Integrated Arctic Observation System

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Final implementation of the observing system: Data delivery and report on results of the observing systems in Fram Strait

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PU	Public, fully open	X
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EXECUTIVE SUMMARY

This document describes the final implementation of new observing systems developed within the INTAROS project. It reports on initial results from the observing systems and describes ways for the delivery of data retrieved by these systems.

AWI developed and tested the experimental system "arcFOCE" (arctic Free Ocean Carbon Enrichment) that enables scientists to study impacts of ocean acidification on small, sediment-inhabiting deep-sea organisms. The first long-term experiment of the system was conducted from October 2018 till September 2019 at the LTER observatory HAUSGARTEN in the eastern Fram Strait. Sediment samples were taken to study anticipated changes in bacterial and meiofaunal numbers, biomasses and community composition due to artificially reduced pH values in bottom waters. All data from the initial arcFOCE experiment will finally be stored in the PANGAEA data repository. The lack of ship time in 2020 allowed to reconfigure and optimize the experimental setup. Short-term in-situ tests of the improved system will be carried out during the RV *Polarstern* expedition PS126 in June 2021; the next long-term deployment (one year) of the arcFOCE system is planned for 2022.

CRNS-UIEM installed a passive acoustics system at Kongsfjorden, Svalbard, which is identical to another system already deployed and running in Greenland, to allow direct comparison of results from these monitoring systems in western and eastern part of the Fram Strait. Acoustic data from the two systems are available via SEANOE (https://www.seanoe.org) or SEXTANT (https://sextant.ifremer.fr/). Results from the acoustics system at Kongsfjorden showed that AIS (Automatic Identification System) data of vessels operating in the area and their acoustic propagations need to be combined with passive acoustic measurements to assess the effect of vessel noise on the acoustic soundscape.

CNRS-LOV continued and improved their measurements at the AWIPEV CO_2 time-series monitoring site in Kongsfjorden, Svalbard. Time-series data generated by in-situ sensors in the fjord and in a Ferrybox flow-through system at AWIPEV is, to our knowledge, the first one at such high frequency. Raw data from the deployed sensors are available in near real-time: https://awipev-co2.obs-vlfr.fr. Quality-controlled data will be uploaded to the World Data Center Pangaea as soon as the final samples will be received and analysed, sometime in 2021. Among the key results is the fact that the fjord is a net sink for CO2 throughout the year.

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1. Introduction

Ocean acidification is a significant and harmful consequence of excess carbon dioxide in the atmosphere. When carbon dioxide dissolves in seawater, the water becomes more acidic and the ocean's pH drops. This acidification may affect ocean life in various ways (physiological and ecological) and controlled experiments are urgently needed to study the impact of the decreasing pH of seawater on marine life, especially at high latitudes where ocean acidification will be most rapid. At the same time, monitoring the carbon chemistry of the ocean is particularly important. Real- and near-real time OA measurements provide notice of

potentially damaging acidic seawater.
As marine species heavily rely on sound to relate with their environment, increasing anthropogenic noise in the ocean is another threat especially to higher marine life. Quantitative information on the sound levels in the sea is very important for assessing the environmental impact of underwater noise.
New and improved observing systems implemented by INTAROS in the Fram Strait, including Svalbard fjords, encompass a moveable experimental set-up (arcFOCE) to study impacts of ocean acidification on benthic organisms and communities, autonomous systems to conduct real-time measurements of pCO_2 and pH measurements, supplemented by weekly discrete measurements of dissolved inorganic carbon and total alkalinity, and a passive acoustic system to monitor natural sounds like the activity of benthic species (bivalves) and those produced by icebergs (including localization and detection) as well as anthropogenic sounds, e.g. introduced by fishing vessels or tourists ships.
The autonomous arcFOCE (arctic Free Ocean Carbon Enrichment) system builds on an existing deep-water system at MBARI, but was adapted to greater water depths (4000 m), extremely low temperatures (< 1°C), and autonomous operation (in contrast to the MBARI system, which is connected via cable to land). Continuous measurements at the AWIPEV Underwater Observatory in Kongsfjorden provide the first time-series for the carbonate chemistry of Arctic coastal waters, while the directional acoustic system with hydrophones was deployed in Kongsfjorden to match a similar system on the Greenland side.
This report gives an overview on the level of implementation of the observing systems as well as information on data delivery and the reporting on results from these systems.

2. Final implementation and operational use of the observing system in Fram Strait

2.1. AWI

Contributors: Thomas Soltwedel, Christiane Hasemann, Jonas Hagemann, Michael Hofbauer, Sascha Lehmenhecker

2.1.1. Results of the final implementation of the observing system

AWI developed and implemented an experimental system that enables scientists to study impacts of ocean acidification on small, sediment-inhabiting deep-sea organisms. The so-called arcFOCE (arctic Free Ocean Carbon Enrichment) experimental setup was integrated in a modular free-falling system (bottom-lander) (Fig. 1). The bottom-lander frame is designed to sink to the seafloor unattached to any cable. After a certain time period, mesocosms (40 cm in diameter) integrated in the system are lowered to the sediment surface.

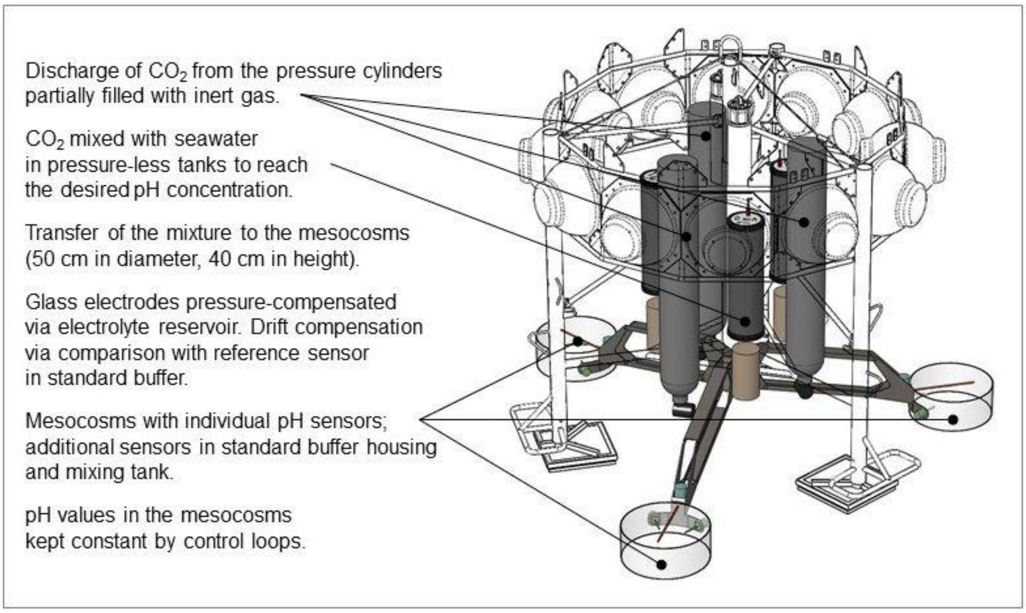


Fig. 1: Sketch showing the structure and major components of the arcFOCE experimental setup.

The water body enclosed by these mesocosms is subsequently acidified at a distinct constant level by repeatedly adding in-situ CO_2-enriched seawater via a pumping system. By the end of the experiment (after several months), sediments and the inhabiting small benthic biota are sampled from the mesocosms using push-corers handled by a Remotely Operated Vehicle (ROV). Afterwards, ballast weights of the bottom-lander are released on acoustic demand and the lander then floats back to the surface by virtue of its positive buoyancy.

Acidification of the sediment-overlying water in the benthic mesocosms is done in two steps: In a first step, ambient seawater is mixed in a separate housing to the anticipated (lower) pH values by adding liquid CO_2 from pressure cylinders. Subsequently, the acidified seawater is pumped into the mesocosms.

2.1.2. Lessons learned and technology challenges identified during the project

The first long-term experiment of the system was conducted from October 2018 till September 2019 in approx. 1500 m water depth at the LTER observatory HAUSGARTEN in the eastern Fram Strait (Fig. 2). By the end of the experiment, the Remotely Operated Vehicle (ROV) PHOCA of the GEOMAR Helmholtz Center for Ocean Research in Kiel, Germany, was used to take sediment samples inside and outside (as controls) of the mesocosms (Fig. 3). The bottom-lander was subsequently recovered to check the performance of the individual components of the arcFOCE system during the long-term experiment.

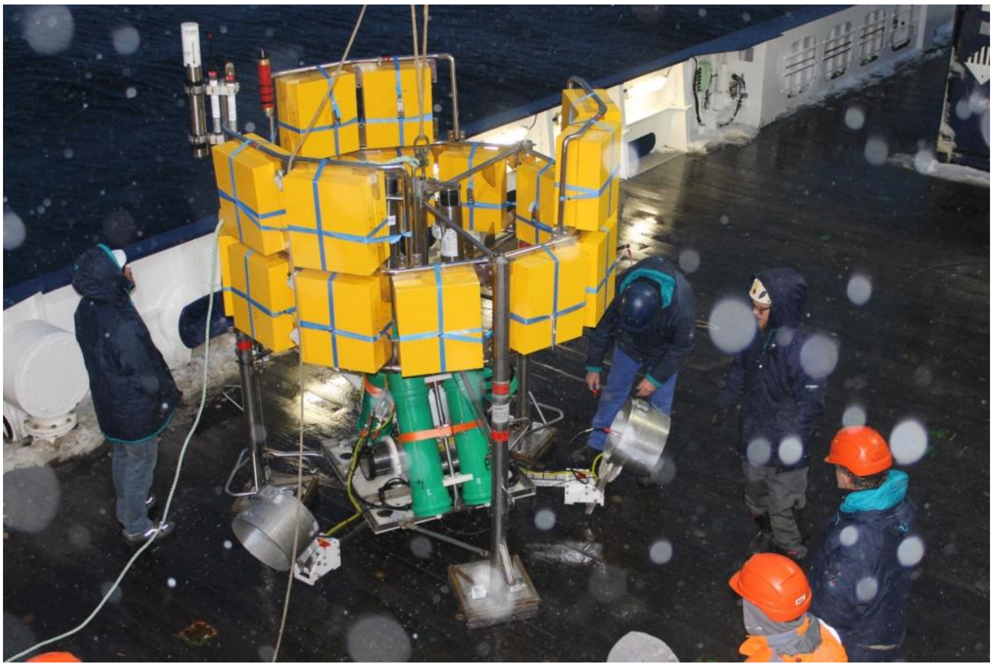


Fig. 2: The arcFOCE experimental setup prior to its first long-term deployment from board RV *Maria S. Merian* in Autumn 2018.

