ice endoscope in development at Université Laval. This endoscope will optimize the acquisition of data in situ over a wide range of sea-ice geometries.		

Domain	Ocean	Sensor/platform	BGC moored sensors (DO, pCO2, pH, nitrate)
Partner	UiB-GFI		
Action	Year-round measurements of biogeochemical variables on INTAROS moorings		
Objective	To collect year-round observations of biogeochemical variables (dissolved oxygen, pCO2, pH, nitrate) on INTAROS moorings deployed north of Svalbard and in the deep Nansen Basin		
Field deployment	Deployments in BGC11 in 2018-2019 and on NERSC-4 in 2019-2020		
Challenges	Stability of BGC sensors, availability of co-located samples for post-deployment calibrations taken during deployments and recoveries. Challenges in operating sensitive BGC sensors on moorings in the ice-covered waters.		
Final results	Two years of year-round time series of measured physical (temperature, salinity, ocean currents) and biogeochemical (dissolved oxygen, pCO2, pH, nitrate) data in the key site north of Svalbard		

Domain	Ocean	Sensor/platform	Ship-borne instruments for stable isotopes
Partner	UiB-GFI		
Action	Ship-based stable isotope measurements in atmospheric water vapour		
Objective	To collect automated ship-borne measurements of stable isotopes in atmospheric water vapour and auxiliary atmospheric and oceanographic data during two field campaigns north of Svalbard		
Field deployment	Two cruises in July-August 2018 (INTAROS2018) and August-September 2019 (CAATEX2019) north of Svalbard		
Challenges	No live transfer or remote access to instruments (in case of problems). Better protection against sea spray and contamination by ship air, and physical damage needed. Corrosion of regular meteo sensors, filter system required.		
Final results	Calibrated, continuous time series of stable isotopes in water vapour collected during two cruises with the main variables including $\delta^{18}O$ (and δD), d-excess, and specific humidity and auxiliary data (atmospheric data, images time series).		

Domain	Ocean	Sensor/platform	Autonomous moored sensors for ocean and sea ice
Partner	IOPAN		
Action	Year-round measurements of ocean physical and sea ice variables on INTAROS and A-TWAIN moorings north of Svalbard		
Objective	To deploy oceanographic moorings north of Svalbard and provide year-round measurements of physical and sea ice variables collected with point and profiling CTDO and ocean current and sea ice sensors and at fixed locations in the key region of the Atlantic water inflow to the Arctic Ocean		
Field deployment	Three year-round deployments of two oceanographic moorings in 2017-2018 (test field season), 2018-2019 (first field season, three moorings, including BGC11), and 2019-2020 (second field season) at two moorings lines (INTAROS at 22°E and A-TWAIN at 31°E) north of Svalbard		
Challenges	Difficult logistics for mooring operations in the remote, ice-cover region, recovery from under the ice, high risk mooring, no surface access. Limitation and restrictions due to COVID-19 in ship access and logistics.		
Final results	Year-round time series of physical ocean and sea ice variables (ocean subsurface temperature, salinity, and dissolved oxygen at fixed depths and profiles of ocean currents, sea ice draft and drift) in the key region of the Atlantic water inflow to the Arctic Ocean north of Svalbard. Concurrent measurements with physical ocean variables collected at CNRS-LOCEAN moorings.		

Domain	Ocean	Sensor/platform	Autonomous moored sensors for ocean physics
Partner	CNRS-LOCEAN		
Action	Year-round measurements of ocean physical variables on INTAROS moorings north of Svalbard		
Objective	To deploy oceanographic moorings north of Svalbard and provide year-round measurements of physical and sea ice variables at fixed locations in the key region of the Atlantic water inflow to the Arctic Ocean		

Field deployment	Three year-round deployments of three oceanographic moorings in 2017-2018 (test field season), 2018-2019 (first field season), and 2019-2020 (second field season) at the INTAROS moorings line at 22°E north of Svalbard
Challenges	Difficult logistics for mooring operations in the remote, ice-cover region, recovery from under the ice, high risk mooring, no surface access. Limitation and restrictions due to COVID-19 in ship access and logistics.
Final results	Year-round time series of physical ocean variables (ocean subsurface temperature, salinity, and dissolved oxygen at fixed depths and profiles of ocean currents) in the key region of the Atlantic water inflow to the Arctic Ocean north of Svalbard. Concurrent measurements with physical ocean variables collected at IOPAN moorings.

