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Deliverable 6.8

Synthesis of ocean carbonate system observations from Svalbard, Barents Sea, and Coastal Greenland

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EXECUTIVE SUMMARY

This document, Deliverable 6.8 - *Synthesis of ocean carbonate system observations from Svalbard, Barents Sea, and Coastal Greenland*, is a result of INTAROS WP6 Task 6.5 on Arctic greenhouse gas exchange. The reported work rests upon results provided by WP3, more specifically tasks 3.1, 3.2 and 3.3. It synthesizes data stored in databases SOCAT and GLODAP and additional data from a Ferry box system crossing the Barents Sea opening and from Greenland fjords.

To show the potential establishing long term monitoring of the carbon system variables as suggested in INTAROS, trends in ocean uptake and transport of carbon, ocean acidification and deoxygenation can be produced. Examples on synthesis of carbon system data are shown, with the aim of analysing trends in ocean acidification in the Nordic Seas

The results reported by each of the marine science partners in Task 6.5 include:

UiB. The main task has been to prepare for a comparison of pCO_2 field extracted from 2018 data in the SOCAT database, and test a self-organising map technique, a type of artificial neural network that uses machine learning. This was implemented to estimate surface water pCO_2 values for the Barents Sea opening (10°E-30°E; 70°N-77.5°N).

NIVA. A FerryBox system was equipped on *M/S Norbjørn* which made approximately 25-30 round-trip crossings per year through the Barents Sea Opening between Tromsø, Norway and Longyearbyen, Svalbard. The FerryBox system included several physical, chemical, and biological sensors.

UA. In Greenland, measuring ocean CO_2 and carbonate chemistry is included in the Greenland Ecosystem Monitoring (GEM) Programme. Although these long-term programs provide essential time-series of change, the three sites do not cover the spatial variation across the vast Greenland coastal zone.

Table of Contents

1. Introduction

The global oceans currently absorb about 25% of the anthropogenic carbon dioxide (CO_2) emitted annually from fossil fuel use and deforestation (e.g., Takahashi et al., 2009; Le Quéré et al., 2016; 2018; Friedlingstein et al., 2019). The uptake of CO_2 by the ocean adds to the total dissolved inorganic carbon content of the ocean which results in reduction of seawater pH – termed ocean acidification – and the saturation state of calcium carbonate minerals, e.g., aragonite and calcite. The present rate of ocean acidification is comparable or higher to rates estimated over the last 55 million years. The rise in CO_2 and decrease in pH are expected to have a significant impact on organisms, the structure and function of the marine ecosystem, and therefore ecosystem services, especially in the Arctic. This is because the Arctic and Subarctic oceans are naturally high in dissolved inorganic carbon due to low temperatures that enhance the solubility of CO_2 in seawater. The Arctic and its coastal areas can be hot spots of biogeochemical process rates, CO_2 exchange rates, and rate of ocean acidification/climate change, and the Arctic Ocean is expected to become undersaturated with respect to calcium carbonate during this century if CO_2 emissions continue as they are today (AMAP 2013; Steinacher et al., 2009). While the projected ecosystem change has implications for various stakeholders including wild fisheries, coastal managers, and indigenous populations that rely on natural resources for sustenance, observations in the Arctic are relatively sparse due to the remoteness and logistical challenges it imposes.

Carbonate system chemistry in the Arctic and Subarctic oceans is very dynamic due to strong/seasonal variability in biological activity (production/respiration), wind and other physical mixing mechanisms, and sea surface temperature. Observations of carbonate system dynamics within the INTAROS project requires a high degree of spatial and temporal coverage due to the seasonal and spatial heterogeneity of the region as well as a high degree of precision/accuracy for detecting long-term changes that are relatively small over short periods of time. Precise estimates of the oceans uptake and release of CO2 and knowledge and predictions of susceptibility to change from various feed-back mechanisms is essential to predict the rate of climate change in earth system models. It is also equally important to observe present day carbonate system chemistry as a baseline and to understand the impact/role of major drivers in carbonate system dynamics. This was the rationale for the observing system design and implementation that was carried out in WP3, namely tasks 3.1, 3.2 and 3.3, and data collected through observations near Svalbard, the Barents Sea Opening, and Coastal Greenland were integrated and synthesized as part of WP6 (Task 6.5) and reported in the present report.