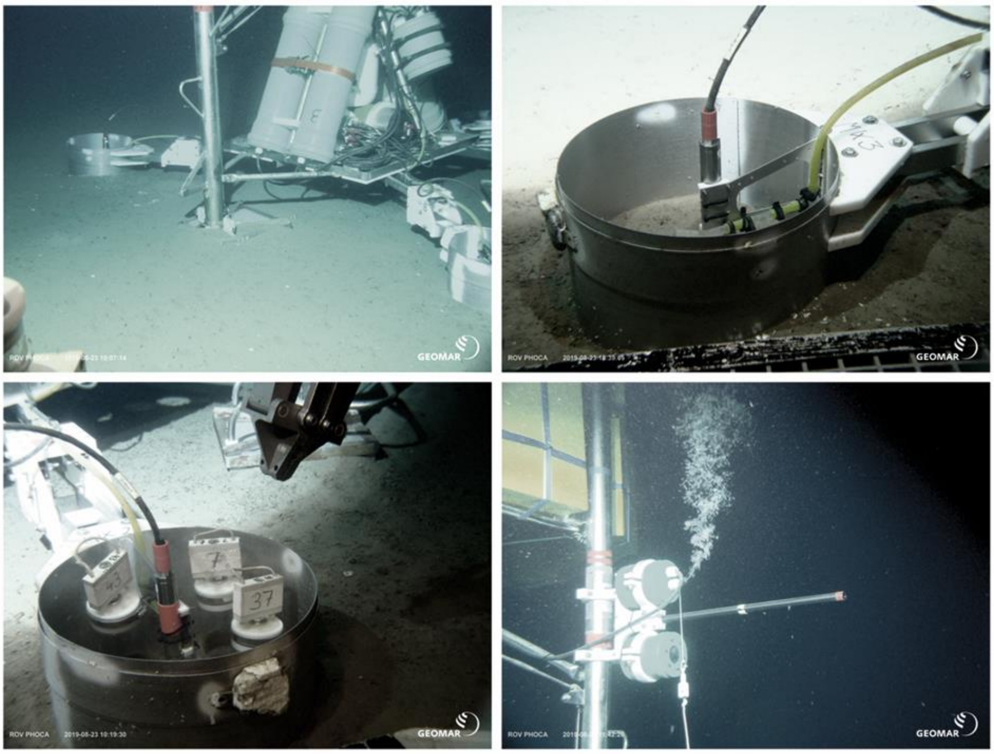


Fig. 3: Sampling of the arcFOCE experiment during RV *Polarstern* expedition PS121: experimental setup at 1500 m water depth off Svalbard (top left), close-up of one of the mesocosms perfectly in place at the seafloor (top right), sediment sampling inside a mesocosms using ROV-handled push-corers (bottom left), blowing off excess CO_2 before recovering the bottom-lander (copyright: GEOMAR).

The mechanical construction, power management, and electronic control of the experimental setup worked well. The same holds for the mixing of CO_2 and seawater prior to its transfer to the mesocosms and the pressure release of excess CO_2 (for safety reasons) by the end of the experiment, i.e. before the recovery of the system. However, the pH-sensors, although thoroughly tested in a pressure tank at the home lab, only partially survived the long-term deployment. For this reason, pH values measured in the mesocosms over time are not reliable, which unfortunately does not allow a reliable evaluation of the experiment.

The lack of ship time in 2020 allowed to reconfigurate and optimise the experimental setup. Recently commercially available optical pH-sensors (optodes; PyroScience) were integrated, replacing the non-reliable glass electrodes. Short-term in-situ tests of the improved system will be carried out during the RV *Polarstern* expedition PS126 in June 2021; the next long-term deployment of the arcFOCE system is planned for 2022

Nevertheless, sediments retrieved by the ROV were analysed for bacterial densities and a number of sediment parameters (e.g. organic carbon content, total microbial biomass) to check whether the size (height, diameter, volume) of the mesocosms is suitable for a long-term experiment, i.e. whether the open top mesocosms might act as traps for settling organic matter, thereby introducing unwanted artefacts to the experiment.

2.1.3. Description of processing and analysis of the obtained data

The availability of phytodetritial matter, which represents the prime food source for benthic organisms, was assessed by measurements of sediment-bound chlorophyll *a* and its degradation products (phaeopigments). Chloroplastic pigments were extracted in 90% acetone and measured with a Turner fluorometer. The organic carbon content was determined using a LECO CS125 carbon analyser. Bacterial cells were counted after staining with acridine orange using epifluorescence microscopy.

Biochemical analyses and bacterial counts (fortunately) revealed that values for analysed biogenic sediment compounds (i.e. chloroplastic pigments indicating the input of phytodetritial matter, organic carbon contents) and bacterial densities inside and outside the mesocosms showed no significant differences (Fig. 4). Thus, the open mesocosms obviously do not accumulate particulate matter and there is no need for modifications in this part of the experimental setup.

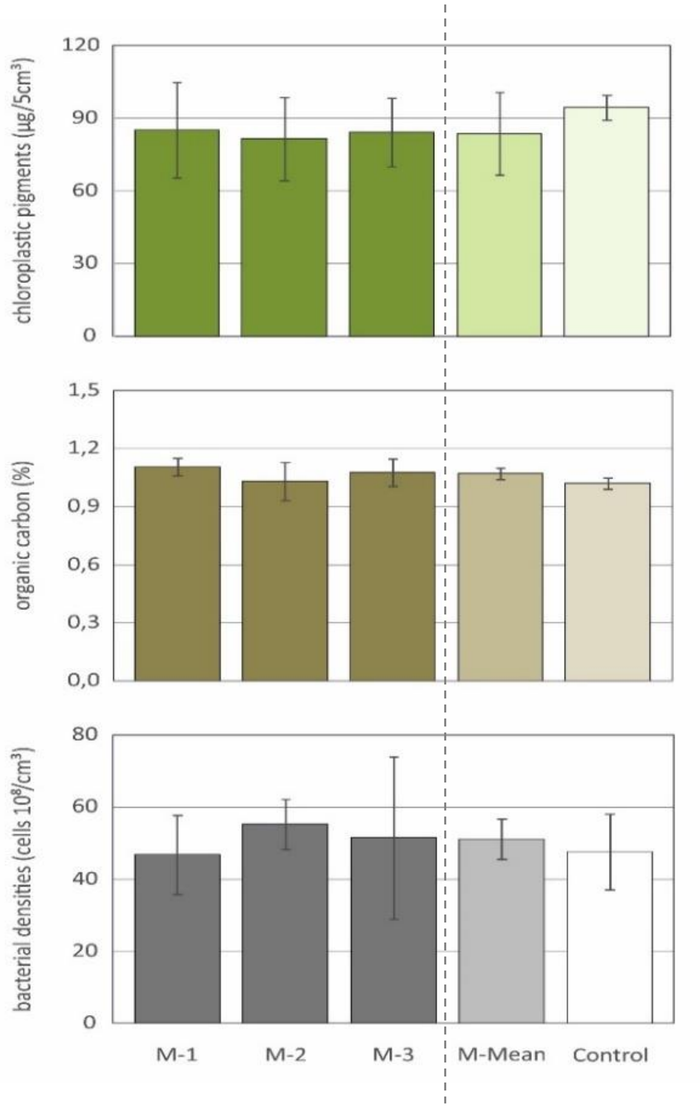


Fig. 4: Chloroplastic pigments from settling phytodetritus (top), total organic matter content (middle), and bacterial densities (bottom) inside the mesocosms and in control sediment taken adjacent to the experimental setup.

2.1.4. Accessibility of the obtained data sets and repositories used

The time periods from sample processing to data provision will vary from one year maximum for sensor data, to several years for organism related datasets. Until then preliminary data will be available to project partners and external users after request to the senior scientist. The finally processed data will be submitted for unrestricted availability to the PANGAEA data library (https://pangaea.de) and registered in the INTAROS catalogue (https://catalog-intaros.nersc.no/).

2.1.5. Future plans for operation of the observing system, including data provision

The arcFOCE experimental setup is designed as a moveable system to be used in repeated experiments at different locations and varying water depths, but also at different time-intervals to study effects of ocean acidifications on the small benthic biota at all temporal and spatial and bathymetric scales. Over the coming years, it is planned to conduct arcFOCE experiments at various sites at the LTER observatory HAUSGARTEN in Fram Strait. However, the arcFOCE system would generally also be available for INTAROS partners and external colleagues for using the experimental setup in their study areas. Data from future arcFOCE deployments will also be registered in the INTAROS catalogue and submitted to the PANGAEA data library.

