Fisheries and Oceans Canada Pêches et Océans Canada

North Atlantic Biogeochemical Carbon Pump
Virtual scientific workshop summary

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Introduction

The ocean plays a critical role in the global carbon cycle, storing 50 times more carbon than the atmosphere and soaks up more carbon than all the rainforests combined. Among all the oceans, the North Atlantic Ocean is one of the most intense anthropogenic carbon sinks on the planet, accounting for approximately 30% of the global ocean CO_2 uptake.

Knowledge of the ocean carbon cycle is critical in light of the ocean's role in sequestering CO_2 from the atmosphere and for meeting goals and targets such as the UN Framework Convention on Climate Change (UNFCCC) Paris Agreement, the UN 2030 Agenda for Sustainable Development, and to contribute to the achievement of the UN Decade of Ocean Science for Sustainable Development (2021-2030)'s challenges. Human emissions predominantly explain increasing levels of CO_2 in the ocean, with fundamental impacts on ocean carbon cycling and ecosystem health.

DFO convened the scientific and technical workshop on the North Atlantic Biogeochemical Carbon Pump (BCP), in response to a commitment made by the Minister of Environment and Climate Change Canada at the G7 Climate and Environment Ministers' Meeting in March, 2021. The workshop was designed and delivered by a steering committee (Annex 4) with members from national and international ocean carbon community. The two-day workshop was held in virtual format on December 15 and 16, 2021. Sixty nine leading scientific and technical experts from 16 countries attended the workshop and contributed to the discussions on scaling up knowledge and monitoring of the North Atlantic biological carbon pump.

The scope of the workshop was, building on the work that has been done by the international ocean carbon community, to advance an approach for an integrated ocean carbon program in the North Atlantic, using the North Atlantic BCP as an exemplar by examining:

- the state of science and understanding with regards to the biogeochemical and physical carbon processes in the North Atlantic BCP
- the methodologies, opportunities and knowledge gaps for quantifying, observing, monitoring, and modelling the North Atlantic BCP
- the links to domestic and international research activities and knowledge already in place and planned

The workshop included key note speeches to set the scene, breakout sessions to have focused discussions on monitoring, modelling and collaborative opportunities and panel discussions on an approach to an ocean carbon project in the North Atlantic. The first day was dedicated to identify gaps, challenges, and opportunities, in research, modelling, observing, and monitoring the North

Atlantic carbon pump. Discussions continued on the second day to identify the scientific elements, steps and activities required to advance an integrated and comprehensive approach to an ocean carbon program in the North Atlantic BCP.

Workshop discussion were around the following questions:

- What is the current state of open ocean carbon knowledge/research, modelling, observing and monitoring (in-situ and satellite) in the NA and what are the gaps to monitor and predict it in the future?
    - e.g. what / where do we need to research, model, observe and / or monitor
- Who are the players and what are they doing? Where are the opportunities to collaborate and how to enhance and coordinate the existing suite of carbon observing and synthesis projects ?
    - e.g. which international parties and partners could contribute (and how) to the design and delivery of the program/observatory?
- What technologies are currently being employed and what new technologies could enhance observations and analysis?
- What key components would comprise a coordinated "pilot" effort?
- What are concrete actions / steps required to scale up efforts (solely from a science perspective)?
    - e.g. what are the prerequisites, implementation steps, time scale, etc.?

Through this workshop, experts identified gaps and path forward in four major areas:

1. science
2. research and understanding
3. technology
4. sustainability and governance

The key outcomes in these areas are summarized in the workshop findings.

The workshop concluded that carbon uptake by the North Atlantic is a crucial part of the earth's carbon cycle, which we need to understand and quantify in a much more systematic and robust way than that we do now in support of climate negotiations. The international community has massive capacity to undertake this task and is poised to act once an overall structure is established.

Workshop findings

The oceans cover over 70% of the Earth's surface and play a crucial role in taking up CO_2 from the atmosphere, absorbing about one-quarter of the CO_2 that humans create when we burn fossil fuels (oil, coal, and natural gas). Building on work of the international ocean carbon community, the goal of this workshop was to advance an approach for an integrated ocean carbon program (research, modelling, observing, and monitoring) focused on the BCP in the North Atlantic. The scope of the workshop focused on:

- the state of science, research and overall understanding (in the areas of monitoring, modelling and technology development)
- governance and coordination with regional and international partners
- technology requirements and limitations
- mechanisms and needs for funding and sustainability

The workshop resulted in multiple findings summarized under the following categories:

Science, research and understanding

The North Atlantic is a major sink for CO_2 due to biological, chemical and physical processes, all of which are likely to change. These unique characteristics make it a key region for scientific investigation with respect to the role of the ocean in climate change, both in its own right and as an exemplar regarding how large scale observing of the ocean carbon cycle can be organized. Meeting participants indicated that the North Atlantic carbon pump represents a viable exemplar for improved understanding of the ocean carbon cycle.

Most previous scientific investigation and observation comprises opportunistic research activities, with no systematic, sustained and coordinated approach to ocean carbon science in this unique area of the ocean.

Scientific research and activities must be undertaken in the North Atlantic to better monitor, understand and predict its ocean carbon processes and functions before we can determine its potential contributions to climate change mitigation.

Participants identified a need to develop a comprehensive integrated scientific approach for the North Atlantic that connects research into carbon processes and functions with modelling and ongoing monitoring programs. It was noted that we need to know the current state to understand how we are altering the ocean carbon cycle and that this requires sustained and coordinated observations.

Technology

Recognizing that significant technologies currently exist and are being used to observe and monitor variables of relevance to the ocean carbon cycle, we should build upon this existing technological foundation. Refinement of our current approach through further investigation is needed to identify appropriate observational and monitoring platforms, refining the performance and accuracy of sensors, designing an integrated and appropriate approach (based on scope and variables to measure), and investigating the use of new and evolving technologies including real time observation.

The North Atlantic BCP offers a unique opportunity and location for using, developing and refining autonomous, low-carbon-emitting observational and monitoring platforms such as gliders, uncrewed automated vehicles, etc. These tools may then be deployed globally elsewhere to conduct similar activities.

Sustainability

Our ability to observe the ocean is strong, but we're not necessarily deploying it consistently from year to year. The majority of scientific investigations on ocean carbon processes in the region reflect opportunistic research of a fixed duration. The region also lacks a sustained research and monitoring program focused on the BCP.

Understanding the potential role of the ocean in mitigating climate change fundamentally requires sustained observations in this large and seasonally-dynamic region. Participants urged that an integrated ocean carbon program in the North Atlantic should be a sustained operational system that can function for long-term benefits, complemented by individual research studies.

Governance

Currently the scientific community brings international expertise, interest, and a strong foundation of ocean carbon research, observing and modelling to build upon, including ocean carbon research and monitoring activities in the North Atlantic. However, the international community lacks integration and there is no comprehensive, coordinated observing system with international oversight and governance.

We must improve communication of the impacts associated with ocean carbon in climate change and ocean health, and resulting societal impacts to policymakers and funding agencies.

Workshop program

Building on previous work completed by the international ocean carbon community, the workshop was designed to advance an approach for an integrated ocean carbon program (research, modelling, observing, monitoring and modelling) focused on the BCP in the North Atlantic. The objective of day 1 was to identify gaps, challenges, and opportunities, in research, observing, monitoring, and modelling of the North Atlantic carbon pump. In day 2, workshop participants considered the current state, gaps, and opportunities identified in day 1, and discussed and identified scientific elements, steps, and activities required to advance an integrated and comprehensive approach to an ocean carbon program in the North Atlantic.

Introduction

Mr. Keith Lennon (Director, Ocean and Climate Change Science Program, Fisheries and Oceans Canada) emphasized the importance of the workshop by highlighting the significant role that the ocean plays with respect to carbon and the absorption of anthropogenic CO2 emissions, noting that the North Atlantic Ocean is one of the most intense and unique carbon sinks on the planet. As such, Canada recognizes the need to increase our collective understanding of the leading role the ocean plays in regulating Earth and Earth's climate. Current knowledge and understanding of the North Atlantic carbon sink is not adequate to accurately forecast how future modification in emissions will impact the carbon cycle. Understanding the ocean's potential role in sequestering and emitting CO2 and improving climate change modelling is critical.

Fisheries and Oceans Canada (DFO) was pleased to convene this scientific workshop, a recommendation from the 2021 G7 Climate and Environment Ministerial, to further discuss the scientific approach employed to measure, monitor, and model the carbon cycle in the ocean, as well as to identify gaps in scientific knowledge and potential opportunities using the North Atlantic Ocean as an exemplar for a globally-applied framework.

Setting the scene

Ocean carbon experts set the scene for the workshop through:

- keynote presentations
- providing a high-level overview of the current state of the carbon knowledge
- observations, monitoring, modelling
- the players involved in these activities

Current state of open ocean carbon knowledge/research, observing and monitoring (including technologies) in the North Atlantic

"The ocean carbon community has to step beyond a piece-meal ocean research approach, we need sustained and coordinated observations."

Dr. Rik Wanninkhof (Senior Scientist, Atlantic Oceanographic and Meteorological Laboratory (AOML) of the National Oceanographic and Atmospheric Administration (NOAA) provided an overview of the current state of carbon knowledge, research, observing and monitoring in the North Atlantic Ocean.

Noting the importance of decreasing global CO_2 to achieve the Paris Agreement targets for atmospheric temperature, he provided examples of previous efforts as a foundation for an improved ocean carbon research approach for the North Atlantic. The ocean carbon community has to step beyond the piece-meal ocean research approach, we need to know the current state to understand how we are altering the ocean carbon cycle. We need sustained and coordinated observations and adaptation of a regional approach where studies can be conducted over longer and larger time and space scales, respectively, taking into consideration the regionally-unique attributes that affect the ocean carbon system.