The main product described in this report, characterizing inorganic carbon chemistry in the ocean region around Svalbard, is application of a self-organizing map technique to estimate surface water pCO2 values for the Barents Sea opening and identifying correlations between additional data layers from the multi-disciplinary INTAROS database and observed atmospheric mixing ratio patterns. Such correlations may help to identify source and sink processes for GHGs in the Arctic, and therefore contribute to improving their representation in process modelling frameworks. Our activity specifically targets the Earth System Modelling community as stakeholders, with the aim of supporting the representation of biogeochemical processes in high-latitude ecosystem models. Reduced uncertainties in the resulting future climate simulations will in turn help local communities as well as decision makers in economy and management to improve adaptation measures towards climate change impacts in the region. The outcome of D6.8 give important information to carry out the roadmap for the future Arctic Observing System (Task 1.5).

2. Synthesis of INTAROS carbonate system observations

2.1 A synthesis of pCO_2 data extracted from a selected area covering the Barents Sea opening (UiB-GFI)

The goal of the marine component of Task 6.7 was to prepare for a comparison of pCO_2 field from observations made in WP3 (Deliverables 3.11 and 3.13) with those extracted from 2018 data in the SOCAT database using a self-organising map technique. The method, a type of artificial neural network that uses machine learning, was implemented to estimate surface water pCO_2 values for the Barents Sea opening (10°E-30°E; 70°N-77.5°N). Initially, the network was trained using satellite observations of chl-a, sea ice concentration, sea surface temperature and salinity, as well as bathymetry and estimates of mixed layer depth. The training data was labelled with pCO_2 observations from the SOCAT database, which enabled preliminary maps of monthly sea surface pCO_2 for the year 2018 to be created. The network is now ready to include the training and labelling data sets from INTAROS partners. Atmospheric CO_2 estimates from inverse modelling efforts will be used as an additional training parameter and surface water pCO_2 from NIVA's FerryBox observations will be used to label the training data. The SOCAT data used in the preliminary phase of network development will be used as validation data for the final output of the self-organising maps. As an example, refer to Fig. 1.

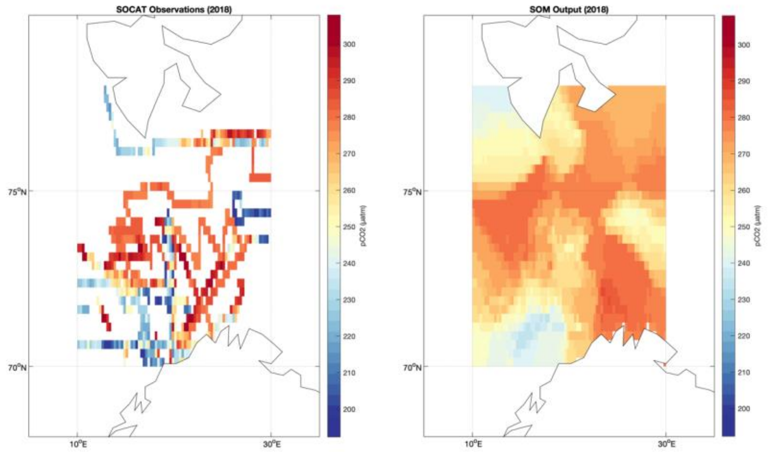

Figure 1. Left panel data = data extracted from the SOCAT-database for year 2018. Right hand side an example of an output of self-organization map.