2.2. CNRS-IUEM

Contributors: Laurent Chauvaud, Erwan Amice, Gaëtan Richard (CNRS-IUEM) and Delphine Mathias (SOMME)

2.2.1. Results of the final implementation of the observing system

During the three years of the INTAROS project, around 14500 hours of recording have been collected, including 14300 hours from long term recordings. These recordings have been added to data collected before the project in 2013 by the team (Fig. 5). Long-term recordings consisted in deploying autonomous recorders at the entry of the Kongsfjorden (Fig. 6), with the purpose of assessing the soundscape of this Arctic fjord.

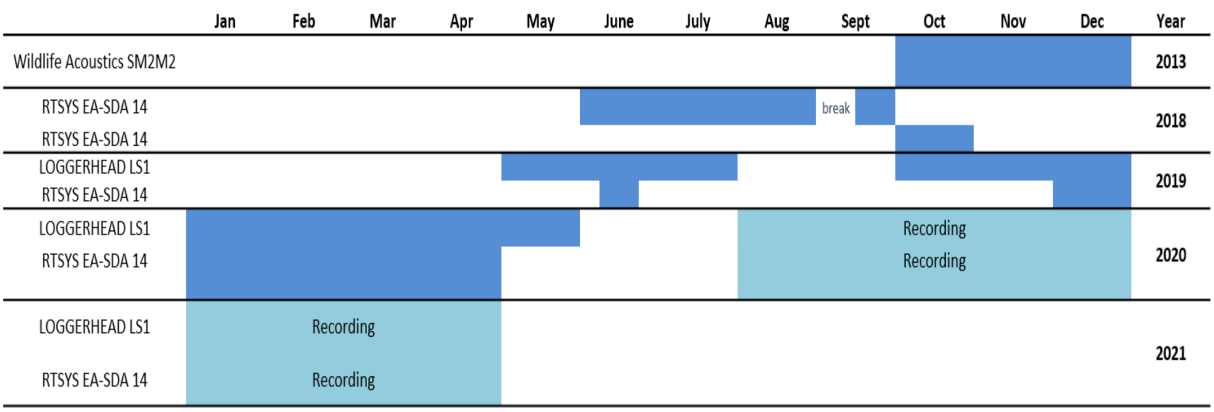


Fig. 5: Summary of deployments per year with recording duration.

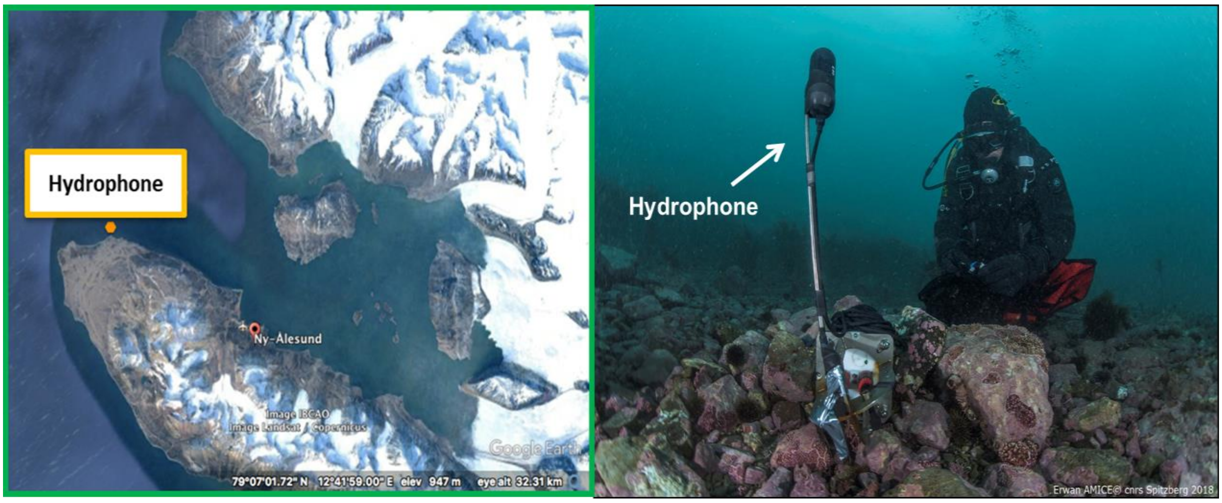


Fig. 6: Hydrophone location and mooring system.

Additional acoustic short period recordings were also conducted during these three years. Three different type of experiments were performed:

- Recordings of urchin in tanks: six deployment of 85 hours
- Recordings in the kelp forest and outside the forest: two experiments, one with two distinct recorders (in and out the kelp forest, 24 hours) and the other with one recorder paired with three hydrophones in the kelp forest at different depths, and one hydrophone outside (6 hours).
- Drifting recordings, i.e. a hydrophone on a buoy launch from a small boat to record walruses and ice sounds (4 hours of recording among three experiments).

We recovered AIS data of boats visiting Kongsfjorden during the recording period, from Rune Roland Hansen (University of Oslo and DNV Group). These locations allowed us to estimate number of vessels in the area and their distance to the acoustic mooring. From these positions, we show that tourist-shipping activity has tripled this last decade in Ny-Ålesund waters (Fig. 7).

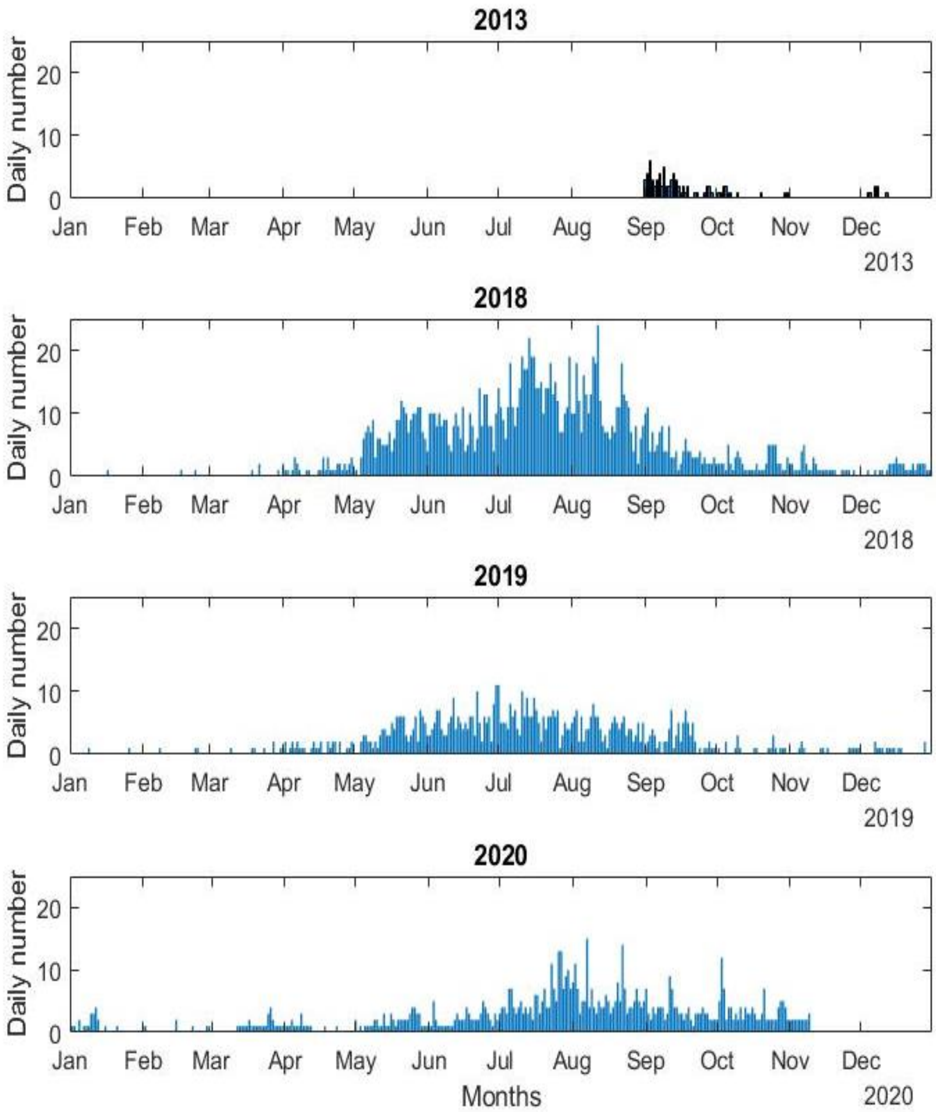


Fig. 7: Evolution through the recording years of the daily number of vessels visiting Kongsfjorden (from AIS data).

2.2.2. Lessons learned and technology challenges identified during the project

The INTAROS project has allowed to collect valuable underwater acoustic data in an environment with growing anthropogenic pressure. During the first half of the project, our main challenge was to deploy acoustic recorders with sufficient battery capacity (the cold-water environment and the high sampling rate increase the battery consumption) to record for a 6-month duration, so that divers were only needed twice a year. Therefore, we decided from ‘Year 2’ to deploy several recorders simultaneously with differed starting time to increase our recording capacity. Unfortunately, the pandemic situation showed us that this was not sufficient. Indeed, several campaigns have been delayed or cancelled, meaning that the 2019/2020 dataset will not be as rich as anticipated (we did manage to recover and redeploy instrumentation at the end of July 2020). We believe that deployments with acoustic releases need to be investigated in order to be recovered and redeployed without the CNRS-IUEM divers' team.

The AIS data combined with the acoustic propagation results show that it would be interesting to deploy an additional recorder in the northern part of the fjord. Therefore, we hope to be able to conduct such experimentation during our next fieldwork in late summer 2021.