Domain	**Ocean**	**Sensor/platform**	**Passive contaminant samplers for mooring**
Partner	NIVA		
Action	Collection of passive contaminant samples on the moorings north of Svalbard		
Objective	To collect year-round passive contaminants samples on moorings north of Svalbard		
Field deployment	Clusters of 2-3 passive samplers deployed on three INTAROS moorings for 2018-2019 (one mooring recovered after 2 years in 2020)		
Challenges	Access to moorings, post-recovery procedure (when recovered by other groups)		
Final results	Data collection of concentrations of polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), organochlorinated pesticide residues such as DDT, HCHs and hexachlorobenzene, polybrominated diphenyl ethers (PBDEs) and selected UV filter including UV-328 in the key locations north of Svalbard		

Domain	**Ocean**	**Sensor/platform**	**Moored ADCP/echosounder for ocean biology**
Partner	IMR		
Action	Implementation of a novel ADCP/echosounder instrument on the mooring north of Svalbard		
Objective	To collect year-round measurements of the upper ocean currents and biological activity (from large zooplankton to fish) on selected moorings north of Svalbard		
Field deployment	First deployment in 2019-2020 (instrument failure), second deployment for 2020-2021 (mooring to be recovered in November 2021)		
Challenges	Malfunction of the instrument during the first deployment, delayed data delivery		
Final results	To be yet obtained after recovery in late 2021, will include time series of ocean current profiles and high-resolution backscatter measurements for biomass in the upper ocean		

Domain	**Ocean**	**Sensor/platform**	**Moored sensor package with UVP6**
Partner	AWI		
Action	Deployment of the OCTOPUS sensor package for biogeochemical and biological observations north of Svalbard		
Objective	To collect year-round physical, biogeochemical and biological observations with the prototype senor package (including the camera system UVP6, nitrate sensor, and Ecotriplet fluorometer) at the mooring in the Atlantic water inflow north of Svalbard		
Field deployment	One-year deployment in 2018-2019 at the BGC1 mooring		
Challenges	Collection of additional samples for calibration during deployment/recovery,		
Final results	One-year time series of raw particles data (measured size, abundance) and analyzed visual images of particles in Ecotaxa. Time series of the nitrate data as well as fluorescence data of chlorophyll, cDOM and particle backscatter.		

Domain	**Ocean**	**Sensor/platform**	**Moored ocean bottom pressure recorders**
Partner	UNIS		
Action	Year-round measurements with Ocean Bottom Pressure Recorders north of Svalbard		
Objective	To collect time series of ocean bottom pressure and temperature on INTAROS moorings in key locations north of Svalbard		
Field deployment	BPRs deployed on two INTAROS moorings in 2018-2019		
Challenges	Delays in instruments purchase/delivery.		
Final results	Year-round high resolution time series of pressure and temperature at the bottom to obtain the weight of the water column above the ocean sea floor		

Domain	Ocean	Sensor/platform	Ocean bottom seismographs
Partner	UiB-GEO and GEUS		
Action	Deployment of the Ocean Bottom Seismographs (OBS) for year-round seismic observations around Svalbard		
Objective	To monitor seismic activity in key locations around Svalbard		
Field deployment	Three year-round deployments in 2017-2018 and 2018-2019 west of Svalbard in in 2019-2020 in Storfjorden		
Challenges	High risk in recovery operations. ROV support recommended for operations in ice-covered areas. Limitations in battery power. Long-term operations with real-time data transfer needed for seismic hazard assessment		
Final results	Year-round recordings of seismic waves with four components (vertical, two horizontals and hydrophone channel) with auxiliary data on precise timing, source location and the seismometer location. Time series of pressure changes at the sea bottom (from hydrophones).		