Further comparison with atmospheric models in Task 6.5 projecting the pCO_2 field in the same area were prohibited because of delays caused by COVID-19. The intention was to make independent outputs from atmospheric inverse modelling constrains regional to global scale greenhouse gas (GHG) budgets based on transport fields and time series of GHG mixing ratios from a network of towers. Geostatistical inverse modelling (GIM) techniques extend this approach, allowing assimilation of additional ancillary data layers that may provide useful information on how the simulated flux fields vary in both space and time

2.2 Barents Sea Opening FerryBox observations (NIVA)

A FerryBox system was equipped on M/S Norbjørn which made approximately 25-30 round-trip crossings per year through the Barents Sea Opening between Tromsø, Norway and Longyearbyen, Svalbard (cf. Deliverable 3.13). The FerryBox system included several physical, chemical, and biological sensors: a Seabird SBE38 inlet temperature sensor, a Seabird SBE45 conductivity-temperature sensor, a Franatech/NIVA membrane equilibrator pCO_2 sensor, a NIVA spectrophotometric pH sensor, and a TriOS microFlu chl-a (chlorophyll-a) fluorometer. Observations from 2017-2020 are shown in Fig. 2.

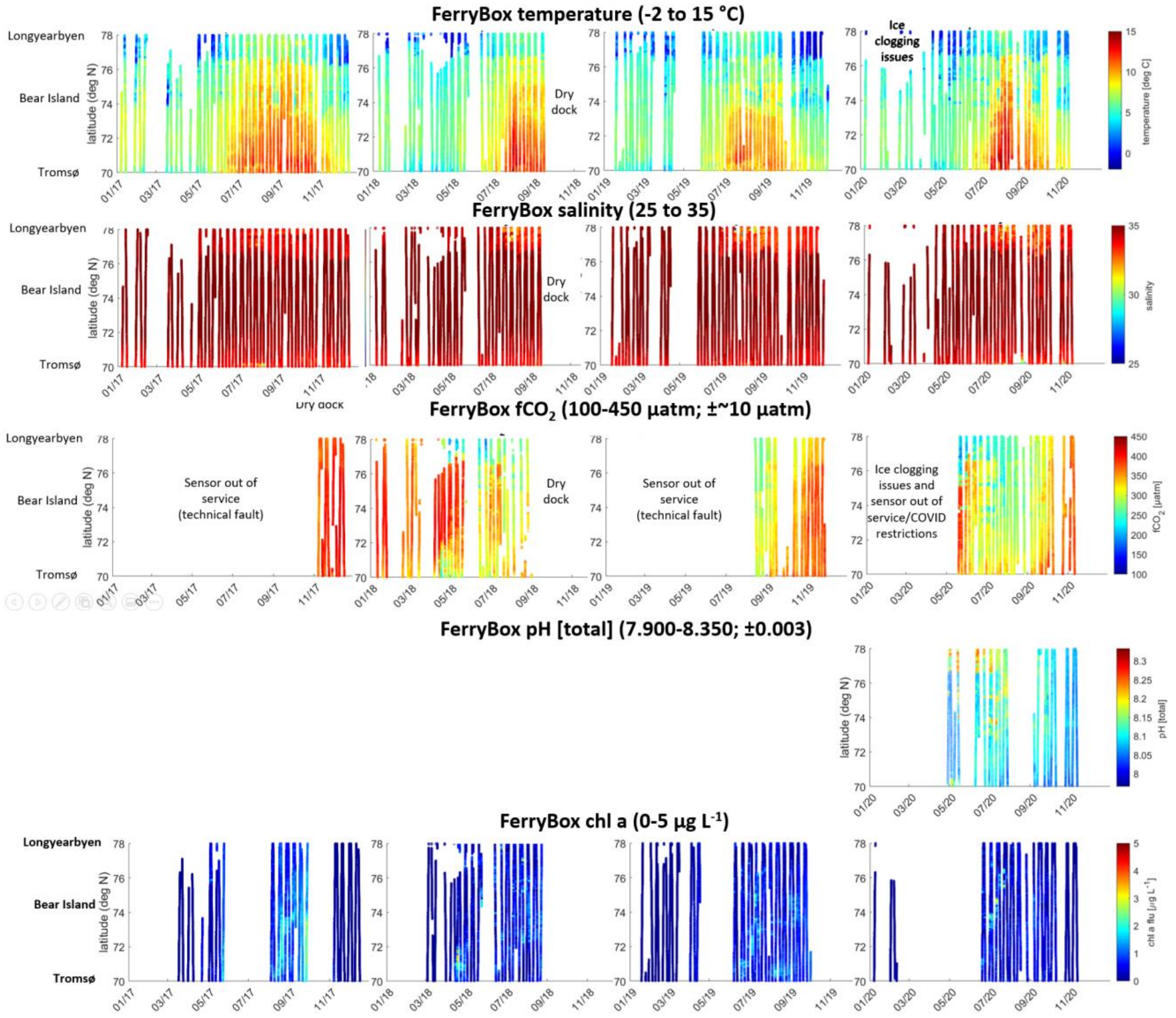

Figure. 2. Barents Sea Opening FerryBox data from 2017-2020 at ~5 m depth intake. Top panel: temperature °C); second panel: salinity; third panel: fCO_2 (µatm); fourth panel: pH (total scale); fifth panel: chl-a (µg L^{-1}).

At ~70-72° N (near Norwegian coast) in late April/early May 2018, fCO_2 was drawn down to ~280-310 µatm – high chl-a fluorescence confirmed the presence of phytoplankton and spring bloom during this period. fCO_2 increased ~30 µatm in mid-May, consistent with a 2° warming and low productivity (low chl-a). Low fCO_2 in the coastal region continued into July and August of 2018. Although, fCO_2 in July/August 2020 was at times as high as ~350 µatm possibly due to anomalously warm sea surface temperatures and low productivity (low chl a in summer 2020). At ~77-78° N (coastal Svalbard), fCO_2 began to decrease to <200 µatm in April 2018 and continued to remain relatively low through July 2018, and a similar decrease in fCO_2 was observed in 2020. Sea surface temperatures were <0 °C at the beginning of this period and warmed to >~5 °C by July. Sea surface salinity was generally lowest in this region with a salinity range within ~30-33. Phytoplankton biomass was above average during spring and summer which could explain some