2.2.3. Description of processing and analysis of the obtained data

Anthropophony – ongoing analysis

From the observations of the increasing number of vessels between 2013 and 2018 (three-fold increase), and the lower shipping activity in 2020 during the European lockdown due to the Covid-19 crisis (Fig. 7), we aimed at quantifying variations of anthropophony in Kongsfjorden.

We measured sound pressure levels (SPL) through different sampling periods and within different frequencies bandwidths to assess noise level evolution through time. Using AIS (Automatic Identification System) data (provided by Rune Roland Hansen) we assessed boats position from the hydrophone (Fig. 8a and b). Simultaneously we assessed evolution of SPL estimated over the whole file at a 1-minute scale between 100-500 Hz (within the vessel acoustic signature).

We then assessed whether the SPL can be explained by the number of boats within a 30 km range area (based upon the maximum distance in the fjord from the hydrophone) and by the distance of the closest boat from the hydrophone. We observed that an increasing number of vessels does not really impact the SPL but this must be explained by the lack of consideration of the distance of the closest vessel, since the SPL is higher for closest boats at a 4 km range from the hydrophone. Values of SPL below 4 km range of the closest boat from the hydrophone seems significantly higher than SPL above 4 km (T-test = 49, $p<0.001$). We thus assessed whether they might be combining effects of the vessel number nearby the hydrophone and the distance of the closest vessel from the hydrophone. We thus plotted one regression per number of vessels within a 30 km range (from 1 to 8) to explain the SPL according to the distance of the closest boat from the hydrophone (Fig. 9). This preliminary analysis seems to reveal an additive effect of the number of boats in the area and the distance to the closest boats. Indeed, if we compared the SPL when the closest boat is at 2 km from the hydrophone when it is alone vs. when 7 other vessels are nearby, we observed an increase of ~20 dB in the SPL predicted by the regressions (Fig. 9).

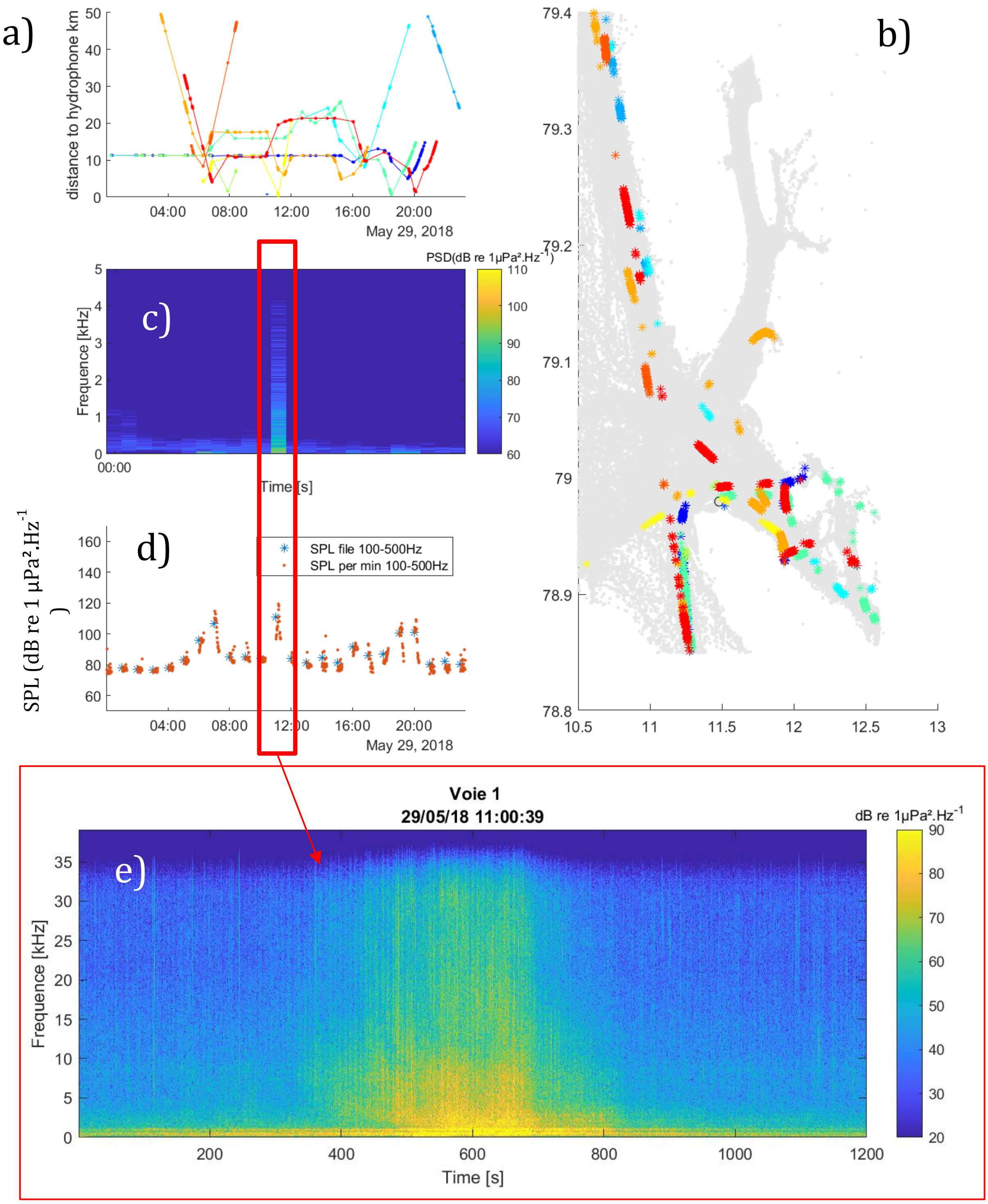


Fig. 8: Comparison of boats activity, i.e. distance from hydrophone (a) and AIS position (b), with acoustics measures, i.e. spectrogram (c) and SPL (d), among one day of recording. Example of a boat passage around 11:10 am with a decrease of distance from the hydrophone in a) and an increase of intensity on c), d) and zoomed in e) (acoustic signature at 600 s of the spectrogram).

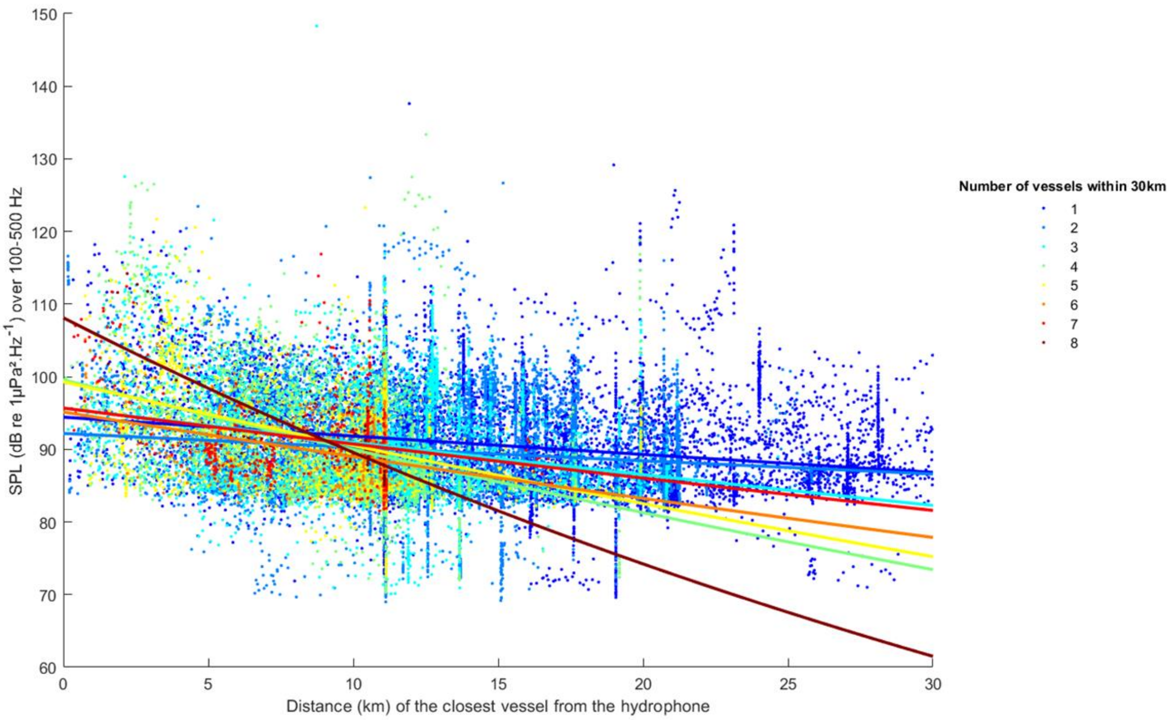


Fig. 9: Linear regressions of the SPL according to the distance of the closest vessel from the hydrophone. One regression was assessed for each number of vessels within the area (from 1 to 8).

Further statistical analyses should be conducted to better assess the combine effect since in Figure 9 we did not consider the distance of other boats (only the closest one). Additionally, propagation model should improve to define the range of the area (here 30 km) within which to consider the number of boats. We thus started to assess sound propagation model within the fjord using a three-dimensional beam tracing model (Bellhop 3D, see Fig. 10). This 3D models allows to propagate rays within the fjord (Fig. 10), and compared to more traditional two-dimensional propagation simulation, it may allow to better explain sounds propagation within our fjord (Fig. 11). The use of a 3D beam tracing model will allow us to determine acoustic footprints of shipping activity in this fjord, knowing the traffic routes from AIS data (Fig. 12). The method has been developed, but results are still in progress.