With a focus on the North Atlantic, Dr. Wanninkhof summarized the state of knowledge within four overarching fundamental and emerging research questions, as outlined in the Intergovernmental Oceanographic Commission (IOC) document "Integrated Ocean Carbon Research (IOC-R): A Summary of Ocean Carbon Knowledge and a Vision for Coordinated Ocean Carbon Research and Observations for the Next Decade"[1] which provides a framework/vision for integrated and coordinated ocean carbon research:

Will the ocean uptake of anthropogenic carbon dioxide (CO_2) continue as primarily an abiotic process?

Several studies have shown that most of the anthropogenic carbon in the world's ocean is stored in the upper 2000 meters, except for the North Atlantic where anthropogenic carbon is detected to the bottom. This can be traced to its well-ventilated ocean waters with unique attributes of Atlantic Meridional Overturning Circulation (AMOC) and boundary currents. Research of the past has

[1] Integrated Ocean Carbon Research (IOC-R): A summary of ocean carbon knowledge and a vision for coordinated ocean carbon research and observations for the next decade (https://unesdoc.unesco.org/ark:/48223/pf0000376708)

shown that carbon uptake changes with the changes in boundary currents. The decade between 1989 and 2003, the uptake pattern of anthropogenic carbon between the North and South Atlantic varied – where the North Atlantic has the smaller uptake, and this is traced directly to changes in the AMOC. Research on the gas exchange processes that control the air and CO_2 fluxes indicate that changing climate will change the wind structures, and that will have an effect on the CO_2 fluxes, including in the North Atlantic.

The North Atlantic has one of the greatest flux densities of the global ocean, as well as one of the greatest uncertainties in air-sea CO_2 fluxes. There is also a difference in the magnitude of fluxes between observations and models. More research is needed to consolidate these differences between observations and models to answer the first question of IOC-R.

What is the role of biology in the ocean carbon cycle and how is it changing?

Dr. Wanninkhof mentioned that biology studies in the North Atlantic are performed in the context of biogeochemistry through process studies, time series (days to years) and an increasingly more nuanced view of carbon pumps. Spring blooms contribute to the North Atlantic's large CO_2 sink. Studies of physical and biological parameters during episodic events illustrate the challenges of using chlorophyll concentrations to interpret carbon concentrations[2]. Time-series data on a seasonal to interannual scale show that the carbon cycle is heavily influenced by biology[3].

What are the exchanges of carbon among land, ocean and ice, and how are they evolving over time?

Most of the studies in this respect are local and there is not an adequate amount of research done on a regional scale. Local studies show changes in surface temperature resulting from changes in current structure. The east coast of Canada and the US is very heavily influenced by coastal currents, and particularly the interplay between the northward-flowing Gulf Stream and the southward-flowing coastal currents, which originate from the Labrador Sea. The balance of the northward and southward currents has a determining effect on carbon chemistry and biology.

How are humans altering the ocean carbon cycle, and what is the resulting feedback, including possible purposeful carbon dioxide removal (CDR) from the atmosphere?

[2] Short timescale variations of fCO_2 in a North Atlantic warm-core eddy: Results from the Gas-Ex 98 carbon interface ocean atmosphere (CARIOCA) buoy data (https://doi.org/10.1029/1999JC000278)
[3] Variability of pCO_2 on diel to seasonal timescales in the Sargasso Sea near Bermuda (https://doi.org/10.1029/98JC00247)

Dr. Wanninkhof mentioned that to address marine CDR we need better understanding of current conditions, noting it is important to invest in sustainable observations and research in a comprehensive and holistic manner as part of CDR research.

In closing, Dr. Wanninkhof summarized that:

- The North Atlantic is a prime region to implement an improved ocean carbon research strategy and a critically important region for carbon sequestration.
- There is a solid foundation upon which to build and substantive base knowledge is available. A well-developed research community and sustained observation efforts and ample resources are available to make the next step and execute the work that is of societal importance.
- There are ocean-based tools (i.e., autonomous sensors and platforms), remote sensing (i.e., CSA NASA and ESA) and modelling (including machine learning/artificial intelligence) capabilities that can be used to address and scale the problem.
- Coastal systems in a changing climate are subject to changes due to ice melt, seasonal ice cover and changes in convection depth, yet it is not clear what impact those changes will have on carbon uptake. Change in coastal systems is a foundational question that needs to be addressed by research programs to better understand the overall carbon cycle.
- Temperature changes are very different between land and the ocean, creating very sharp gradients that are going to have an impact on both atmospheric and ocean physics. Understanding these dynamics is important to understand and predict the effects of climate change in the coastal zone.

Current state of modelling activities at the regional scale to help produce integrated estimates of the carbon sink, and to make predictions/projections of future changes in the sink

"Current models are suited for developing mechanistic understanding and are not designed for carbon accounting and making accurate estimates of exactly how much carbon exchanged and for making accurate projections."

Dr. Galen A. McKinley, Professor of Earth and Environmental Sciences at Columbia University and the Lamont Doherty Earth Observatory, together with Ms. Lauren Moseley from Columbia University, presented the current state of modelling activities in the region. They elaborated on using regional-scale models to understand the current and future state of the North Atlantic carbon sink.

Dr. McKinley's summary of current modelling capabilities is presented in table 1 below. The four classes of models are categorized on spatial coverage, resolution, coupled vs. hindcast and forward vs. data assimilation. Dr. McKinley noted that the models have similar physical resolution between coupled and hindcast models, but the biogeochemistry of these global models is not optimized for the North Atlantic. She further emphasized that physical and biogeochemical structure matters significantly to model results when talking about the carbon system.

Table 1: Summary of current modelling capabilities

	Forcing	Physical resolution	BGC	Utility	Example N. Atlantic references
Earth System Models (ESM) (e.g. CMIP5/CMIP6)	Coupled	~0.5-2°	Globally optimized	Predictive capabilities	Lavoie et al. (2019) Lebehot et al. (2021)
Global Hindcast models (e.g. GCB)	Reanalysis	~1°	Globally optimized	Forced with observed meteorology	Friedlingstein et al. ('21) Fay & McKinley (2021)
Regional models (e.g. ASTE-BGC)	Reanalysis	~0.1-0.5°	Regionally optimized	Biogeochemical mechanisms	McKinley et al. (2018), Moseley et al. (in prep)
Coastal models (e.g. ROMS)	Reanalysis	~0.05-0.1°	Locally optimized	Coastal/shelf processes	Fennel et al. (2006), Laurent et al. (2021)

Dr. McKinley noted that various decisions need to be made to put together an ocean model, including consideration of the model grid, whether the model is going to be global or regional, the number of grid points to include, and model forcing. She mentioned the following points:

- Equations need to be written to represent the all physical, chemical and biological processes.
- A hindcast (reanalysis data forced) model can be quite different from Earth System Models (ESMs) because hindcast models forced with observations cannot make projections or predictions and also coupling with atmosphere in the ESM means that the model output should be statistically consistent with observations, but is not designed to replicate any actual years as they were observed in the past.

It was noted that data assimilation starts with all the machinery of an ocean model, but then adds significant technical work to bring the model state toward the observations. In some approaches to data assimilation, such as Kalman filters, the model can be pulled quite close to observations, but with unphysical state changes (i.e. breaking physical rules such as conservation of mass). Unphysical losses of mass would be very problematic if the modeling objective is to determine a carbon budget. Dr. McKinley noted that she is in favor of the adjoint approach, which does not fit the data as closely, but does maintain conservation of mass and respects all the physical equations of the model.

Dr. McKinley mentioned that ESMs demonstrate the future sink changes with emissions and that the North Atlantic will exhibit intense changes[4]; therefore, we need to develop in-depth understanding to diagnose and project these changes accurately. Additionally, she suggested that there needs to be more work to improve models so that they align better with observations. Dr. McKinley noted that studies investigating the difference in performance between regional and ESM models show that regional models perform better than ESM, when comparing the results to observations of salinity, temperature, chlorophyll and nitrate. It is also important to note that all regional models require boundary condition forcing from EMSs or other models. Furthermore, model performance compared to observations can vary depending on the variables being investigated. She provided the example that a model that compares well for observations of temperature, does not necessarily indicate that the model will perform well when compared to observations of salinity or chlorophyll. Availability of observations to feed these comparisons is important, and more work is needed to better understand how models can capture observed trends.

Dr. McKinley indicated that ESM resolution is not a proxy for skill[5]. Studies on observed mean fluxes using hindcast ocean models on global carbon budget show that improvements to ocean models are needed to better represent ocean carbon uptake processes[6]. She noted that ESMs need to be used for the projection of future changes in the carbon sink. Regional or coastal models can be run with ESM boundary conditions for projection of large-scale future changes in the carbon sink.

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[4] Ocean carbon uptake under aggressive emission mitigation (https://bg.copernicus.org/articles/18/2711/2021/bg-18-2711-2021.pdf)
[5] An observation-based evaluation and ranking of historical Earth system model simulations in the northwest North Atlantic Ocean (https://bg.copernicus.org/articles/18/1803/2021/)
[6] Observed regional fluxes to constrain modeled estimates of the ocean carbon sink (https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2021GL095325)

Dr. McKinley emphasized the importance of knowing the initial state, which is not perfect in current models for near-time prediction. Therefore, current work is ongoing to use a machine-learning approach to make predictions.

Summarizing the current state of modelling activities at the regional scale in the North Atlantic for integrated estimates of the ocean carbon sink, Dr. McKinley mentioned the following:

- ESM are global and developed for many purposes, leading to trade-offs
- global hindcast models are similar to ESM, but are ocean only and forced with observed meteorology
- regional and coastal models tend to have better biogeochemical fidelity, but sustainability of such models is a challenge because the resources are provided by individual PIs
- data assimilation is a great approach which improves physics, but is not yet being routinely applied to BGC due to the lack of geochemistry observations, adequate knowledge of the driving equations, and the high level of non-linearity

Identification of current players and their activities in the ocean carbon domain in the North Atlantic

"A step change of investment is necessary to address the current observations gaps and future observation needs in the North Atlantic."