of the reduced fCO_2 during this time. In the open sea portion of the Barents Sea Opening (~72-76° N), fCO_2 was near equilibrium with the atmosphere during winter months (~400 µatm) and began to decrease to <~350 µatm around June, <~300 µatm around August, and remained low through ~September/early-October. In the fall, SST began to decrease and fCO_2 increased back to wintertime concentrations.

Both pH and fCO_2 measurements were available in 2020, and as would be expected, pH reflected the inverse of fCO_2 – higher fCO_2 waters were lower in pH and vice versa. The measurement of both carbonate system variables also validated fine-scale variability where both pH (lower) and fCO_2 (higher) varied over small distances, and these regions were also places where SST was also lower and phytoplankton biomass was higher. This implies that fine-scale heterogeneity in mixing and nutrient influx that supports primary production and CO_2 drawdown was observed.

2.3 Coastal Greenland observations (AU)

In Greenland, measuring ocean CO_2 and carbonate chemistry is included in the Greenland Ecosystem Monitoring (GEM) Programme. Although these long-term programs provide essential time-series of change, the three sites do not cover the spatial variation across the vast Greenland coastal zone. Thus, data allowing an analysis of large-scale differences in pCO_2 and carbonate chemistry related to distribution of major water masses and input of glacial meltwater is one of the key knowledge gaps. Through support from the Danish Center for Marine Research, Aarhus University (AU) was able to complete two scientific cruises to east and west Greenland fjords (Fig. 3). One of the objectives was to collect pCO_2 and carbonate system data for a comparison of Greenland fjord systems to evaluate how representative the GEM data collection sites where for wider regions in Greenland (cf. Deliverable 3.10). A scientific paper is in preparation and upon publication the data will be Open Access. About 750 individual pCO_2 measurements were made across 11 different fjord transects. Despite the considerable variation within local fjords primarily related to the amount of glacial meltwater, clear differences between summer surface (0-50 m) conditions in pCO_2 where found. Most notable the variation between sites and with depth was notably smaller along the East Greenland coast (Fig. 4) compared to West Greenland (Fig. 5). This results in a comparably lower undersaturation (on average) in west Greenland, but also over-saturation at depth (Fig. 6).