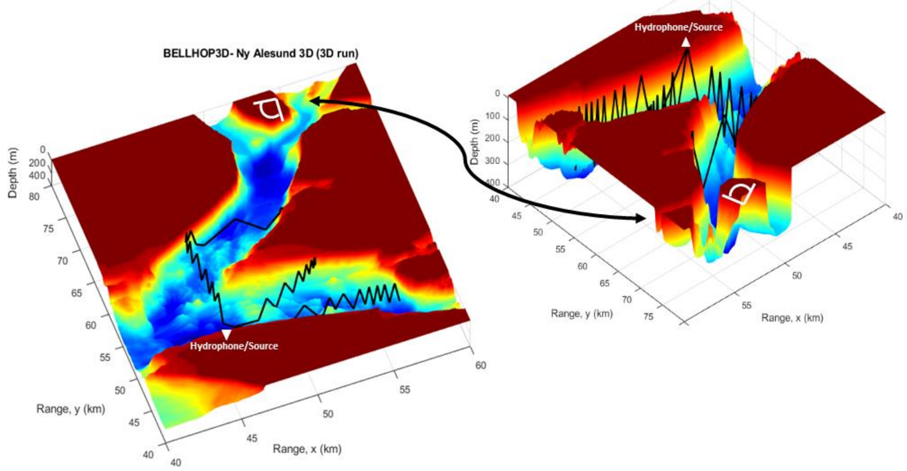


Fig. 10: Example of 3 rays' propagation in the fjord using Bellhop 3D (view from South on the left, and from North on the right). Tin this example we noticed that the 3D beam tracing model allow the sound to enter within the northern part of the fjord.

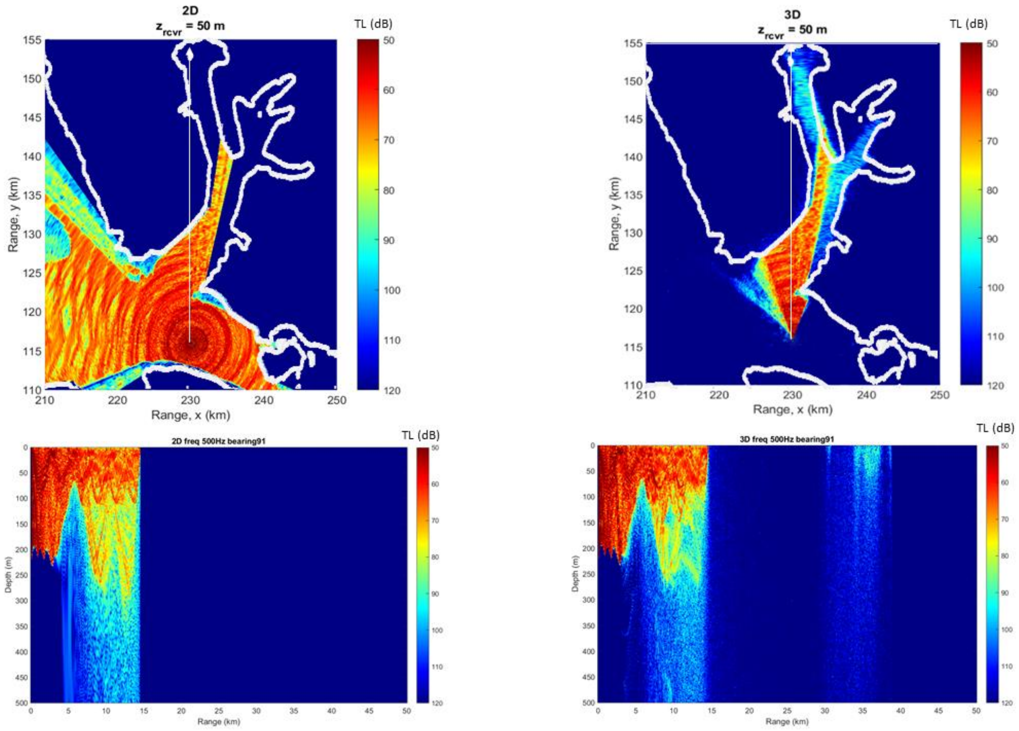


Fig. 11: Transmission loss (TL) estimation from a 2D approach on the left panels vs. a 3D approach on the right panels. Upper panels represent a map of the TL in the fjord, and lower panels represent TL in a plan (depth x range) among the transect northward (white arrow on top panels). In the 2D approach we propagates rays in plans (2D) for every angle between 0° and to 360°, resulting in a nx2D approximation of the 3D. Conversely, the 3D approach was simulated only toward the north, allowing rays to propagate in any direction. Our example clearly shows that the 3D beam tracing methods allows to insonify the northern part of the fjord, despite physical barriers.

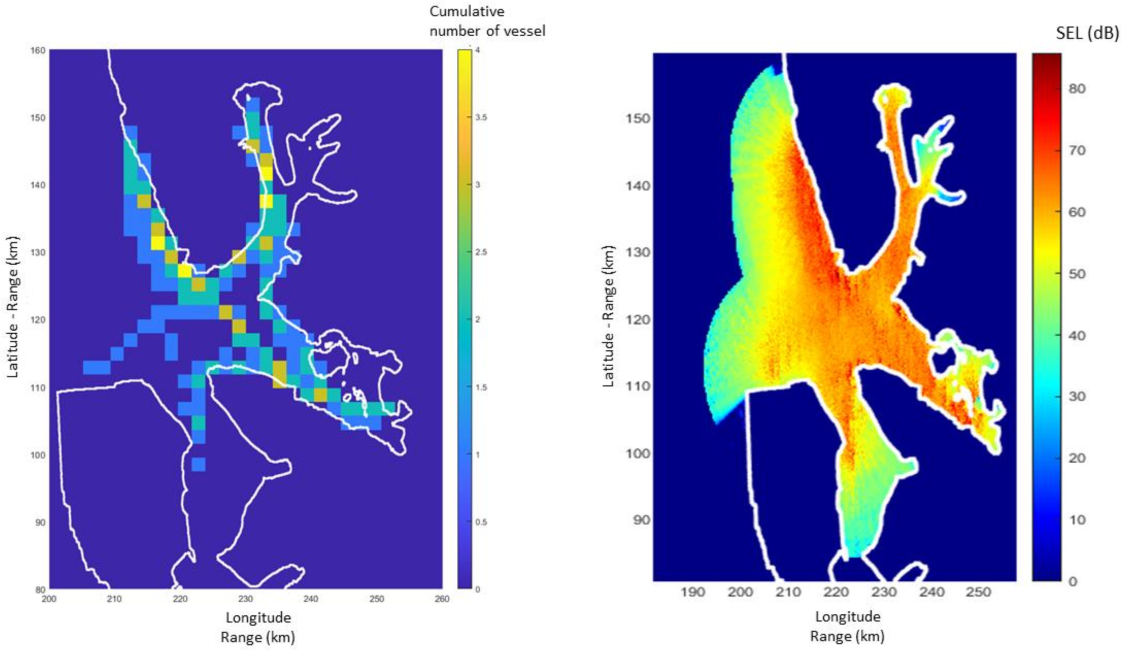
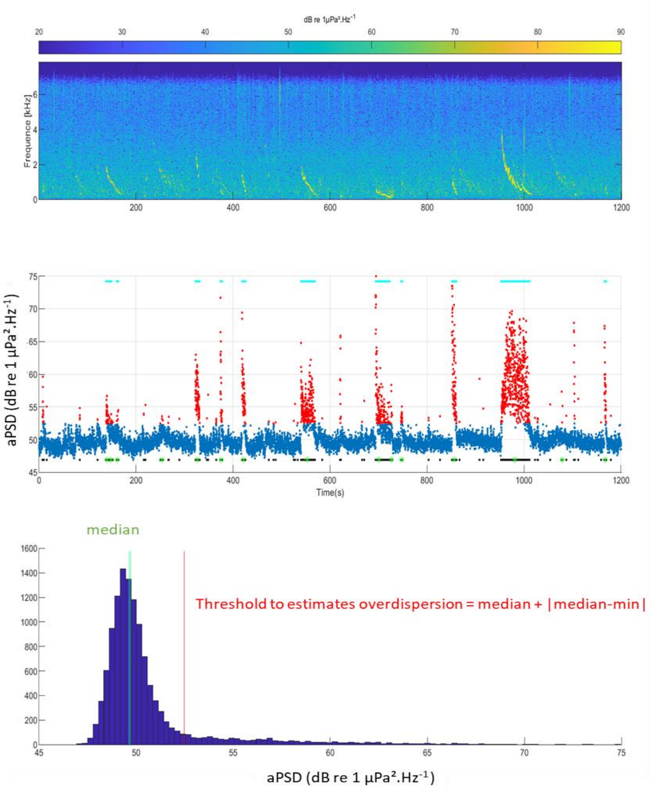


Fig. 12: Map of the cumulative number of vessels passing 2 km cells during one day in summer (on the left), with the sound exposure level for the same day

Biophony – preliminary insights

We commonly observed in our recordings bearded seals sounds, since a colony is present in the Kongsfjorden. These sounds could last from a few seconds to 1 minute and are produced between 0.1-6 kHz. As these sounds could overlap with the frequencies monitored to estimate boat activity (100-500 Hz) we want to assess when seals vocalization is present in our recordings to avoid overestimating boats acoustic activity in the soundscape (e.g. an increasing of SPL due to seal activity instead of vessels passing by). We thus started to implement vocalization detector. The detector is a tonal sound detector based upon i) an energy detection (Fig. 13a) and ii) upon a contouring detection of the energetic event previously found (Fig. 13b). This method should allow detecting seal occurrence on our recordings (Fig. 14), but the method needs be tested (test of sensitivity) and compared to other tonal detectors. Besides, other species are present in the fjord and so their detection should also be assessed. Within this purpose, a master student is currently developing and applying the method.