Dr. Richard Sanders, the Director of the Ocean Thematic Centre in the Integrated Carbon Observation System (ICOS) discussed the major agencies and activities in the ocean carbon domain in the North Atlantic. Noting the importance of the North Atlantic in absorbing a large amount of anthropogenic carbon, Dr. Sanders described the impacts that the future activities (such as net-zero initiatives) will have on our understanding of the North Atlantic carbon sink and reaffirmed that observing the North Atlantic should be a collaborative international enterprise, stimulating additional scientific effort and sharing of expertise among nations to advance observation activities to fill in knowledge gaps.

Dr. Sanders stated that the North Atlantic is arguably the best observed ocean basin, yet it is not sufficiently observed to provide the relevant information to understand the carbon cycle. He noted that the North Atlantic has massive spatial (i.e., horizontal) and temporal variability in carbon uptake and there are very important observing systems currently in place to quantify both the horizontal and vertical carbon transfers. Some of the observing methodologies currently in place include:

- GO-SHIP (hydro section)
- OceanSITES (long term time series stations)
- moored arrays
- ship-based time series
- surface ocean observing systems
- autonomous systems (i.e. gliders, floats)
- synthesis actions, sediment traps
- large scale fisheries surveys
- process studies (primarily for model improvements)
- satellites (observe ocean surface)

Noting that observing the North Atlantic is an international effort carried out by many nations, Dr. Sanders mentioned that:

- Canada
- the United States of America
- the United Kingdoms
- Norway
- France
- Germany and
- Spain

are amongst the key players in progressing observation efforts in the North Atlantic. Dr. Sanders elaborated on existing carbon observing efforts in the North Atlantic using a number of current and planned near future examples and highlighted the notion that the value of these efforts can be greatly enhanced when brought together at a global and/or regional level and linked with other studies, models and activities. He noted that a North Atlantic Carbon Observatory (NACO) could fill the need to better coordinate, manage and communicate North Atlantic observation activities.

Considering that studies on global carbon have shown that there is a mismatch between model output and observed data, meaning that the data we collect are not necessarily efficient or adequate for the models that require them, Dr. Sanders noted that this mismatch is becoming more prominent at a time when it is critical to understand the ocean carbon uptake clearly. He mentioned that it is not clear what is causing this mismatch, but it could be due to lack of data or biased sampling or other reasons we have not yet determined. Additionally, we see that while we have the ability to observe the ocean, observation capacities are not deployed consistently for extended periods of time, leaving gaps in various years of observation. Concluding the presentation, Dr. Saunders provided the following recommendations:

- There is an enormous effort going into observing and understanding the North Atlantic Ocean carbon sink, yet there is a gap between the observations being collected and their relevance to advancing the understanding of the ocean carbon sink in the North Atlantic.
- It is not clear what future variability is expected in the North Atlantic Ocean carbon sink as a result of modifications to emissions pathways, and the ability to define the variability is declining due to the lack of connection between what is being observed and our general understanding of the carbon sink.
- Efforts to better coordinate observations so they contribute directly to our understanding of the North Atlantic carbon sink and how future modification in emissions will impact it are paramount.

- While there are many groups and activities related to ocean carbon, there is no single place that coordinates or integrates the various activities related to North Atlantic, or even global carbon observing.
- A North Atlantic Carbon Observatory (NACO) can fill this crucial void in arguably the most important place and serve as a global exemplar.

Breakout sessions

Breakout sessions were arranged under three themes to address specific questions to identify gaps, challenges, and opportunities, in research, modelling, observing, and monitoring in the North Atlantic carbon pump.

Theme 1: What current gaps and opportunities in carbon knowledge/research, observations and monitoring require a coordinated and comprehensive carbon program in the North Atlantic?

Dr. Doug Wallace from Dalhousie University, Canada led this session. Dr. Wallace conducted a pre-workshop survey of the participants in order to gain an understanding of knowledge gaps and key issues of carbon observing and monitoring in participants' home countries. The results of the pre-workshop survey can be found in Annex 5 and demonstrate the numerous common issues among the respondents. The survey identified carbon measurement density as a need for major improvement, with most other issues showing room for improvement. Sustained access to infrastructure such as ship time was identified as a major impediment. There also appeared to be a few phenomenon that are currently lacking observational data, such as:

- the skin effect (near surface gradients)
- interannual/sub-decadal variability
- the effect of deep mixing on the air-sea flux
- discrepancies between model results and observational data

What aspects of North Atlantic monitoring require international collaboration?

During the discussion, participants worked to identify knowledge gaps that limit the ability to constrain estimates of current carbon exchange in the North Atlantic. Overall, the group identified major knowledge gaps in fundamental understanding of the North Atlantic carbon pump. In general, the participants identified an overall lack of long-term monitoring studies that would help to answer known knowledge gaps and perhaps identify some additional unknowns. Additional and more specific knowledge gaps included the lack of understanding of the connection between organic and inorganic carbon, the 'alkalinity issue', and the discrepancy of salt conservation in physical models. Finally, there was a lot of discussion about the knowledge gap pertaining to interactions with the carbon pump, such as:

- land-sea interactions
- the coastal-open ocean link

- mixed layer depth
- surface-atmosphere interactions
- deep mixing exchange
- circulation
- overturning frontal systems
- the transport of fresh water and heat

What impediments are holding us back? How could we overcome them?

In the discussion, participants pointed towards barriers to international collaboration, including:

- infrastructure
- human resources
- bureaucratic barriers
- governance
- funding

Participants noted the importance of sustained monitoring, recognizing that there are examples of good international coordination (e.g. JGOFS, WOCE) but noted that they are few and involved enormous effort. It was further noted by participants that international coordination among countries in regard to scientific priorities is a historically complex issue. However, there are existing examples, such as the European Organization for Nuclear Research (CERN) that could be used as possible models to follow. It was discussed that some of these issues such as infrastructure could be addressed through ocean observing technologies appropriate for ocean carbon observing and monitoring such as more autonomous vehicles (gliders, Argo floats) and shared international vessel use Continuous Plankton Recorder Surveys (CPR), Global Ocean Monitoring and Observing (GOMO).

Although specific discussions around funding were beyond the scope of the workshop, participants commented on issues related to funding as an impediment to sustained observations, including that timing is a critical factor among nations in regards to election and funding cycles, noting that sustained funding is more important than more funding for individual observations. Additionally, individual nations tend to make funding decisions in isolation, rather than collaborating on funding with neighboring nations. Participants noted a need to coordinate and collaborate internationally.

Theme 2: What gaps and opportunities in carbon modelling require a coordinated and comprehensive carbon program in the North Atlantic?

Dr. Diane Lavoie from DFO led this session and introduced the following questions related to the modelling of ocean carbon, with a focus on the North Atlantic.

What are current modelling capabilities in the North Atlantic and how to improve model outputs and reduce uncertainties?

Participants noted that there are many questions to be answered, for example, what kind of modelling systems should we focus on, with what features, and what degree of complexity. It was noted that there are a range of models available, with various scales e.g., ESMs, regional models, and data assimilative models. Contributions are possible from the full spectrum of models being developed, e.g., driving of regional models by ESMs, use of ESMs for interregional comparisons, and use of higher-resolution regional models to address more localized processes.

Participants highlighted a number of applications and opportunities, such as the use of models to fill gaps in areas where observational data are sparse, informing observational strategies, and understanding processes.

Resolving the mesoscale circulation, with a particular focus on eddies, was noted as being important towards understanding the effects of circulation on primary production and on the variability of carbon concentrations in the North Atlantic. Participants also highlighted that better defining the remineralization length scale (sinking rate versus remineralization rate of organic matter) would help get the appropriate biogeochemical conditions on the vertical scale and in the different water masses.

Discussions concluded that there are various modelling needs requiring multiple approaches in areas such as:

- mesoscale processes
- high-quality data assimilation systems
- combining physical and biogeochemical models
- overall collaboration and coordination in model development

However, it was suggested that ESMs should still be a priority, since they are the ones coupled with the atmosphere, and their output can be downscaled to force regional models. It was noted that it is key to have a targeted and coordinated approach for the development and downscaling approach of regional models.

What are the key observations required to validate and improve model processes, and how can models inform observational strategies?

Participants agreed on the importance of sustaining existing long time series of observations, noting that repeated observations are needed to resolve processes that occur over longer time scales or occur in more dynamic regions (e.g., coastal areas), and to establish uncertainties. Due to limitation of resources, it was suggested that it is more important to sustain the existing observation network to have long, repetitive, time series rather than add new types of information. However, if resources were sufficient to add additional observations, the emphasis should be made on rate measurements (such as remineralization rates, primary production, etc.). The number of such observations is inadequate and needs to be expanded, noting that the models can be used to inform observational strategies with different techniques to identify over-sampled or under-sampled areas.

The importance of increasing the number of observations just below the pycnocline was also noted (majority of current available observations are at the surface). There may be opportunities for greater use of Lagrangian tools (which can be (partially) validated with floats) that can help identify processes and source regions of biogeochemical tracers and their evolution.

How can regional modelling activities across institutions be coordinated to maximize their value?

Participants suggested that it is straight forward to compare ESMs in the Coupled Model Intercomparison Project (CMIP) experiments, because they have well-defined protocols and common outputs. However, they noted that regional models are hugely different, and recommended that guidelines could be developed for some aspects (e.g., standardized output, targeted goals, like what controls the rain ratio, how does it vary) that could lead to an intercomparison exercise. Participants noted that there can be a lack of transparency in model design and consequently identified a need to share model design between modelers. An initial step could be to start developing a model inventory and identify the groups interested in model intercomparisons. It is also important to identify an organization that could help with these tasks and develop a guide.