Domain	Ocean	Sensor/platform	arcFOCE experimental setup for ocean acidification
Partner	AWI		
Action	Development and implementation of an experimental arcFOCE (arctic Free Ocean Carbon Enrichment) experimental setup		
Objective	To study impacts of ocean acidification on small, sediment-inhabiting deep-sea organisms		
Field deployment	The first long-term deployment from October 2018 till September 2019 in approx. 1500 m water depth at the LTER observatory HAUSGARTEN in the eastern Fram Strait. Short-term in-situ tests of the improved system were carried out during the RV Polarstern expedition PS126 in June 2021; the next long-term deployment of the arcFOCE system started in summer 2022.		
Challenges	Pressure adapted glass pH sensors controlling the system, failed to perform reliably. The exchange of the glass sensors by optical sensors (optodes) will most probably solve these problems.		
Final results	Overall performance of the arcFOCE experimental setup during its first long-term deployment at the LTER observatory HAUSGARTEN in the eastern Fram Strait was very promising, although a central component, i.e. the pressure adapted glass pH sensors controlling the system, failed to perform reliably. Retrieved sediments were analysed for bacterial densities and a number of sediment parameters (e.g. organic carbon content, total microbial biomass). The improved system proved successful during short-term in situ tests.		

Domain	Ocean	Sensor/platform	Passive acoustic recording system
Partner	CNRS-IUEM		
Action	Deployment of passive acoustic recording system in Kongsfjorden		
Objective	To assess the soundscape (biophony, geophony, antropophony) of the Arctic fjord		
Field deployment	Long-term recordings were collected during nine deployments of autonomous recorders at the entry of the Kongsfjorden in 2018-2021. Additional acoustic short period recordings were also conducted during these three years (in/outside kelp forest, from drifting platform and in tanks for urchins).		
Challenges	The Covid-19 pandemic seriously affected the necessary field work to install/replace instrumentation.		
Final results	Simultaneous deployment of several acoustic sensors with different starting times generally increased the recording capacity. Approx. 15000 hours of recordings within the INTAROS project were collected. Acoustic data time series at the Kongsfjorden outlet demonstrated a 3-fold increase of ship traffic (AIS data for fishing vessels and tourist ships) between 2013 and 2018, but also the lower shipping activity in 2020.		

Domain	Ocean	Sensor/platform	Land-based FerryBox senors (pH, AT, T, S)
Partner	CNRS-LOV		
Action	Improving the AWIPEV CO_2 monitoring system in the Kongsfjorden		
Objective	To obtain a high frequency time-series of carbonate chemistry variables in the high-Arctic		

Field deployment	Continuous in situ measurements with a land-based FerryBox system equipped with a set of sensors. The FerryBox system receives water from an underwater pump station at 11 m water depth. At this pump station, a remotely controlled profiling sensor carrier fitted with another set of sensors performs a vertical cast every day.
Challenges	The extreme conditions incurred incidents such as interrupted supply of seawater in the FerryBox due to frozen pipes or damages resulting from icebergs pounding on the field instruments. Resolution of these incidents sometimes took weeks to months until temperature warmed, making de-icing possible. Delays due to COVID-19 also occurred to bring technical staff, including divers, to repair damages. New regulations were introduced at Ny-Ålesund for the use of HgCl2 and transportation of preserved samples and in consequence, discrete samples could not be taken after January 2021.
Final results	Additional variables including partial pressure of CO_2 in seawater, pH, total alkalinity and air-sea CO_2 flux were added during INTAROS to CO_2 monitoring system in the Kongsfjorden. It was proved feasible to operate a high frequency time-series of carbonate chemistry variables in the high-Arctic, provided by staff is available to proceed with discrete sampling and the use of mercuric chloride made possible.