a. Energy based detector



b. Contour shape analysis

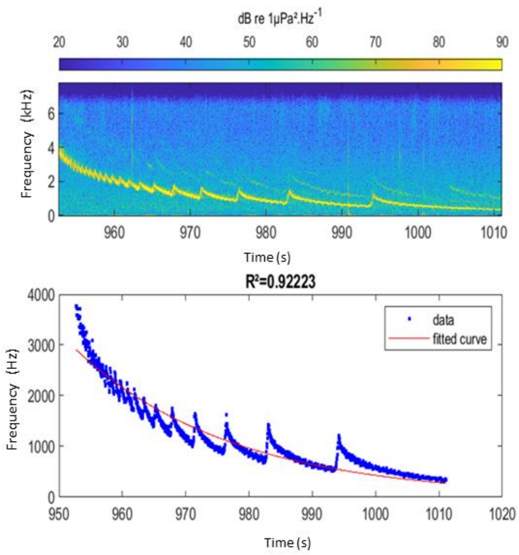


Fig. 13: Principle of the detector, with the energy-based detector (a.) applied on 20 minutes of recordings with seal vocalizations (on top in a.). In the middle (a.): the averaged power spectral density (aPSD) is estimated every 10 ms within a frequency bandwidth of interest (0-4 kHz here). The distribution of the aPSD is then computed (bottom histogram) and we fit the hypothesis that without any vocalization, the aPSD of the ambient noise should follow a normal distribution, thus it should stop at the red line (which the symmetrical value from the median). We set this value (median+|median-min|) as the threshold above which the aPSD values are considered as over-dispersed (i.e. outliers). These outliers are in fact peaks of energy within the recording file. When applying a condition on the duration of following 10 ms peak of energy we can remove false detection. Once energetic events detected (a.) we assess a contour shape analysis (b.). We found for every unit of time at which frequency we obtain the maximum pressure (to find the tonal). Therefore, we obtained the contour in the bottom figure of b. Based upon the postulate that a vocalization is a tonal, we assumed it should fit a polynomial equation (fitted curve in red), if the R^2 is good enough (set at 0.75) we could determine whether the maximum of energy is indeed a tonal.

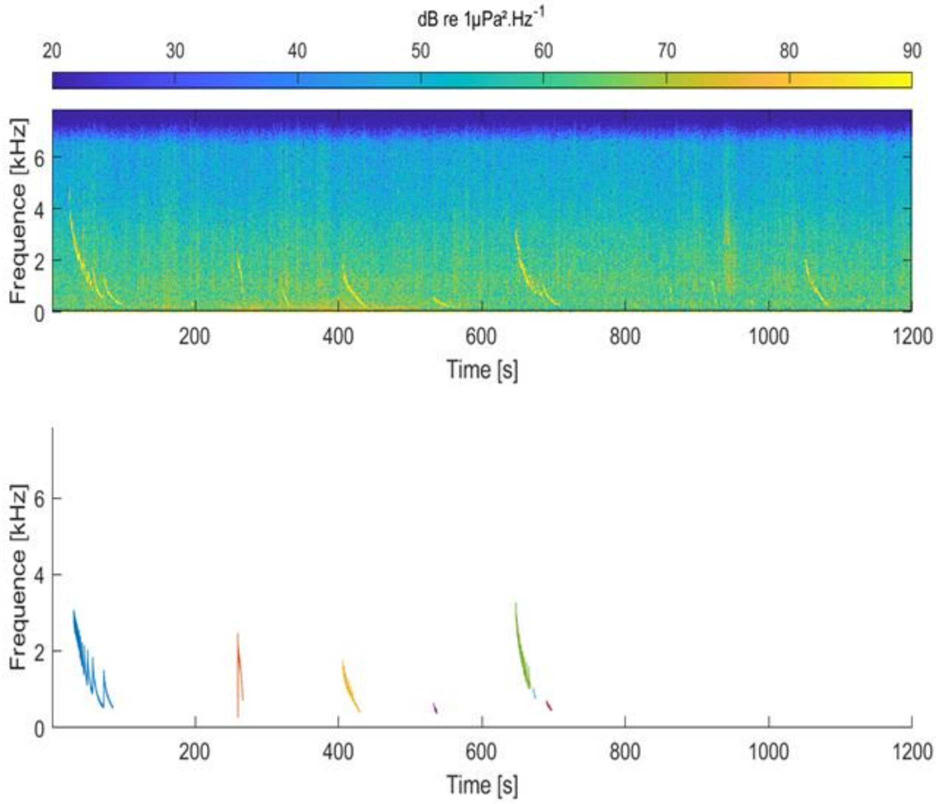


Fig. 14: Example of the automatic detection of seals vocalization over a 20 min file. First vocalizations are well detected but a few one are missed at the end.

We also started to investigate the soundscape in kelps. We used a descriptive approach by comparing spectrograms over the whole deployment (Fig. 15) and we compared SPL at different frequencies between the hydrophone within the kelps (at different depths) and the hydrophone outside the kelps (Fig. 16). In general, we noticed lower SPL outside the kelp than inside (Figs 15 and 16), which is likely due to the biological activity in the kelps and the kelp movements themselves. We also noticed a higher sound pressure level at the top of the kelps than within the kelps (mid-depth and seafloor) for lower frequencies, i.e. below 250 Hz (Fig. 16) that might be due to currents above the kelps. However, a significant higher SPL between 2 and 5 kHz was found in the mid-depth of the kelps, hypothetically revealing cues of the biodiversity in the kelps. However, very few data have been collected on this experiment and a longer recording should be conducted (next mission, cf. 2.2.5.), especially to test whether kelps could provide acoustic protection from anthropophony for wildlife.

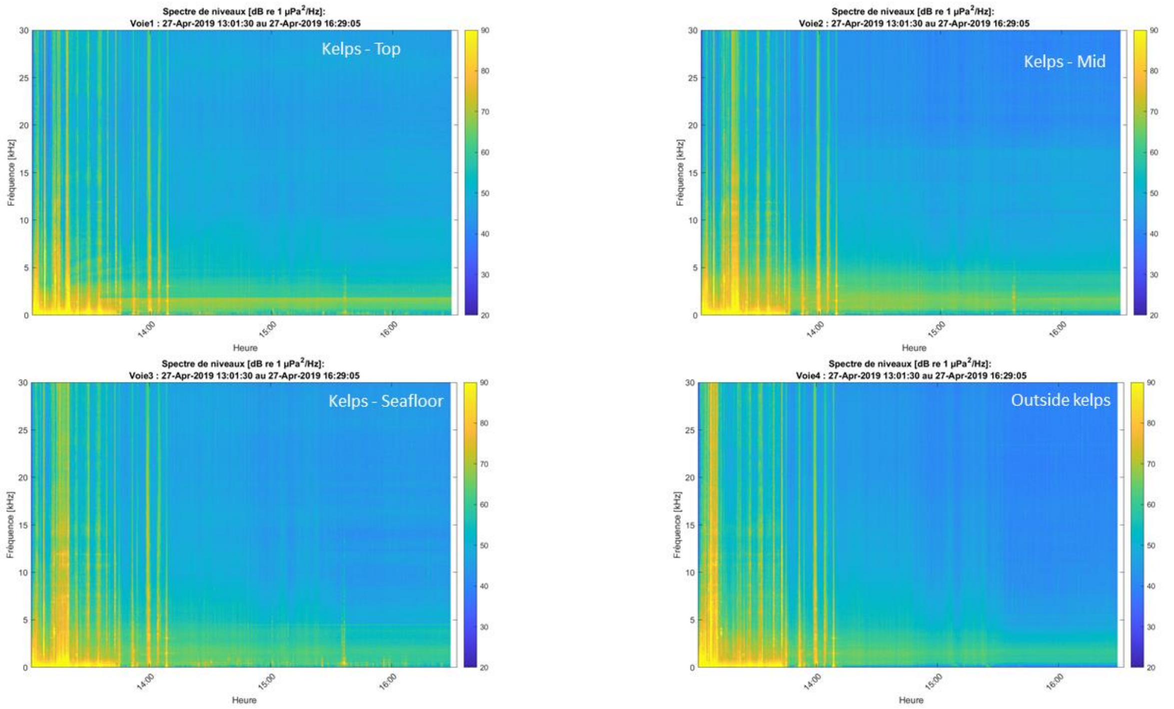


Fig. 15: Comparison of spectrograms for the experiment with 4 hydrophones set at different depths in the kelp and outside of kelps.