The participants agreed on the importance of coordination of modelling activities, especially in regard to things like:

- the use of common approaches
- standards
- protocols and output

- model intercomparisons
- knowledge exchange

Further discussion is needed to identify collaboration mechanisms on a local, regional and global scale. A feasible initial approach suggested was to start with a small group of interested countries, working under the umbrella of a parent organization.

What gaps and opportunities in carbon modelling require a coordinated and comprehensive carbon program in the North Atlantic?

Participants identified:

- data availability, especially below the mixed layer, at time scales appropriate for various modelling systems (e.g., near-real-time)
- data processing (quality control) into products (average and gridded) suitable for model evaluation, as primary gaps

Participants agreed that there is an opportunity for collaboration with the observing community to transform the data into usable products, noting that a North Atlantic program would be an opportunity to strengthen the collaboration and coordination between the observing community and modelers to leverage/optimize efforts. This includes collaboration on modelling activities, as well as between modelers and observers (e.g., resolution, system design, quality control).

What is the pathway to developing data-constrained analyses and near term (seasonal to decadal scales) predictions of the North Atlantic carbon sink?

In order to achieve the predictability of carbon in the North Atlantic, we need to achieve the predictability of other variables, such as nutrient concentrations, phytoplankton biomass, and primary production. Increasing the amount of measurements of biogeochemical parameters at relevant time scales in the thermocline is key to achieving the predictability of these variables.

Further discussion focused on the timeliness of data delivery, which depends on the time scales of the predictions. The scale of the model projection determines how fast observations should be available to modelers to prepare the best initial state for the projections. Near-real time data delivery is required for near-term projection; delayed-mode data (obtained a few months after collection) is adequate for decadal projections, which is important for understanding the carbon sink.

Participants agreed on the importance of improving ESMs for understanding the North Atlantic, dynamic processes in the region (e.g., the sub-polar gyre, the seasonal cycle) and the importance of ocean-atmosphere-ice coupling. However we need to use a combination of approaches and it was noted that statistical models are a complementary tool (for short term interpretation) that can produce information on the correlation among different processes.

Theme 3: Where are the opportunities to collaborate within the international community and how can we move forward to enhance coordinated approach?

Dr. Anya Waite, Chief Executive Officer (CEO) and Scientific Director of the Ocean Frontier Institute (OFI) and the co-chair of the Global Ocean Observing System (GOOS), led the discussion on opportunities to collaborate within the international community and to make progress in a coordinated approach.

How do we coordinate what is already there?

Dr. Waite acknowledged that there has been a huge investment in recent years in enhancing ocean observation research and technologies in the North Atlantic. While the participants acknowledged that more observations are needed to resolve temporal and spatial gaps, they agreed that there is more benefit in pulling observations together, coordinating and making them useful to enhance understanding and to deliver information that can inform policy and decision-making. Participants stated the need to formulate and answer clear questions that would help in shaping the North Atlantic Carbon observing/monitoring and coordination efforts, such as:

- what do we want to achieve?
- what areas need better coverage and observations?
- what temporal scale are we aiming for to predict change?
- but mostly, what is the societal value of establishing a NACO?

They noted that it is crucial to get the needed support of policymakers and nations. Given the vast geographic area that a NACO would cover, it was suggested that regional networks might be helpful in defining needs and the stakeholders with whom we should cooperate. Participants were of the view that a NACO should not be a 'business as usual' project, but rather a pilot project through which the ocean could be observed in a smarter way, bringing a step-change in the function and impact of ocean observation. Participants agreed on the importance of learning and building on the outcomes of other initiatives, and on promoting shared infrastructures, knowledge, data management and coordination tricks to do things differently this time.

It was noted that to date, despite the success of major observation initiatives and models, there is no systematic global framework that quantifies the ocean carbon sink, tracks its changes, and resolves the mechanisms behind it. At the moment, there are many large efforts, many goals, requirements and methods which are uncoordinated and makes it difficult to visualize the complete picture and understanding of the global oceans. It was suggested that a NACO could be the first operational system to deliver this information, and to communicate it in a systematic and standardized way to final users (i.e. policy makers, general public). The participants agreed that work in the North Atlantic Ocean should consist of multi-faceted approach, including increased and better observations that can improve the performance of assimilation models to understand the drivers of change, as well as to understand the past, present and future state of the North Atlantic. We need to forecast adequately.

Although North Atlantic Carbon activities would focus on a specific region (i.e., North Atlantic Ocean), participants considered this to be a reasonable exemplar by serving as a regional pilot operational system that is linked to global-scale systems. The learning and defined best practices gleaned from this pilot program could inform a system that could be applied broadly to help understand the global ocean. It was noted that the more we learn during the establishment of NACO, the more opportunities will be available to scale up globally and/or in several regional "hot spots".

How to deliver/communicate our data to be used by policymakers?

Participants agreed that the ocean carbon community has an opportunity to better communicate the importance of ocean carbon and the data that could be easily used and comprehended by policymakers. Consequently, there is a need to make NACO's outcomes more comprehensible, appreciable, and useful to policymakers. It was recognized that a NACO has to have societal benefits that the ocean science community can use to better communicate the need for a sustained ocean carbon program in the North Atlantic and globally and this could be achieved by linking NACO to marine ecosystem services, resources, coastal areas, etc. Participants noted the importance of societal buy-in, for example, the reason to maintain long temperature-records to serve our ocean observation, monitoring and decision-making efforts is because people are interested in forecasted weather, due to its impact on their own daily lives. It was suggested that in order to create buy-in, there must be coordinated efforts to educate different types of audiences on the benefits of ocean data and of understanding the North Atlantic BCP, by forecasting and describing what the expected changes mean to society. It was noted that a NACO could be used by countries to calculate ocean carbon uptake as they do for fossil fuel emissions. In order to look at the human impacts, we have to quantify the current situation. We need a baseline.

What might a coordination structure look like?

Participants recognized that there is a lot of ocean carbon work going on, but that it needs to be pulled together in a coordinated way and urged that a NACO be different from individual research studies, whose purpose is to carry out a short-term study and then publish the results, suggesting that a NACO should be a sustained operational system that can function for long-term benefits, not just for the short term (i.e. research papers). We need to work on a sustained ocean carbon observatory baseline, an infrastructure that is adequate to fulfill the different aspects that NACO would cover, from physical and biological oceanography to modelling and other socio-economic topics (carbon accounting, fisheries, etc.). Thus, it was suggested that it may be useful to advertise NACO as a regionally-owned system that supports science, carbon accounting, and resources (i.e. fisheries).

On the other hand, participants made it clear that society and policymakers should be more involved in the proposed operational system. Scientists should try to think out of the box (their business-as-usual tasks: science experiments and studies), and focus on identifying the important pieces that we need to clearly understand how the climate system is operating to try to answer questions of societal importance. Participants noted that there is no single entity that would be the sole driver of this, so collaboration is important.

What are the international organizations that we should be talking to at this point?

To help catalyze the discussion, Dr. Waite provided a few examples of international networks and organizations that could help fulfill the objectives of this theme in finding opportunities to enhance coordinated approach through collaborations with the international community. Participants agreed on the importance of engaging through non-traditional venues such as the G7, the High Level Panel for a Sustainable Ocean Economy, etc., which would help to improve NACO's visibility, ocean science coordination, and promote the ability to address societal needs. Moreover, participants stressed the need to distinguish between voluntary-driven networks/organizations and fully funded ones, as it was noted that a sustained observing system is what is needed, which therefore requires sustained momentum for an ambitious pilot project such as a NACO. It was noted that while there are many organizations available and contributing to ocean carbon activities, none of them offer a suitable coordination structure needed to advance a NACO. Participants suggested that some organizations are challenged by a lack of funding, while others do not reach out to all players in the ocean carbon field. Taking into consideration that there is no organization or network that is dealing with an operational ocean carbon system, some participants suggested the establishment of a new hub that could attract potential key actors and funders to speed up the process. Other participants suggested that we solicit the support of individual nations' ministries for initial planning, then establish and operate a NACO, with the help of GOOS. Participants also stated the lack of international coordination efforts in the topic of biogeochemical modelling, which would be a crucial issue to handle in a NACO as well.

What are the scientific, political, technical barriers to move forward with a coordinated approach?

Participants noted that few people are working on biogeochemical models and agreed that one area for improvement is in regard to better integrating observations into models, and thus creating a framework for model/observation feedback. This example could then be applied in other regions. However, they suggested that there is no coordination effort in modelling, in particular to address priorities areas regarding model quality or fine-tuning, or to write and publish collaborative papers. Also, it was noted that models might have weaknesses in detecting seasonal variability. So, we need to know what kind of observations are needed to make the assimilation models better. Participants noted that we have seen many projects on carbon topics, but we need more pilot projects to establish a coordinated system and that we need to talk about system operation, delivery and coordination. The existing networks/organizations are not working on system operational aspects (except for ICOS), and that's what may be required.

Plenary session

The objective of the plenary session was to discuss and identify the scientific elements, steps and activities needed to advance an integrated and comprehensive approach to an ocean carbon program in the North Atlantic, taking into consideration the current state, gaps and opportunities identified during the discussions on day one of the workshop.

Dr. Paul Snelgrove, (DFO Departmental Science Advisor, Associate Scientific Director of the Ocean Frontier Institute and Professor of Ocean Sciences and Biology at Memorial University of Newfoundland, Canada) led the discussions. Four ocean carbon experts joined as panelists:

- Dr. Stephanie Henson (Principal Scientist at the National Oceanography Centre (NOC) and Honorary Professor at the University of Southampton, UK)
- Dr. Brad de Young (Oceanographer at Memorial University, Canada)
- Dr. Maria Hood (Head of the EU Office of the G7 Future of the Seas and Oceans Initiative (FSOI) Coordination Centre and the G7 Action Coordinator for the EU4OceanObs)
- Dr. Andrew Watson (Royal Society Research Professor and the Head of the Exeter Marine and Atmospheric Science research group, UK)

The following questions were discussed:

Q1: Climate change is widely recognized as a societal issue, but ocean carbon is not seen as a societal issue. How can we make ocean carbon a societal issue?