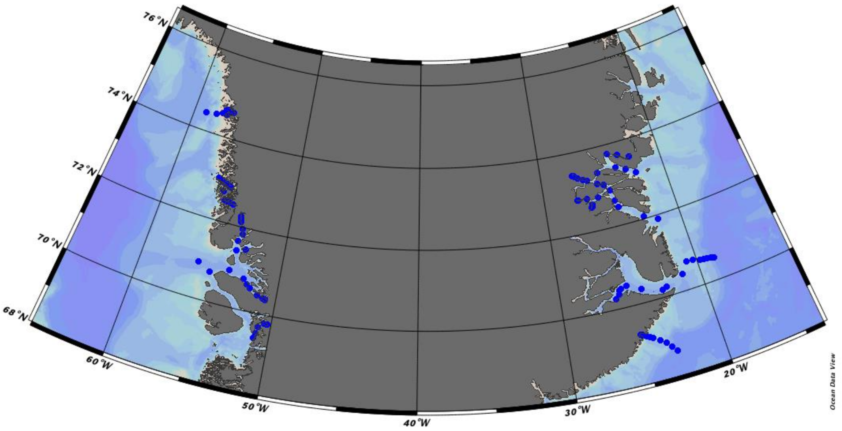

Figure 3: Sampling sites for pCO_2 in Greenland

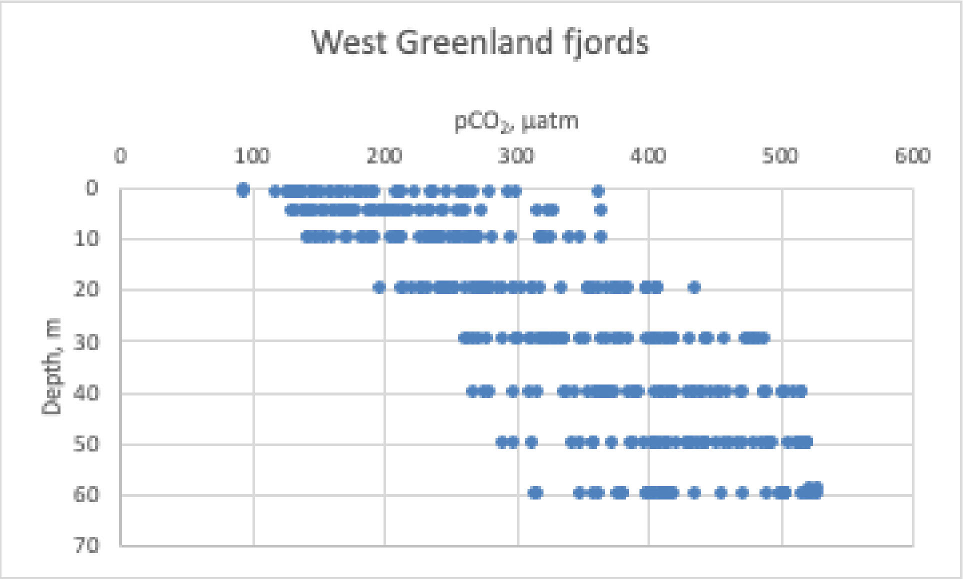

Figure 4. All observations on partial pressure of CO_2 (pCO_2) across six different fjord system in West Greenland sampled in August 2016.