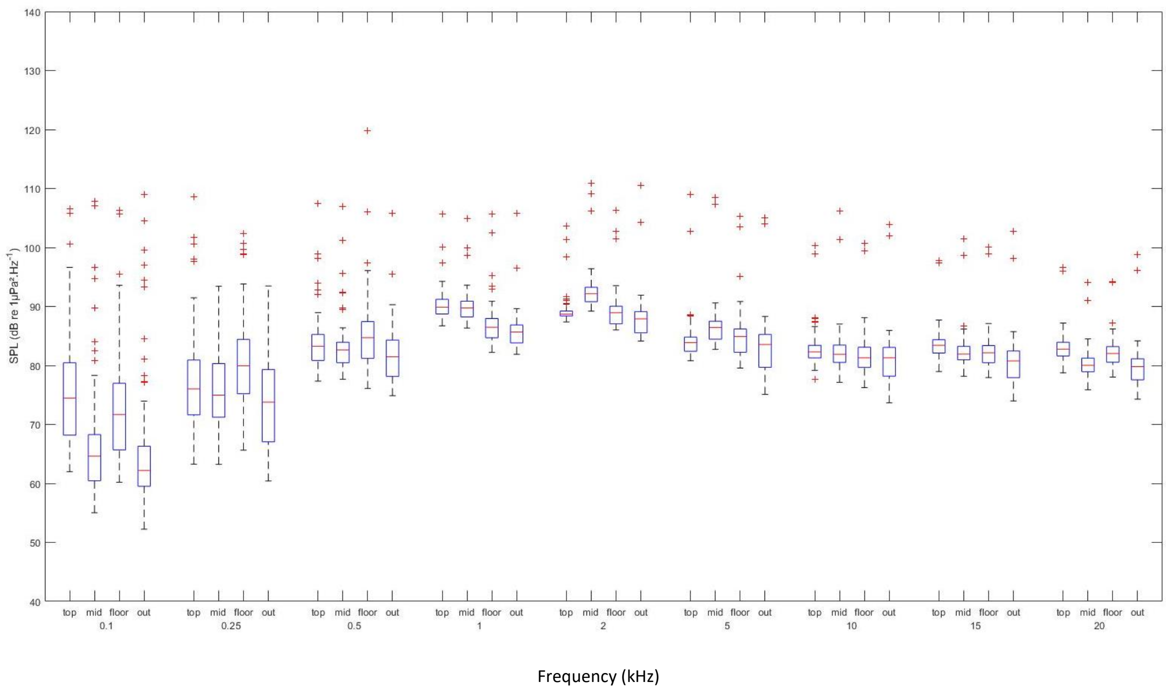


Fig. 16: Comparison of sound pressure levels between the locations (4 hydrophones), measured at different frequencies.

2.2.4. Accessibility of the obtained data sets and repositories used

Dataset registered in the INTAROS catalogue (https://catalog-intaros.nersc.no/). Information will also be added to ArcticPAM, a Pan-Arctic Passive Acoustic Monitoring (PAM) Network from the Norwegian Polar Institute, led by Dr. Heidi Ahonen:

https://geokart.npolar.no/Html5Viewer/index.html?viewer=ArcticPAM

The full raw acoustic dataset (2.2 To) is stored at the Datarmor SuperComputing Center (Ifremer Research Centre, Brest, France). Link available upon request. We will add this information on the INTAROS catalogue.

2.2.5. Future plans for operation of the observing system, including data provision

The final recovery of all equipment is scheduled late Summer 2021. A deployment of a recorder paired to 4 hydrophones will be deployed in the kelps, as performed in 2019. The purpose will be to set the 4 hydrophones at different locations: 3 within the kelps at different depths, and one outside the kelp forest. The recording will last a week to register the biological activity within the kelp forest by comparing the biophony within vs. outside the kelp forest. Finally, we will compare anthropogenic sound levels and measure whether the kelp forest may attenuate such sounds (in comparison to sound level measured outside of the forest).

The 2020 summer/autumn acoustic dataset will allow comparing the ambient noise during the pandemic situation (and associated reduced tourist-shipping activity) with previous years.

2.3. CNRS-LOV

Contributors: Jean-Pierre Gattuso, Samir Alliouane (with Philipp Fischer, AWI)

2.3.1. Results of the final implementation of the observing system

Study site

Data were collected at the COSYNA-AWIPEV underwater observatory in the Kongsfjorden Arctic fjord system at 78°55'50.37'' N - 11°55'12.10'' E, at 11 m water depth on the west coast of Spitsbergen.

The observatory

The INTAROS instruments 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 fitted with another set of sensors. The profiling unit performs a vertical cast every day at 12:45 UTC from 11 m to 0 m water depth. At the end of the cast, the profiling unit is positioned in one of the following positions 1, 3, 5, 7 or 9 m (distance from the sea bottom) and remains there for 24 h.

Discrete sampling and measurements

Seawater was sampled in the FerryBox, usually at weekly frequency. Samples were immediately poisoned with mercuric chloride. Dissolved inorganic carbon (CT) and total alkalinity (AT) were analysed within 6 months via potentiometric titration following methods described by Service National d'Analyse des Paramètres Océaniques du CO_2 at Sorbonne University, France. 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. pH was measured spectrophotometrically within 6 months of sampling using purified m-cresol purple. Three to four replicate measurements were performed for each sample on a Cary 60 UV-Vis spectrophotometer. Repeatability was very good: the standard deviation of the replicates ranged from 0.00033 to 0.0091 pH units and the average of 44 mean standard deviations was 0.0021 pH units.

CO_2 partial pressure

An HydroC CO_2 FT sensor was set-up in 2016 (measuring range of 200-1000 µatm, resolution < 1 µatm, accuracy ± 1%). It was positioned first in the loop of sensors of the FerryBox in order to avoid alteration of pCO_2 through exposure to air. Two sensors were swapped over the year; while one was monitoring pCO_2, the other one was factory-calibrated. Thus, pCO_2 was measured continuously and data logged every minute.

pH values

Two SeaFET Ocean pH sensors (Sea-Bird Scientific) were put in service in 2017. They were swapped every year and while one was monitoring pH and temperature on the profiler, the other one was factory-calibrated. pH (volts) was measured continuously and data logged every minute. Volts were converted to pH on the total scale (pHT). The calibration parameters calculated from spectrophotometric pH measurements as well as associated salinity and SeaFET temperature were averaged for each deployment period. Several Durafet III pH electrodes (Honeywell) were available. They were swapped only once. pH was measured continuously via a Dual Input Analytical Analyzer UDA2128 (Honeywell) and data logged every minute. pH measurements were displayed on the total scale (pHT). Reference samples that matched a pH measurement were used. The pHinsi function of the R package seacarb was used to express pH at temperatures other than the measurement temperature from pH, salinity as well as the original and normalized temperature. The dissociation constants used are provided below.

Data flow and quality insurance

The data collected at 1-minute frequency were assigned with quality flags following a series of quality tests.

Operational use

The extreme conditions prevailing at the site of measurement 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 also occurred to bring technical staff, including divers, to repair damages. The Covid-19 pandemic also generated data gaps. Nevertheless, data were usable 50 to 75% of the time during the period of measurement (Fig. 17A). pCO_2 and pH are available throughout the year and well distributed across months, including winter months (Fig. 17B).

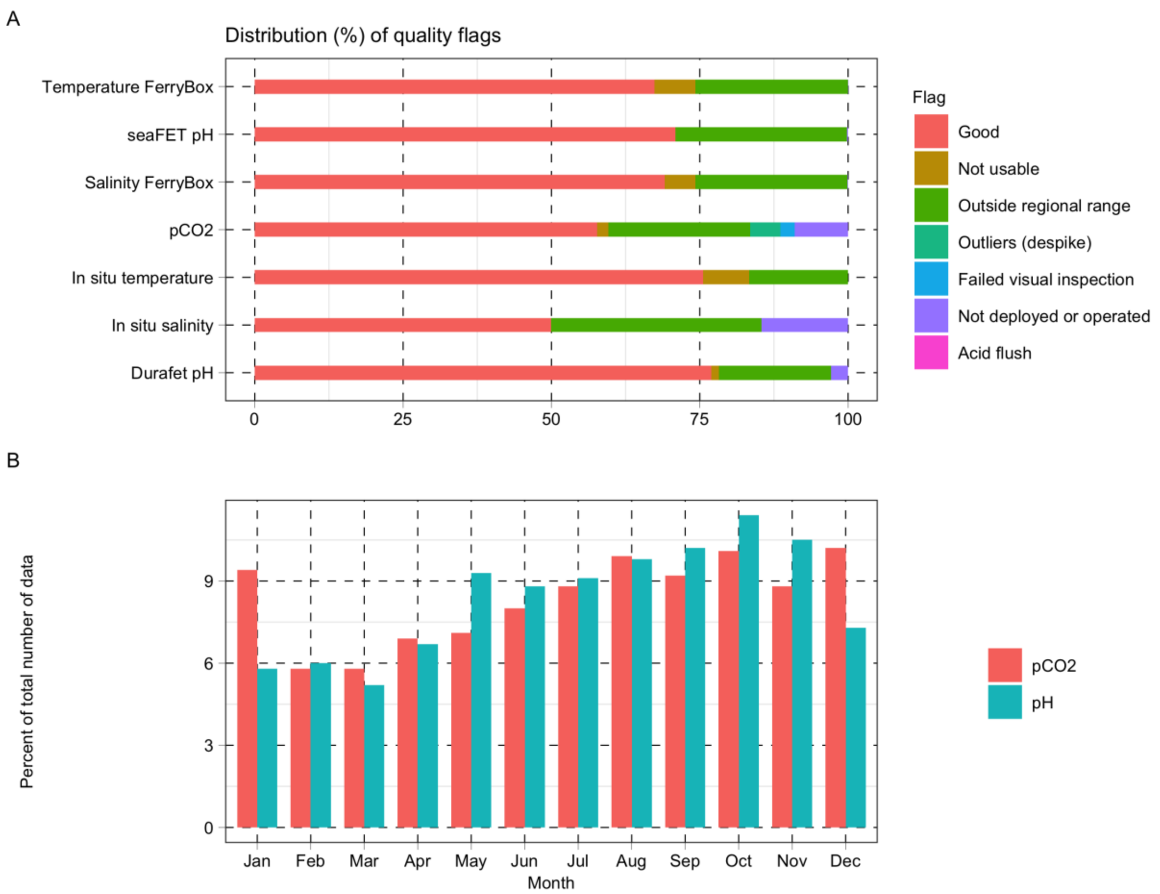


Fig. 17: Distribution of the quality flags assigned to data collected every minute over the period July 2015 to December 2020, except for the durafet pH and SeaFET pH which were set-up in August 2017.