There is a communication gap in delivering scientific findings to policymakers and general public. It may be beneficial to have professional communication specialists, social scientists or theory of change specialists facilitate the dissemination and translation of the science into a meaningful message directly to end users, including policy makers and the general public. The scientific community collectively needs to speak more to the societal needs and less about science projects. Oceanographers need to be seen as service providers (e.g., medical personnel) directly contributing to the society.

Q2: What must we measure and how well positioned are we to take those measurements?

The Global Carbon Project report in 2021[7] estimated ocean CO_2 uptake based on the average of observed and modelled rates. In 2010 the CO_2 uptake from the atmosphere measured using

[7] Global carbon budget (https://www.globalcarbonproject.org/carbonbudget/index.htm)

traditional methods was considered to be accurate to within ± 10% , but current precision is much lower, due to the lack of observations compared to 2010. Thus, there is a need for sustained carbon uptake observations using a standardized method. Further, it is required to have 3-dimensional observations of the biogeochemistry, preferably facilitated autonomous technology (i.e., gliders, autonomous vessels) deployed in in locations inaccessible to research vessels, with the data/measurements from research ships as a reference. An important point is that more development is needed before we can rely on the data from sensors; many of them are still prototypes that require further validation before they can replace ship-based measurements.

Q3: If the required money is available today, is the technology there yet?

Panelists fundamentally agreed that some platforms and sensor technology are available, although they might not currently provide the necessary geospatial coverage (e.g., more Argo floats required to cover the North Atlantic basin). However, there are some limitations in current technology when considering some research questions, such as defining the mechanisms underlying the changes in biological carbon pump. Current technology is also not fully compatible with the extreme environmental conditions in the north Atlantic (i.e., autonomous platform operation under winter conditions). To address this challenge, ships of opportunity could be leveraged to expand the observational capacities, and new technologies such as sail drones for pCO_2-type ocean surface observations could provide high quality data that could advance the state of knowledge. Parallel progress has to be made in all areas i.e., research, technology, science, etc. An example for such a parallel-run initiative is the European Commission funded projects EuroSea[8] for research, Blue Cloud[9] for data management, and TechOceans[10] for technology and sensor development, where progress is made in all areas simultaneously. The sensor technology development is going to be the key to meeting the goals of a pilot North Atlantic observing system.

Sustainability is another important element for a successful observing programme in the North Atlantic. The National Meteorological Service is a good example of how to create a sustainable observing system. Sustained or operational funding is obtained on a standard criterion of having operational systems that are automated with real-time data distribution, where data do not have to pass through the hands of scientists before they are released. It was suggested that the oceanographic community needs to move towards a similar path to develop a sustainable system.

[8] EuroSea (https://eurosea.eu/)
[9] Blue-Cloud (https://www.blue-cloud.org/)
[10] Technologies for Ocean Sensing (https://cordis.europa.eu/project/id/101000858)

Q4: What needs to be done to close the spatial gap between observation process studies and models?

Ingesting inaccurate data into the models can produce inappropriate and incorrect outcomes and conclusions. There should be an effort ensure that the data feeding the models are quality-assured and controlled. The oceanographic field needs to move towards a process similar to that employed by the atmospheric community where there is particular focus on model development and intercomparison, which then leads to interaction with data to fix the various errors that may exist in the data (or the models). In order to understand how to improve the use of data for models, things like expected model performance, spatial and temporal scale, and model representation need to be pre-defined and understood. Prioritized efforts should include resourcing the groups that can address these questions effectively. The best way forward is to have a range of model types with various scales and selecting appropriate model for the question.

Q5: Keeping in mind the identified need for coordination between disciplines; coastal and offshore, atmosphere and ocean, organic and inorganic, surface and subsurface ocean, biologists and physicists, what would a key component of a coordinated structure look like?

The governance structure for this type of coordination would need a top-down approach, with stronger links to an intergovernmental framework. Research funding in most countries is granted separately from funding for sustained monitoring. Both research and monitoring are important, and research can be nested within a more sustained monitoring system. A tropical mooring array is a good example of a sustained monitoring system that is also used for process studies. A governance structure should include a combination of research and monitoring. There are a few existing coordination structures, often with minimal funding such as AtlantOS[11], the Galway Agreement that works through the All-Atlantic Ocean Research Alliance (AAORA)[12], and the Integrated Carbon Observing System (ICOS)[13], which, could potentially be leveraged to develop a pilot experiment for the North Atlantic. The pilot project should address governance, coordination structure and a resource strategy to develop a sustained monitoring system.

The International Ocean Carbon Coordination Project (IOCCP), which is part of the GOOS biochemistry panel, was primarily developed to coordinate the ocean carbon observations taking place in different programs and systems. It has been around for a long time, has an honourable history, and is supported by scientists. IOCCP does not do operational coordination; however, it is

[11] AtlantOS (http://atlantos-ocean.org/index.html)
[12] All-Atlantic Ocean Research Alliance (https://allatlanticocean.org/whoweare)
[13] Integrated Carbon Observation System (https://www.icos-cp.eu/)

a suitable place for nations to come together and agree on many aspects, like best practices for a pilot project. Having linkages to GOOS would make it possible to address member states directly, through IOC, the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP) to obtain their buy-in.

Some panellists also suggested initiating the pilot project in the North Atlantic and then building the global governance structure in parallel, similar to the approach taken by the Argo program. A focus at the basin scale would be the right approach to initiate this effort, because bordering nations could immediately concentrate on the issues of concern and interest to them.

Gaps in coordination between the observation and modelling communities are primarily due to issues of communication and mindset. Every model has a different structure, and it is difficult to understand model outputs without a good understanding of the model structure. Developing standards to describe model structure will help to resolve this issue. Introducing new traces into a complex earth system model is not feasible unless presented as a simple parameterisation on a good quantity of observations. Observers and modellers need to collaborate and communicate to understand models, generate models that are closer to observations and understand why model outputs are different from observations. Another challenge is the level of support needed to integrate new measurements into the models and evaluate their effectiveness. The base level of operation of the models has not happened yet and is still a research endeavor. Compared to observing community groups, there is a lack of well-organized groups in modelling community for better coordination within the community to make progress in areas such as standard developments. There is also a shortage of knowledgeable people to do the work. There is a need to arrange training programmes to produce more skilled people.

It was suggested that current scientific approaches are compartmentalized into observations, research, modelling, etc., and that this needs to changed to a sustained system that examines the continuum of scientific questions as a whole.

Q6: National Science programs focus more on process. However, continuity and sustainability of observation is a challenge. Is there a balance or difference in approach needed to advance the needs of process studies and ongoing observation and modelling for that matter?

One current challenge that was identified is to define a program that continues from research through to operations along the value chain, along with technology readiness levels, where at some point the system evolves to qualify for sustained funding from national and international funders.

It was suggested that there needs to be focused research funding on issues of environmental concern in terms of the ability to address those issues, techniques and technologies (e.g., the European Union initiative Horizon 2050[14]). Although funding was beyond the scope of the workshop, it was suggested that any new funding structure must sit outside the standard science funding envelope, which is limited by the way science gets funded. Based on current experience, it was argued that a NACO governance structure should facilitate nations to contribute to a combined fund, so that they can achieve the societal values for which they are looking.

Q7: What are some concrete actions or steps required to scale up efforts solely from the science perspective, i.e., prerequisites, implementation steps, time scales, etc.? Is there a pilot phase or stepped-up approach that could get us from where we are to where we want to be? Does this need to be top down?

Participants suggested that a first step would be the development of a pilot program in the North Atlantic that includes autonomous platforms (i.e., BGC Argo floats, and gliders) to support the existing networks within the next year. A good approach would be to set up the NACO as a multi-year pilot project, with a focus on both research and monitoring.

Before adding more instruments, some panelists suggested looking at the delivery of existing observational data which are not optimally used at the moment. Streamlining the delivery of observations into data and information could be an initial step. Some panelists also supported the idea to organize a meeting/conference to increase the attention and awareness of ocean carbon on the planet and what it means to the general public. Clear and simple communication could mobilize the awareness, help the public to understand the ocean carbon sink, and create excitement in the community to contribute towards ocean-carbon-related activities.

Another approach that was brought forward was to identify a geographically-defined area to monitor and clearly demonstrate the ability to answer some common societal questions, before expanding the approach to be implemented in other ocean areas. This type of focused approach would simplify the process to identify proper equipment, observational parameters, spatial and temporal density, models, etc.to answer targeted societal questions.

Participants noted that knowing what questions need to be answered would help define the requirements of an observing system, suggesting that we need to work toward understanding the implications of ocean carbon uptake and the pathways to net zero. It was mentioned that we need to translate the information that we are gathering in a scientific sense into something that people

[14] 2050 long-term strategy 2050 long-term strategy (europa.eu)

will care about - i.e. communicating science to the public and policy makers. This message needs to be delivered in a creative way with the right terminology to provide an understanding of the pathways to net zero. Finally, it was agreed that we need a substantial, sustained initiative, building on the foundational pieces that have already proven themselves in pilot mode for the last 20 years. to demonstrate and shift things to a new level, with a giant leap into ocean carbon activities.

Q8: What would you take as the next step after today to move this North Atlantic Carbon initiative forward?

One of the initial requirements identified was to strive towards a sustainable program that builds on existing foundations that have a long and good history and are likely to be able to advance this effort. It was agreed that better communication with policy-makers, funders and the general public will be necessary to inspire action, change behavior and justify a sustainable program.