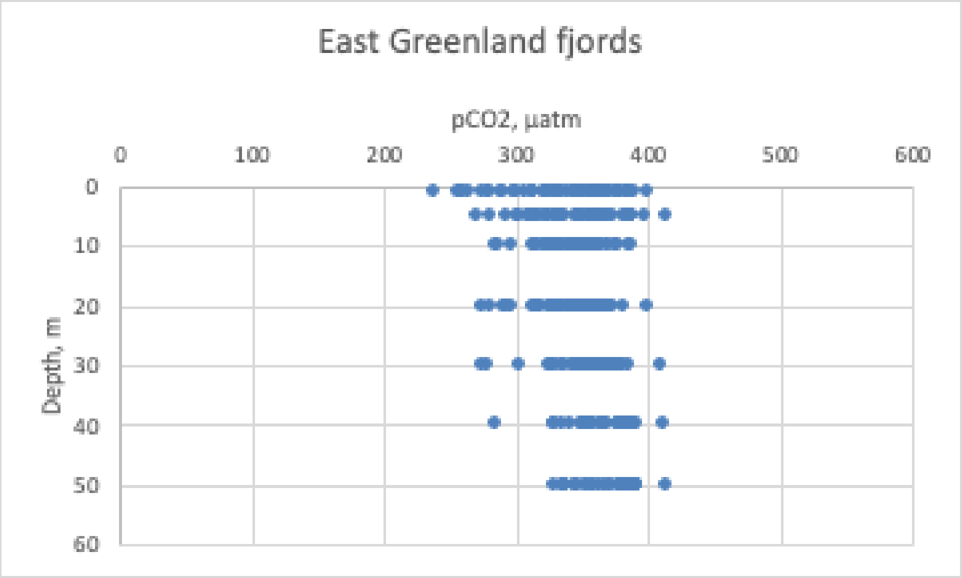

Figure 5. All observations of pCo2 from five fjord systems in East Greenland sampled in August 2019

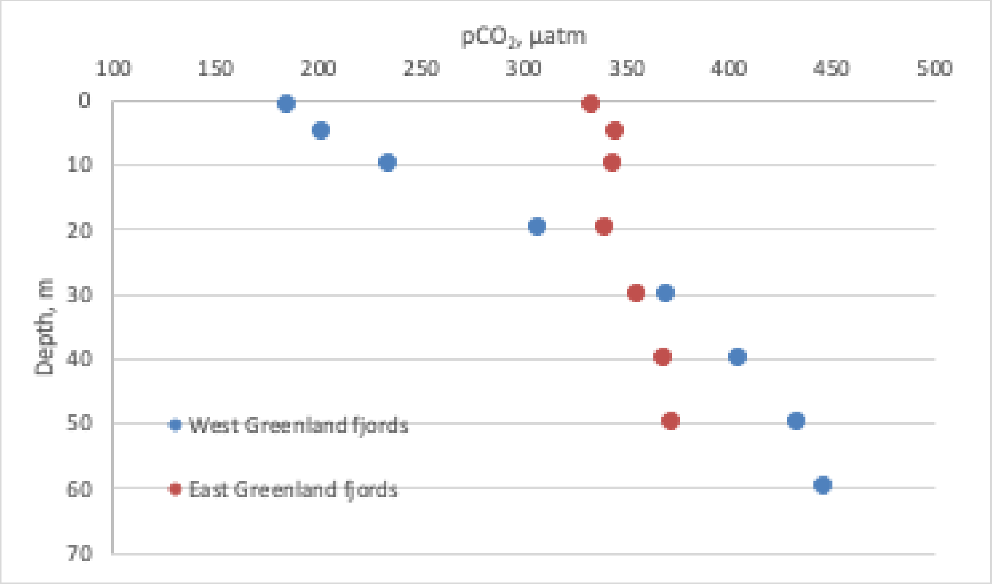

Figure 6. Average pCO2 conditions in surface waters in West and East Greenland fjords

2.4 Synthesis work on trends of ocean acidification (all)

The potential in establishing long term monitoring of the carbon system variables as suggested in INTAROS, relies, e.g., in producing trends in ocean uptake and transport of carbon, ocean acidification and deoxygenation. An example of key regions of the Nordic seas where such trends (Fig. 7) can be the analysis provided by Fransner et al (2021These include Arctic environments and, in the future, including the recent data from the North of Svalbard multivariable mooring concept, FerryBox and ships of opportunities - that will become more applicable when the Arctic Sea cover shrinks - and approaches along

Greenland Fjords to monitor meltdown of the Greenland Ice Sheet, the trend estimates will improve.