Domain	**Ocean and sea ice**	**Sensor/platform**	**Ice-tethered IAOOS platform**
Partner	IOPAN (in collaboration with Equipex-IAOOS)		
Action	Deployment of ice-tethered IAOOS platform in the central Arctic Ocean		
Objective	To provide ocean, sea ice, and atmospheric measurements in the central Arctic collected from drifting ice floe		
Field deployment	Autumn 2019 in the central Arctic Ocean (close to the North Pole)		
Challenges	Short-living platform, destroyed by a polar bear, problems with robustness		
Final results	Monthly time series of ocean physical measurements in the upper 600 m (temperature, salinity, dissolved oxygen), temperature profiles through air-snow-sea ice-ocean (derived snow depth and ice thickness) and atmospheric measurements (air temperature and pressure, lidar observations) along the ice drift trajectory		

Domain	**Ocean/sea ice**	**Sensor/platform**	**Autonomous moored sensors for ocean/sea ice**
Partner	IOPAN (in collaboration with UiB-GFI and NERSC)		
Action	Deployment of deep ocean multidisciplinary mooring in the Nansen Basin		
Objective	To provide year-round physical, biogeochemical, and acoustic measurements at fixed location from the deep basin in the Arctic Ocean		
Field deployment	September 2019 to July 2020 in the deep Nansen Basin		
Challenges	Difficult logistics for mooring operations in the remote, ice-cover region, recovery from under the ice, high risk mooring, no surface access. Limitation and restrictions due to COVID-19 in ship access and logistics.		
Final results	Year-round measurements of physical (ocean subsurface temperature and salinity at fixed depths and profiles of ocean currents, sea ice draft and drift) and biogeochemical (dissolved oxygen, pCO2/pH) variables, passive acoustic measurements (by collaborating partners) in the Nansen Basin. Concurrent measurements with physical ocean variables were collected at three CAATEX acoustic moorings.		

Domain	**Sea ice/snow on ice**	**Sensor/platform**	**SIMBA snow and ice mass balance buoys**
Partner	FMI		
Action	Deployments of SIMBA snow and ice mass balance buoys in the central Arctic Ocean		
Objective	To provide measurements of temperature profile through air-snow-sea ice-ocean and identify their interfaces, to collect additional data as ice floe drift trajectory, air temperature and pressure		
Field deployment	Deployment of up to 38 SIMBA buoys (partially contributed by INTAROS) during five main cruises and filed campaigns in the Arctic Ocean in 2018-2020		
Challenges	Liability and robustness of the of measurement during melting season, vulnerability of thermistor chain to ice raft and deformation, polar bear risk, unified data processing not yet available		
Final results	Time series of temperature profiles in air-snow-sea ice-ocean and drift trajectories from SIMBA buoys with average lifetime of about one year, drifting mainly in the Beaufort Gyre and the Transpolar Drift Stream. Derived snow depth and ice thickness, and interface locations between snow, sea ice, and ocean		

Domain	Sea ice and atmosphere	Sensor/platform	Fixed and mobile radiation sensors
Partner	FMI		
Action	Fixed station and UAV-based radiation measurements during the MOSAiC expedition		
Objective	To collect surface broadband and spectral albedo measurements in the Central Arctic during the MOSAiC campaign		
Field deployment	Fixed broadband radiation station deployed from November 2019 to November 2020. UAV-based measurements of spectral and broadband radiation (17 flights, corresponding to ~5 flight hours) and photography mapping of target area (35 flights, corresponding to ~11.5 flight hours) during MOSAiC leg 5 (August-October 2020).		
Challenges	Cleaning pyranometers from condensation or brine/ice formation required on daily basis. Operating drones in Arctic environment (ice formation on propellers, unreliable navigation system in proximity of the North Pole, low, visibility, harsh working conditions for drone operator). Mobile target for drone measurements.		
Final results	Time series and snapshots of broadband longwave and shortwave fluxes, broadband and spectral albedo, surface maps obtained from drone-based photo-mosaics		