A number of simple tasks were put forward which could be prioritized to improve coordination of activities, starting with mapping and collating the existing knowledge and gaps in the areas of observation and research, boosting sensor and technology development, defining and understanding the specific questions to be answered. Parallel to these activities, efforts should be made to take a leap with a big investment in ocean carbon observation, research and modeling activities in the North Atlantic.

Another area of focus was on creating public awareness, through public forums focused on the North Atlantic carbon observations as a key to communicating the societal importance of this effort. It was suggested that the general public does not have enough understanding of the ocean's role in the global carbon budget, which has led to a lack of sustained programming and coordination. By raising this awareness, it is hoped that this will facilitate collaborations with partners to initiate the big investment needed for a giant leap in ocean carbon activities. It was also noted that more people and more training are required to properly analyze and interpret data and to generates products from them.

Summary of the discussions

Climate change is accelerating, and society will increasingly demand better answers and greater certainty than what is currently offered. This is a great challenge that will require resources, time, multidisciplinary and multinational efforts. Participants agreed that this should be addressed in smaller strides by focusing on single regions to build a better global picture.

All participants agreed on the important role of the ocean in climate change and particularly the North Atlantic, a global hotspot for carbon uptake. Consequently, the North Atlantic is sufficiently compelling as a location to initiate a major effort that will provide an exemplar for future initiatives in different regions.

There was a consensus that there is an increased recognition by society that climate change is a problem, and that the science to understand climate change is plentiful and of good quality. There is also good expertise, a foundation of activity to build on, and wide interest in science community. However, efforts remain largely uncoordinated, and there's a shortage of resources and people to carry out the tasks. Participants noted that there is a need for greater integration and coordination, not only to reduce redundancy, but more importantly to increase the impact of the work. There were also concerns about:

- sensor stability
- the availability of real-time observations
- the effective integration and use of data
- sustainability of observations in a large and seasonally-dynamic region that is changing over long time scales

This is an opportunity and a compelling reason for a giant leap in ocean observation and modelling to better understand how the North Atlantic Ocean contributes currently to the mitigation of climate change and, perhaps more importantly, to project how its contribution will change in the future.

Participants identified some high-priority measurements and knowledge gaps in carbon cycling, such as the role of calcification in determining alkalinity. They also stressed the critical gaps in understanding across physical, scientific and political boundaries, in particular between:

- coastal and offshore researchers
- atmosphere and ocean
- organic and inorganic carbon

- ocean biologists
- physicists and geochemists
- the challenges of working across international boundaries

Participants agreed that work can be done more effectively by integrating activities, not only to make the best use of available resources, but also to move quickly to address data and modelling needs and gaps and to reduce the unevenness of observations on both temporal and spatial scales. Participants agreed that we should aim big, with the ultimate goal being to revolutionize ocean carbon research, through the entire value chain, from sensor technology to process studies, data management, data modelling and governance.

Effective communication with policymakers, funding agencies and civil society was noted as being critical and needing drastic improvement. It was suggested that the first step would be to consult partners to create an ocean carbon governance working group and that the working group should explore a method to inventory and integrate existing programs and models, and identify strategies to address the critical gaps among existing programs. These gaps will likely include the scale and density of observations, the precise location of the initial phase, which technologies to use, and what a program should look like in terms of a big initiative that would attract attention.

Participants agreed that initial discussions should include considerations for the design of an observing system, the ways and investments required to move it forward, the expected outputs and what they would inform. Such a structure should include international efforts, multiple disciplines and both modelling and observational approaches.

Finally, this workshop has revealed that the extent of interest, willingness, knowledge and resources are already in place to build a better, integrated and systematic approach for an international North Atlantic ocean carbon program. Canada has demonstrated significant interest in advancing the understanding of ocean carbon in the North Atlantic and will continue the conversation toward understanding, observing and monitoring ocean carbon in the North Atlantic.

Annex 1: Workshop agenda

North Atlantic biogeochemical carbon pump

Virtual scientific workshop

Goals of the workshop:

Building on the work that has been done by the international ocean carbon community, advance an approach for an integrated ocean carbon program (research, modelling, observing, and monitoring) in the North Atlantic (using the North Atlantic biogeochemical carbon pump as an exemplar).

Day 1: (4 hours)

Objective: Identify gaps, challenges, and opportunities, in research, modelling, observing, and monitoring the North Atlantic carbon pump.

1. Welcome
2. Introduction and purpose of the workshop
3. Setting the scene — High level presentations to set the stage for:
    a) current state of open ocean carbon knowledge/research, observing and monitoring (including technologies) in the North Atlantic
    b) current state of modelling activities at the regional scale to help produce integrated estimates of the ocean carbon sink, and to make predictions/projections of future changes in the sink
    c) identification of current players and their activities in the ocean carbon domain in the North Atlantic
4. Breakout sessions — Building on previous discussions identify gaps and opportunities in the current regime

Theme 1. What current gaps and opportunities in carbon knowledge/research, observations and monitoring require a coordinated and comprehensive carbon program in the North Atlantic?

Questions:

- what/where/when do we need to research, observe, and monitor?
- what are the similarities and differences in North Atlantic compared to other ocean regions regarding carbon sequestration (i.e. to learn from the work done in other ocean basins)?

- what knowledge gaps limit our ability to constrain estimates of current carbon exchange in the North Atlantic?
- what are the technologies appropriate for ocean carbon observing and monitoring?
- what aspects of North Atlantic monitoring require international collaboration and who are the critical players needed to achieve success?

Theme 2. What gaps and opportunities in carbon modelling require a coordinated and comprehensive carbon program in the North Atlantic?

Questions:

- what are current modelling capabilities in North Atlantic and how to improve model outputs and reduce uncertainties?
- how can regional modelling activities across institutions be coordinated to maximize their value?
- what is the pathway to developing data constrained analyses and near term (seasonal-decadal) predictions of the North Atlantic carbon sink on seasonal to decadal scales?
- what are the key observations required to validate and improve model processes, and how can models inform observational strategies?

Theme 3. Where are the opportunities to collaborate within the international community and how can we move forward to enhance coordinated approach?

Questions:

- who are the key players (organizations) that need to be involved? (e.g. International Oceanographic Commission (IOC), Scientific Committee on Ocean Research (SCOR), International Commission for the Exploration of the Sea (ICES), various countries)
- what might a coordination structure look like in order to effectively engage diverse, necessary, and scattered ocean research, modelling, and monitoring communities?
- what are the key linkages to domestic and international activities that should be considered as part of the structure?
- what are the scientific, technical barriers to move forward with a coordinated approach?

5. Return to plenary (short debrief and outline for day 2)

Day 2: (3 hours)

Objective: Taking into consideration the current state, gaps and opportunities identified in day 1, discuss and identify the scientific elements, steps and activities required to advance an integrated and comprehensive approach to an ocean carbon program in the North Atlantic biogeochemical carbon pump.

6. Welcome to day 2
7. Report back from breakout sessions

Session leads from the 3 breakout sessions will report summary of the discussions

Theme 1. – key findings and observations

Theme 2. – key findings and observations

Theme 3. – key findings and observations

8. Discussions/questions of clarifications on breakout session findings
9. Plenary session - Facilitated discussion by DFO Departmental Science Advisor moving towards – the scientific elements, steps and activities required to advance an integrated and comprehensive approach to an ocean carbon program in the North Atlantic biogeochemical carbon pump.
   - What would be the key components of a coordinated effort, and what would a coordination structure look like? Critical elements might include:
     - Governance of science activities
     - Integration of modelling and observational themes
     - Dovetailing national science activities with international objectives to avoid duplication and achieve a sum that exceeds the parts.
   - What are concrete actions / steps required to scale up efforts (solely from a science perspective) (e.g. what are the prerequisites, implementation steps, time scale, etc?)
10. Summary of the workshop and next steps
    - Provide a summary of the workshop discussions that will be included in the final workshop report.
11. Closing

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Annex 3: Background

North Atlantic biogeochemical carbon pump

Virtual scientific workshop

December 15 and 16, 2021

(This is to provide additional context to prepare participants in advance of the workshop)

Introduction

The ocean stores 50 times more carbon than the atmosphere and soaks up more carbon than all the rainforests combined. Among all the oceans, the North Atlantic Ocean is 1 of the most intense anthropogenic carbon sink on the planet[15], accounting for approximately 30% of the global ocean CO_2 uptake.

Knowledge of the ocean carbon cycle is critical in light of the ocean's role in sequestering CO_2 from the atmosphere and for meeting goals and targets such as the UN Framework Convention on Climate Change (UNFCCC) Paris Agreement, the UN 2030 Agenda for Sustainable Development, and to contribute to the achievement of the UN Decade of Ocean Science for Sustainable Development (2021-2030)'s challenges. Human emissions predominantly explain increasing levels of CO_2 in the ocean, with fundamental impacts on ocean carbon cycling and ecosystem health[16].

A credible path forward on international climate targets and associated national policies, particularly Net Zero, must include the ability to measure and model the impact of ocean carbon on the global climate system. Climate change models hinge on understanding how the ocean and its living ecosystems influence carbon cycling. Although we understand ocean carbon uptake in a general sense, significant uncertainties in regional patterns of uptake, and in long term feedbacks

[15] The role of the ocean in global net-zero ambitions: Context for the North Atlantic Carbon Observatory (NACO) (https://docs.google.com/document/d/1_7-hwFZexd82wa0xxVij7tZdS_QfIc20Rm6RQqiDjTU/edit)

[16] Integrated ocean carbon research: a summary of ocean carbon research, and vision of coordinated ocean carbon research and observations for the next decade (https://unesdoc.unesco.org/ark:/48223/pf0000376708)

limit our ability to constrain uncertainty in climate change models[17]. Some areas identified by previous models as carbon sinks have recently been identified as major areas for carbon release back to the atmosphere, based on a modest number of new observations.