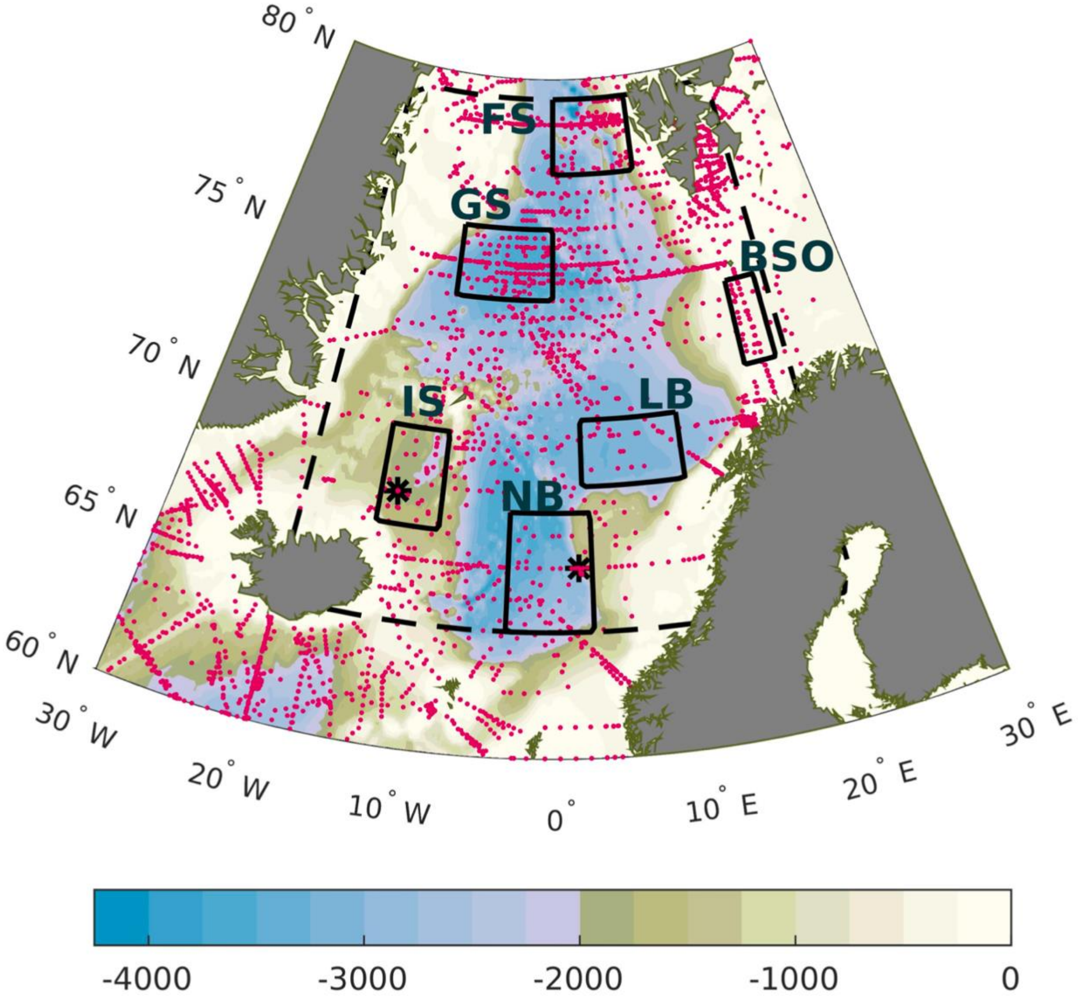

Figure 7. Map of the Nordic Seas with sampling locations (magenta). Also shown are the locations of the six regions where trends have been analyzed (rectangles); BSO: Barents Sea Opening; FS: Eastern Fram Strait; GS: Greenland Sea; IS: Iceland Sea; LB: Lofoten Basin; NB: Norwegian Basin. The dashed line marks the area that we define as the Nordic Seas. The asterisk markers in the Norwegian Basin and the Iceland Sea show the positions of Ocean Weather station M and the Iceland Sea time-series station, respectively. The filled contours illustrate the bathymetry at 250 m intervals.