Domain	Ocean	Sensor/platform	New sensors and samplers for FerryBox
Partner	NIVA		
Action	Development and implementation of novel sensors and samplers for the Barents Sea Opening FerryBox		
Objective	To develop and implement three different types of sampler/sensors, including a microplastics sampler, a combined deployment of spectrophotometric sensors for measuring pH and CO_3 ion, and an integrated sphere absorption meter sensor for measuring optical properties of seawater including dissolved organic matter and phytoplankton chl a and taxon-specific pigments for FerryBox measurements		
Field deployment	Microplastic sampler deployed in 2019. Combined spectrophotometric pH/CO_3 system field-tested in 2018, refined in 2019 and 2020 and deployed from May 2020 to August 2021 (but offline from December 2020 to April 2021 for upgrade). Integrated sphere absorption meter sensor tested in 2019 and 2020 and installed in 2021.		
Challenges	Delays in development, fabrication, installation, maintenance, and calibration due to COVID-19 (limited lab access, limited to FerryBox system, boarding restriction, limited personnel, delayed delivery of equipment). Technical issues with sensor for measuring CO_3 ion concentration (signal instability and high signal-to-noise ratio) and integrated sphere absorption meter sensor (LED failure). Problems with pump and flow.		
Final results	Microplastic samples from several transects between Norway and Svalbard processed and analyzed. Advances made in autonomous collection of microplastics particles from seawater, assessment of ocean acidification by measuring two carbonate system variables with low volumes of seawater, and measurements of optical properties including chlorophyll, cDOM, and phytoplankton accessory pigments. FerryBox data along transects including temperature, salinity, chlorophyll a fluorescence, microplastics concentration by size fraction; seawater pH (total scale) and CO_3 ion concentration ($\mu mol\ kg^{-1}$) and absorption spectra (m^{-1}) from 360-750 nm.		

Domain	Ocean	Sensor/platform	Underwater gliders
Partner	CNRS-LOCEAN		
Action	Endurance glider lines in the northern Fram Strait		
Objective	To collect high resolution measurements of physical and optical ocean properties with autonomous underwater gliders along the repeated endurance lines		
Field deployment	Several missions in summer/autumn seasons of 2017-2020		
Challenges	Navigation in ice-infested waters, control of glider trajectory in a strong boundary current, glider missions' time constraints (low battery autonomy, availability of recovery options)		
Final results	High resolution measurements of physical (temperature and salinity) and biogeochemical (dissolved oxygen, Chl-A and CDOM fluorescence, particulate backscattering) variables in the upper 1000 m ocean column. Derived geostrophic and total depth-averaged ocean currents.		

Domain	Ocean	Sensor/platform	BGC Argo floats
Partner	CNRS-Takuvik		
Action	Deployments of BGC Argo floats in the Baffin Bay		
Objective	To monitor biogeochemical properties of the Baffin Bay with the deployment of a fleet of BGC Argo floats dedicated to navigate in ice-infested waters		
Field deployment	17 BGC Argo deployed in 2016-2019 (deployment in 2020 cancelled) and 5 floats recovered. 4 refurbished floats to be deployed in October 2021.		
Challenges	Surfacing for geo-localization and using satellite networks for data transmission and command reception in ice-covered waters. High risk, ice-detection system (ice sensing algorithm) required to make floats operational in the Arctic Ocean. Challenges related to bathymetry, ice coverage and circulation in Baffin Bay. Missing flexibility in sensor integration.		
Final results	Almost 2000 profiles acquired so far with time series of physical (temperature salinity, pressure) and biogeochemical (dissolved oxygen, Chl-a and CDOM fluorescence, backscattering, nitrates) data, including under ice profiles during wintertime. Integration of new sensors (a highly sensitive radiometer and UVP6 sensor) on BGC Argo floats.		