Global climate targets and their associated carbon budgets depend on reliable estimates of the future behavior of the ocean carbon sink, and its complex biological, geochemical, and physical components. Scaling up knowledge of carbon absorption in the North Atlantic and its Arctic gateways, crucial to the ocean's ability to absorb carbon, would be an important first step in quantifying a critical vector for net zero.

Canada, as a follow up to the 2021 G7 Environment Ministerial, and G7 Leaders Summit Nature Compact, will convene this scientific workshop between leading international scientific, and technical experts to examine the state of knowledge of the world's most important carbon sinks, and the scientific approaches now used to measure, monitor and model carbon cycles/fluxes in the North Atlantic in order to advance approach an integrated ocean carbon program (research, modelling, observing, and monitoring) in the North Atlantic using the North Atlantic Biogeochemical carbon pump as an exemplar. This workshop will build on work done over the last decade by the international ocean carbon community.

Background

Based on detailed scientific assessments, international experts urge the global community to achieve net-zero Green House Gases (GHGs) emissions by 2050 in order to meet the Paris Agreement's goals, and to avoid potentially dangerous climate impacts (IPCC, 2021). To meet global climate targets, the UN has launched a "Race to Zero Campaign" (UNFCCC), constituting the largest alliance committed to achieving net-zero carbon emissions by 2050 at the latest, including almost 130 countries (who have now set or are considering a target of reducing emissions to net-zero by mid-century) and 'real economy' actors (cities/regions, businesses, biggest investors, and Higher Education Institutions) (Net Zero Tracker | Energy & Climate Intelligence Unit (eciu.net)). Also, several nations including Canada, adopted 2050 net zero plans, including long-term climate-neutral strategies.

[17] Canadell et al. (2021), Global Carbon and other Biogeochemical Cycles and Feedbacks. In: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

The Canadian Net-Zero Emissions Accountability Act, introduced in Parliament on November 19, 2020, will formalize Canada's target to achieve net-zero emissions by the year 2050, and establish a series of interim emissions reduction targets at 5-year milestones toward that goal, soliciting the support and engagement from all parts of society, including provinces, territories, Indigenous Peoples, youth, scientists, and businesses (Net-Zero Emissions by 2050 - Canada.ca).

At the May 2021 G7 Climate and Environment Ministers' Meeting, the minister of Environment and Climate Change (ECCC) noted Canada's intention to host a scientific and technical workshop on the North Atlantic biogeochemical carbon pump. The minister of Fisheries, Oceans and the Canadian Coast Guard, at the Commonwealth Secretariat's Blue Reset event for World Oceans Day 2021, also made a commitment to convene leading scientific and technical experts in the coming months to discuss scaling up knowledge and monitoring of the North Atlantic biogeochemical carbon pump. Fisheries and Oceans Canada (DFO) has convened a Steering committee, with members from DFO, Environment and Climate Change Canada, the G7 Future of the Seas and Oceans secretariat, Ocean Frontier Institute (OFI) and the Global Ocean Observing System (GOOS) to deliver the scientific workshop.

The scientific workshop will take place virtually for 3-4 hours each day on December 15 and 16, 2021.

Overall goal of the workshop

Building on the work that has been done by the international ocean carbon community, advance an approach for an integrated ocean carbon program (research, modelling, observing, and monitoring) in the North Atlantic (using the North Atlantic biogeochemical carbon pump as an exemplar).

Scope of the workshop

The scope of the workshop is to advance a roadmap for an integrated ocean carbon program by examining:

- the state of science and understanding with regards to the biogeochemical and physical carbon processes using the North Atlantic biogeochemical carbon pump as an exemplar
- the methodologies, opportunities and knowledge gaps for quantifying, monitoring, and modelling the North Atlantic biogeochemical carbon pump
- the links to domestic and international research activities and knowledge already in place and planned

Questions to be addressed/discussed at the workshop

1) what is the current state of open ocean carbon knowledge/research, modelling, observing and monitoring (in-situ and satellite) in the NA and what are the gaps to monitor and predict it in the future.
   - e.g., what / where do we need to research, model, observe and/or monitor
2) who are the players and what are they doing? Where are the opportunities to collaborate and how to enhance and coordinate the existing suite of carbon observing and synthesis projects?
   - e.g., which international parties and partners could contribute (and how) to the design and delivery of the program/observatory?
3) what technologies are currently being employed and what new technologies could enhance observations and analysis?
4) what key components would comprise a coordinated "pilot" effort?
5) what are concrete actions / steps required to scale up efforts (solely from a science perspective)
   - e.g., what are the prerequisites, implementation steps, time scale, etc.?

Pre-workshop reference materials

Here is a (non-exhaustive) list of scientific material on ocean carbon:

- OFI scoping document
- GCOS Status Report has good text re. motivations, critical gaps
- Framework for Ocean Observing - requirements/user driven needs for ocean observations (and prediction)
- an example of in depth execution of the FOO, driven by user/policy needs,
- integrated ocean carbon research: a summary of ocean carbon research, and vision of coordinated ocean carbon research and observations for the next decade
- Global Carbon Project (GCP)
- JPI Oceans scoping workshop on Carbon

Annex 4: Steering committee

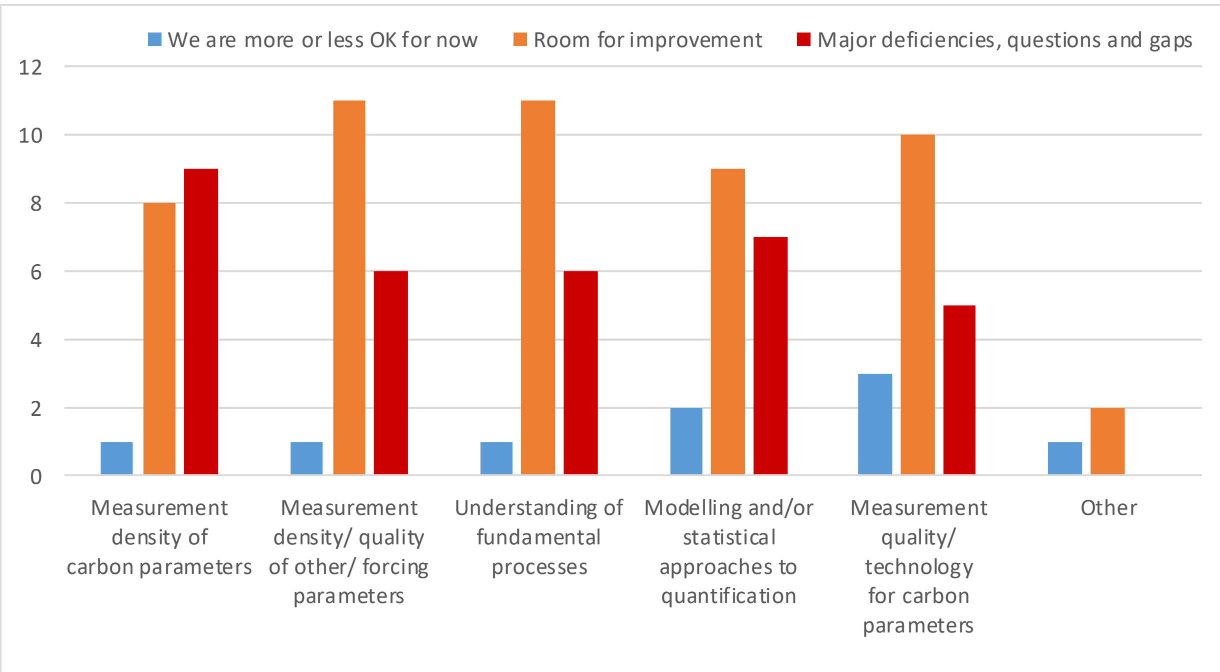
Fisheries and Oceans Canada (DFO) has convened a steering committee to deliver the scientific workshop. Here is the list of members of the steering committee and their affiliations.

Name	Affiliation
Dr. Andrew Watson	U of Exeter
Dr. Angela D. Hatton	NOC
Dr. Anya Waite	OFI/GOOS
Dr. Douglas Wallace	Dalhousie University
Dr. Katy Hill	NOC
Dr. Kumiko Azetsu-Scott	DFO
Dr. Lisa Miller	DFO
Dr. Maria Hood	Mercator Ocean International
Dr. Neil Swart	ECCC
Dr. Paul Snelgrove	MUN/DFO
Dr. Sophia Johannessen	DFO
Mr. Andrew Stewart	DFO
Mr. Keith Lennon	DFO
Ms. Champika Gallage	DFO

Annex 5: Pre-workshop survey results breakout group 1

Pre-workshop survey results on "what current gaps and opportunities in carbon knowledge/research, observations and monitoring require a coordinated and comprehensive carbon program in the North Atlantic?"