Time-series of key parameters

Preliminary data are shown in Figure 18. The complete analysis requires analysis of discrete samples which are still at Ny-Ålesund (see below). It should be pointed out that this is a unique high-frequency time-series of parameters of the carbonate chemistry.

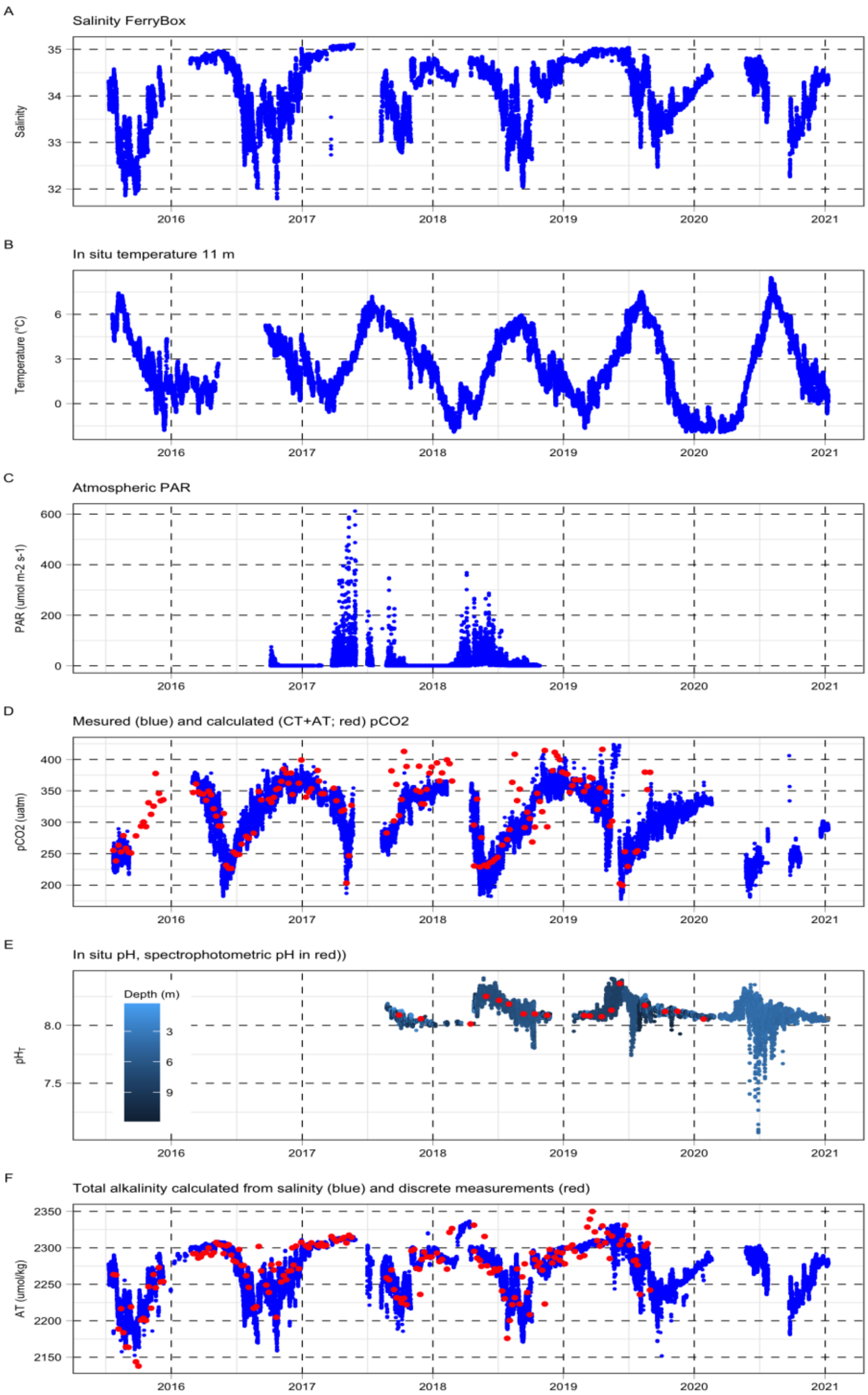


Fig. 18: Time-series of key environmental parameters.

2.3.2. Lessons learned and technology challenges identified during the project

The deployment of the new sensors was successful. All of them performed as expected. 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.

As mentioned above incidents occurred. The first main cause is damage incurred by icebergs, even though the study location was protected on one side by a pier. Twice in 5 years, an iceberg came around the pier and pounded on the field instruments incurring damages. The second kind of incident is winter freezing of the pipe bringing seawater in the FerryBox. This happens when a pump stops. There is a duplicate one but freezing occurs if the switch is not done quickly enough. In such cases, there is no way to defrost the pipes until seawater warms, several weeks later.

How could these incidents be avoided? It is very difficult without having permanent staff closely overseeing the project. Pump issues could be remedied with more efficient automated switching and more redundancy.

The main challenge faced came late in the project (second half of 2020) and actually brought the project to an end in January 2021. Discrete samples cannot be analysed on site for dissolved inorganic carbon, total alkalinity and pH because the required instruments and staff are not available. They must then be preserved and shipped to France for analysis. Preservation is very common on-board ships. The best practices recommend the use of mercuric chloride, a toxic compound that preserves samples for months. Following a perceived contamination (proven inexistent after extensive tests), new regulations were introduced at the AWIPEV research base and at Ny-Ålesund for the use of HgCl2 and transportation of preserved samples. The consequence is that discrete samples could not be taken after January 2021, in effect terminating the project. Changes in transportation rules also made shipments more difficult and three times more expensive. Some samples are still stuck at AWIPEV.

If staff and instruments remain unavailable, the issue with the use of mercuric chloride must be solved before a similar time-series can be initiated.

2.3.3. Description of processing and analysis of the obtained data

The variables added by INTAROS are:

- partial pressure of CO_2 in seawater (every minute, averaged every hour)
- pH (every minute, averaged every hour)
- total alkalinity (weekly measurements and every hour using the AT vs. salinity relationship derived from discrete samples)
- air-sea CO_2 flux (every hour)

As mentioned above, data analysis will be finalised when the samples still stuck at Ny-Ålesund will be shipped and analysed.

2.3.4. Accessibility of the obtained data sets and repositories used

Once the analysis will be completed, data will be published in Earth System Science Data and data archived in Pangaea. It is anticipated that this will be effective in the summer 2021.

2.3.5. Future plans for operation of the observing system, including data provision

Instruments will be recovered in June 2021. INTAROS has demonstrated that it is challenging but 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.

3. Performance and fitness-to-purpose of the platforms, sensors and systems implemented during INTAROS for a future sustained Arctic observing system

The new and improved observing systems developed within Task 3.3 of the INTAROS project proved their general applicability for future sustained observations in the marine Arctic.
The 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. The exchange of the glass sensors by optical sensors (optodes) will most probably solve these problems. Ex-situ tests of the optodes in a temperature-controlled high-pressure tank at AWI went very promising. First in-situ tests at approx. 1500 m water depth off Svalbard during the RV *Polarstern* expedition PS126 in June 2021 will hopefully demonstrate the operability of the improved arcFOCE system in future long-term deployments (12 months), which are planned for 2022/23 and the following years in different parts and water depths of the HAUSGARTEN area.
The passive acoustics system at the entry of the Kongsfjorden, with the purpose of assessing the soundscape of this Arctic fjord, revealed approx. 15000 hours of recordings within the INTAROS project, extending sound records already collected before the project in 2013 in an environment with growing anthropogenic pressure. The simultaneously deployment of several acoustic sensors with different starting times generally increased the recording capacity. Unfortunately, the Covid-19 pandemic seriously affected the necessary field work to install/replace instrumentation. Acoustic data from the time-series work 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 during the European lockdown due to the Covid-19 crisis. The AIS data combined with the acoustic propagation results from acoustic data analyses revealed the necessity to deploy additional recorders in the northern part of the fjord. The deployment of additional acoustic systems is planned for the next field campaign in late summer 2021.

The overall good performance of the improved AWIPEV CO_2 monitoring system in the Kongsfjorden was only marred by occasional failures of individual systems, which revealed the need for continuous professional support of the system and the provision of replacement components to secure continuous operation. Restrictions due to the Covid-19 pandemic also played a role. 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. Regrettably, although proven not existing after extensive tests, new regulations introduced at the AWIPEV research base and at Ny-Ålesund for the use of $HgCl_2$ and transportation of preserved samples prohibited to take and analyse discrete samples for calibrations of the monitoring system after January 2021. Changes in transportation rules made shipments more difficult and three times more expensive, which finally lead to the decision to terminate the project.

4. Summary

This document presents work carried out within the INTAROS project to improve the observational capacities in the Fram Strait region, reports on initial results from the new observing systems and describes ways for the delivery of data retrieved by these systems. The arcFOCE experimental setup, developed and implemented to study impacts of ocean acidification on benthic deep-sea organisms and communities at the LTER (Long-Term Ecological Research) observatory HAUSGARTEN, showed an overall good performance, but needs improvements before operational use. The implementation of a passive acoustics system in Kongsfjorden, similar to an existing system off Greenland, is completed and revealed valuable information about the natural and anthropogenically induced soundscape in the area. New pH sensors integrated in the AWIPEW CO_2 time-series monitoring site in Kongsfjorden provided redundancy and increase confidence in the calculations of the various parameters of the CO_2 system in the marine environment. However, due to new regulations at the AWIPEV research base, the monitoring of the marine carbonate system in Kongsfjorden had to be terminated. Data from the observatories will be quality-controlled and uploaded to the World Data Center Pangaea as well as the publisher of scientific data SEANOE or SEXTANT.

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INTAROS

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