A flavour of results from the data synthesis in combination with modelling is provided in Fig. 8. (Fig. 4 in Fransner *et al.*, 2021). One observes a significant change in pH and omega aragonite between preindustrial time and present day as defined in the figure text clearly demonstrating the ocean response on anthropogenic CO_2 emission.

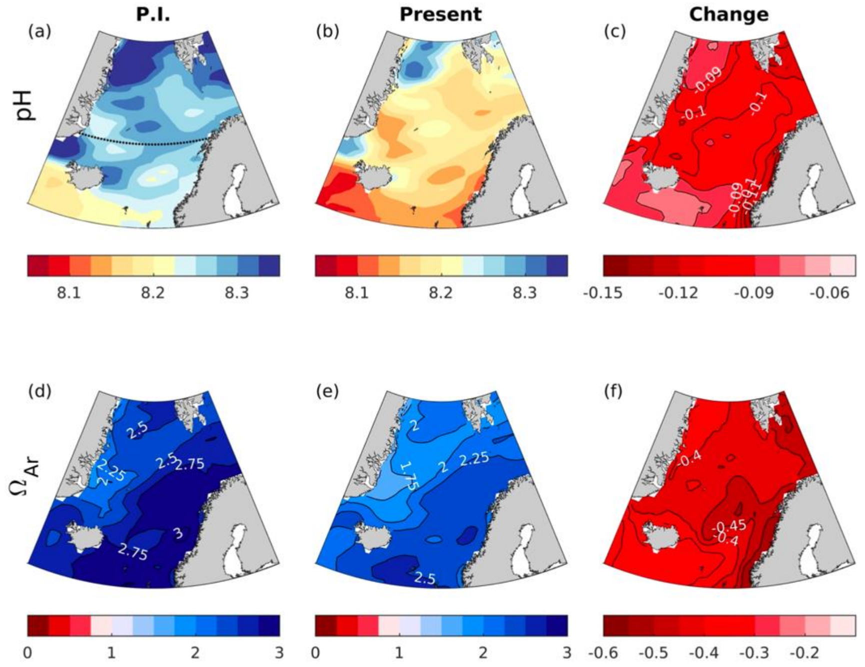

Figure 8. Maps of surface water (0 m) pH and Ω_{Ar} for pre-industrial (P.I., 1850-1859), present-day (1996-2005), and the change in between the two periods. The maps were calculated from the GLODAPv2 gridded climatologies (Lauvset et al., 2016) applying the simulated changes by NorESM1-ME.

2. Summary and conclusions

There is a clear potential to produce carbonate system data in an autonomous fashion using ships of opportunity and other observing platforms, such as moorings, that complement conventional research cruise-based observations. Combined, these observations will give better seasonal, annual, interannual and decadal coverage of the carbonate system and ocean acidification. It will be important to continue to use these data together with existing data in models and data intercomparison exercises for validation of model results. A self-organising map technique, a type of artificial neural network that uses machine learning, seems to be a promising approach to pursue, and that will be followed up in interaction with the atmospheric modelling group of INTAROS.

INTAROS has implemented different platforms and sensors for measurement of carbonate system variables and approaches for integrating/synthesizing existing and new observations. These activities are needed for improving our understanding of the marine carbonate system in Arctic and Subarctic Oceans, and therefore to better manage the region in a sustainable manner. There are still some challenges that need to be addressed before these platforms can produce reliable data that is high quality with good spatial and temporal coverage that can be used to answer questions related to ocean uptake and transport of CO_2 related to both natural and anthropogenic processes, and to assess the rate of change in ocean acidification. There is also the need to improve observations related to phytoplankton blooms and biological production to fully characterize and understand carbon system dynamics. However, the developments in ocean acidification-related sensors in addition to other biological and biogeochemical sensors (e.g., nitrate and oxygen) are on track to be used to measure changes in carbonate system chemistry and deoxygenation in Arctic coastal and open ocean systems.

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