Domain	Atmosphere/land	Sensor/platform	Automated flask sampler
Partner	MPG		
Action	Development and implementation of a flask sampler for the automated collection of air samples under standardized conditions at remote Arctic sites		
Objective	To collect samples of GHG for analysis of the concentrations of CH_4, CO_2, CO, N_2O, H_2, and SF_6. As additional parameters, we sampled the ratios of O_2/N_2, Ar/N_2, and the stable isotope signals $d^{13}C$-CO_2, $d^{18}O$-CO_2, $d^{13}C$-CH_4, and d^2H-CH_4.		
Field deployment	Installation of the instrument was originally planned for the site Ambarchik in Northeast Siberia. Due to unexpected delays linked to customs problems in 2019, alternative deployment site at the Station North on Greenland was chosen and the system started operation in September 2019.		
Challenges	Unexpected delays linked to customs problems in 2019.		
Final results	Time series (seasonal variability and mid-term trends) of six major trace gases that are routinely quantified in the sampled flask air: CH_4, CO_2, CO, N_2O, H_2, and SF_6. The measured time series of the O_2/N_2, Ar/N_2 ratios, and the stable isotope signals for CO_2 ($d^{13}C$-CO_2, $d^{18}O$-CO_2) and methane ($d^{13}C$-CH_4, and d^2H-CH_4) aimed to support the interpretation of large-scale representative concentration levels of these components.		

Domain	Land/atmosphere	Sensor/platform	New heated sonic anemometer
Partner	UNEXE		
Action	Implement a novel heating system for sonic anemomenters		
Objective	To collect continuous CO_2 and CH_4 fluxes during the entire year, with a particular focus on the fall and winter, which are the most uncertain times of the year in terms of both CO_2 and CH_4 emissions		
Field deployment	Test deployments since summer 2019. Deployment of new, improved system since summer 2021.		
Challenges	Originally selected heating system heating of the CSI_CSAT3BH was not appropriate to completely de-ice the sonic anemometer during the fall and winter, which resulted in large data losses, particularly in spring 2020 when we were not able to access the sites.		
Final results	The measured variables include CO_2 and CH_4 fluxes together with air temperature, and the three wind components collected at 10 Hz used to estimate the eddy covariance fluxes. Additionally, a variety of environmental variables (soil moisture, soil heat flux, net radiation, etc.) were also collected to provide an estimate of the temporal trends of the main variables that control the CO_2 and CH_4 fluxes.		

Domain	Land	Sensor/platform	Thermocouples profiles
Partner	USFD		
Action	Installation of installed three high spatial and temporal resolution temperature profiles at the Alaskan sites Atqasuk (US-Atq) and Ivotuk (US-Ivo) and at the US-Bes site near Utqiaġvik.		

Objective	To better characterize the soil freezing and the persistence of unfrozen soils during the cold period.
Field deployment	Temperature profiles included thermocouples every 5 cm from 25 cm above the surface to 90 cm below the surface at US-Ivo and US-Atq since summer 2016 and and 75 cm below the surface at US-Bes since summer 2018.
Challenges	The main challenge in 2020 was that we were not able to access the sites and solve problems to the data collection of several sensors that needed servicing, which resulted in large gaps in the data available for the fall and winter 2019 and the entire 2020.
Final results	Time series of high resolution (30 min) measured soil temperature at a fine resolution to characterize the soil freezing during the fall, and the persistence of unfrozen soil layers later in the fall.

Domain	**Land**	**Sensor/platform**	**Instruments for soil, snow and atmosphere**
Partner	CNRS-Takuvik		
Action	Deployment of improved monitoring instrumentation for soil, snow, and atmosphere at four sites in the Canadian High Arctic at 55, 56, 73 and 83°N		
Objective	To obtain time series of physical environmental variables allowing the investigation and detection of novel climatic feedbacks and the testing of land surface models and in particular their snow schemes; and to extend data base of soil and permafrost carbon stocks and understanding the impact of shrub expansion (a.k.a. Arctic greening) on soil carbon stocks		
Field deployment	During INTAROS we deployed or improved monitoring instrumentation for soil, snow, and atmosphere at four sites in the Canadian High Arctic at 55, 56, 73 and 83°N		
Challenges	Serious issues with some Campbell instruments, which the manufacturer had not reported, such as a bug in the program supplied to run the CNR4 radiometer. Frosting of the upper sensors in winter with heating often insufficient during the polar night. Issues regarding power supplies.		
Final results	Atmospheric variables measured were air temperature and relative humidity, wind speed and direction, upwelling and downwelling shortwave and longwave radiation. Snow variables monitored were snow height and snow temperature and thermal conductivity at several heights. Soil variables measured were thermal conductivity, temperature, and liquid water content at several depths.		

Domain	**Land**	**Sensor/platform**	**SodScat scatterometer and SVC-FMI spectro-albedometer**
Partner	FMI		
Action	Integration of new instruments (the SodScat scatterometer and the SVC-FMI spectro-albedometer) into the multidisciplinary research infrastructure at the FMI Sodankylä-Pallas research station. Testing of new devices (purchased with other funding) and the development of the data acquisition and processing chain (measurement protocol, data quality control, software for raw data processing, data format and storage).		
Objective	To achieve a better exploitation of satellite observations and fulfil the modelling needs for the development of new, multi-sensor retrieval methods at a cal/val site for the NASA SMAP and ESA SMOS missions, representing the boreal forest zone.		
Field deployment	The SodScat radar was installed on a new 24-m observation tower at the FMI-ARC in the summer of 2018 and is operational since October 2019 (continuous measurements). The SVC-FMI spectro-albedometer was installed over a flat, snow-covered wetland site and measured incoming and reflected spectral irradiance and their ratio, the albedo, at high spectral and temporal resolution for about one month during three consecutive springs (2019-2021).		
Challenges	For the SodScat scatterometer, moving parts necessitated by the radar system and SAR imaging such as the displacement rail and 3-axis positioner of SodScat are prone to mechanical failures in cold conditions as well as water condensation and ice buildup during spring melt-refreeze cycles.		
Final results	Operational measurements with SodScat, running in SAR mode, have been available since October 2019 on demand due to the complexity of the dataset. Collection of multi-year timeseries with the baseline acquisition mode (four bands, two polarizations) will continue, while allowing for dedicated campaigns for research projects. The SVC-FMI spectro-albedometer data are collected from March to November and the data acquisition and storage systems are already automatized (data processing is partly automatized).		

Domain	Atmosphere	Sensor/platform	Unattended atmospheric observatory for icebreaker
Partner	MISU		
Action	The concept is built around the Swedish research icebreaker *Oden.* The instrument costs were covered by ACAS, while INTAROS contributed to the engineering and its first deployment.		
Objective	To build an atmospheric observatory – essentially a so-called "supersite" – on an icebreaker and run it unattended or with a minimum staff, allowing deployment on all expeditions with that vessel, regardless of the science focus of individual expeditions		
Field deployment	The semi-automated atmospheric system for IB Oden was first deployed in 2018, while a partial unattended deployment was carried out in 2019 on the so-called Ryder expedition, to the Ryder fjord and glacier on northwest Greenland. The whole system was deployed again in July-September 2021 on the Synoptic Arctic Survey in the central Arctic Ocean. It will continue in 2022 with the ArcOp22 ocean-floor drilling expedition.		
Challenges	This super site has only been tested under summer conditions but should work also in other conditions, given the opportunity of available vessels in other seasons. Some gaps remain, most notably continuous observations of vertical profiles of horizontal winds, and icing of instruments remain a problem. The investment in instruments is expensive. An installation like this is unlikely to be deployed on many ships.		
Final results	During field campains of the IB Oden, the system consisting of several linked parts provided measurements from (i) an advanced weather station (that, in addition to standard meteorological variables such as atmospheric pressure, wind speed and direction, air temperature and moisture, also samples incoming broadband shortwave and longwave radiation and surface temperature by infrared thermometers looking down at the surface; (b) a system for vertical soundings of temperature, atmospheric water vapor, winds and pressure on free-flying helium balloons (radiosoundings); (iii) a surface turbulence flux station with instruments for eddy-covariance mounted in a special foremast of Oden; and (iv) a set of surface-based remote sensing instruments consisting of a W-Band FMCW cloud radar and a scanning multi-frequency microwave radiometer.		

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