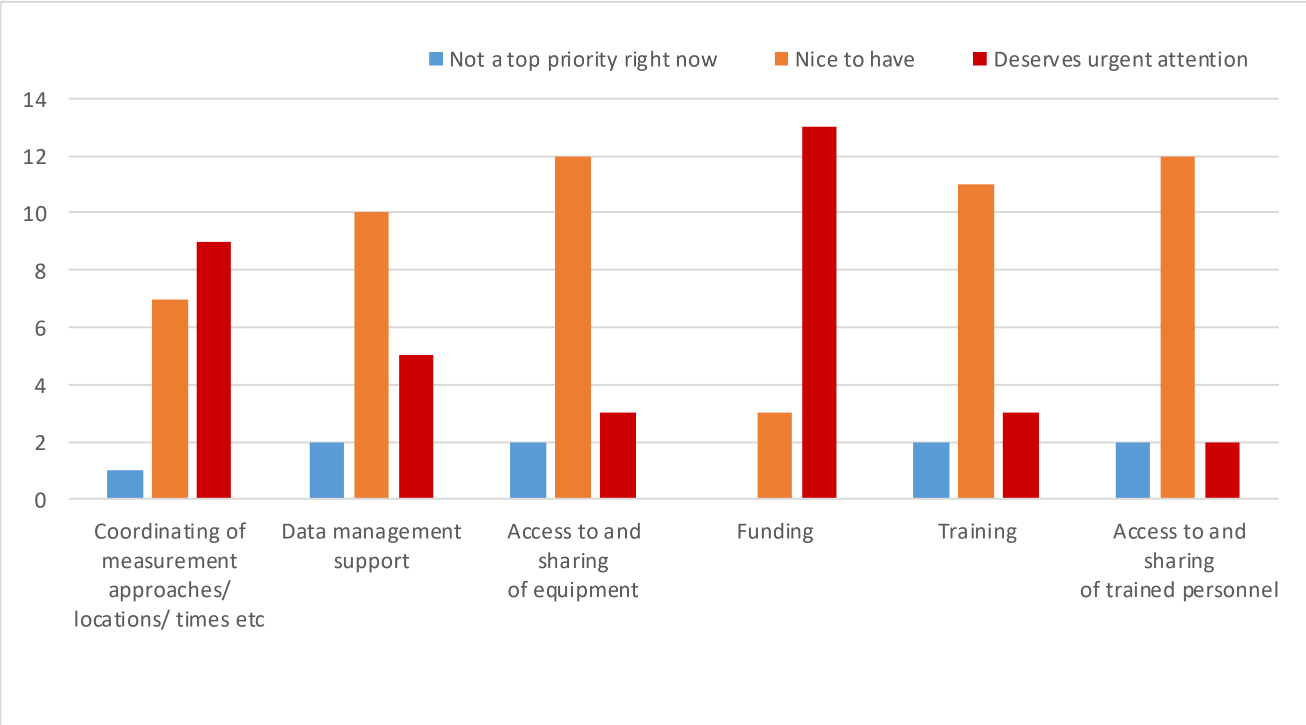
What knowledge gaps limit our ability to constrain present-day carbon uptake?



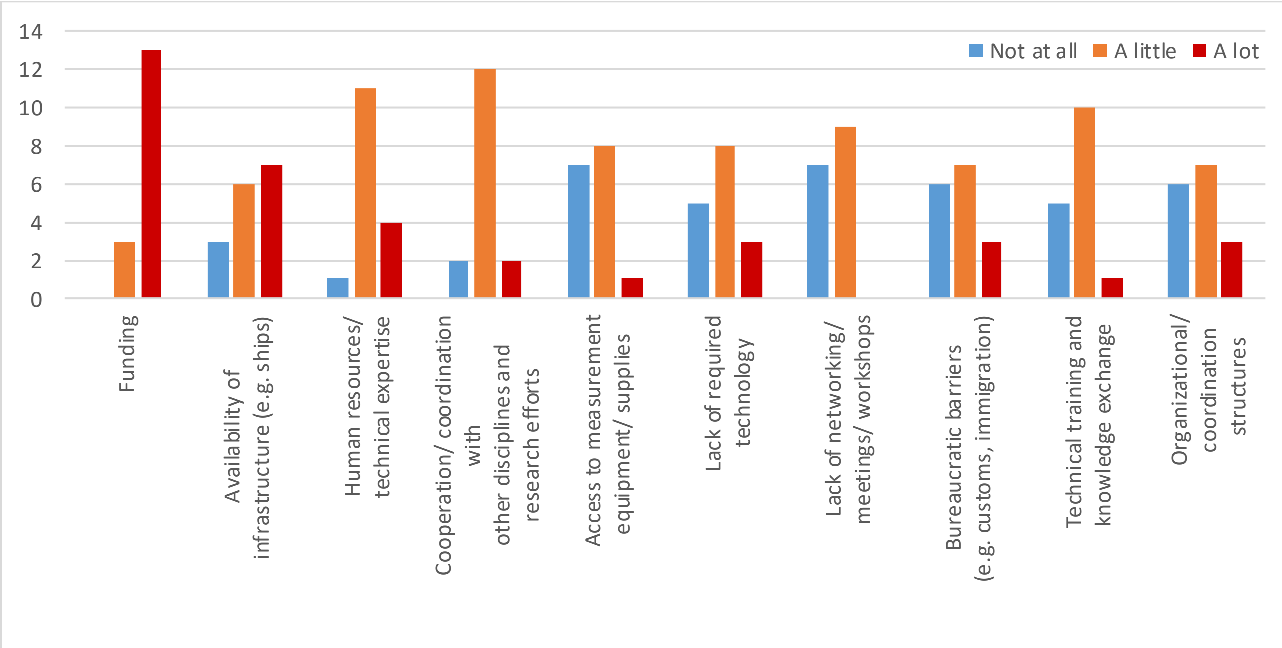
What are the knowledge gaps (and opportunities)?

- mechanisms
  - bio carbon pump: including mixed layer processes and mixed-layer pump
  - air-sea uptake mechanisms: parameterization of gas exchange; skin effect and nar-surface gradients
- understanding of short-term variability (interannual / subdecadal)
- deep mixing effects on air-sea flux
- look at model failures to find knowledge gaps
- upgrading measurement technology / new tech / new sensors

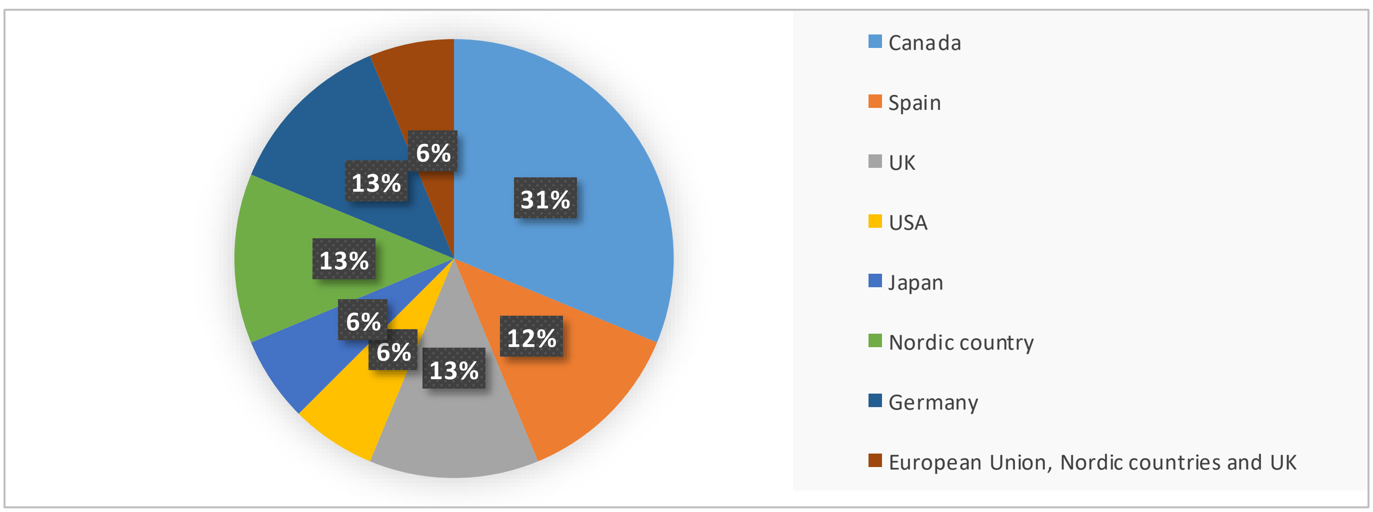
What aspects of North Atlantic monitoring would benefit from enhanced international collaboration?



What capacity gaps and/or other impediments hold you back from our task in your country?



Which country (or group of countries) are you referring to in your answer to the previous question?



Annex 6: Acronyms

AAORA	All-Atlantic Ocean Research Alliance
AOMC	Atlantic Meridional Overturning Circulation
AOML	Atlantic Oceanographic and Meteorological Laboratory
BGC	Biogeochemical
CCMAR	Center of Marine Sciences, Portugal
CDR	Carbon Dioxide Removal
CEO	Chief Executive Officer
CERN	European Organization for Nuclear Research
CMCC	Euro-Mediterranean Center on Climate Change
CMIP	Coupled Model Intercomparison Project
CNRS	French National Centre for Scientific Research
CNRS-L	National Council for Scientific Research – Lebanon
CPR	Continuous Plankton Recorder
CSA	Canadian Space Agency
CSIC	Spanish National Research Council
DFO	Fisheries and Oceans Canada
ECCC	Environment and Climate Change Canada
ESA	European Space Agency
ESM	Earth System Model
FSOI	Future of the Seas and Oceans Initiative
GCB	Global Ocean Biogeochemistry
GEOMAR	Helmholtz Centre for Ocean Research Kiel, Germany

GOMO	Global Ocean Monitoring and Observing
GOOS	Global Ocean Observing System
ICES	International Commission for the Exploration of the Sea
ICOS	Integrated Carbon Observation System
IOC	Intergovernmental Oceanographic Commission
IOCCP	International Ocean Carbon Coordination Project
IOC-R	Integrated Ocean Carbon Research
IPSL	Pierre Simon Laplace Institute
JAMSTEC	Japan Agency for Marine-Earth Science and Technology
JGOFS	Joint Global Ocean Flux Study
LSCE	Laboratory for Sciences of Climate and Environment.
MBARI	Monterey Bay Aquarium Research Institute
NACO	North Atlantic Carbon Observatory
NASA	National Aeronautics and Space Administration
NOAA	National Oceanic and Atmospheric Administration
NOC	National Oceanographic Centre
NORCE	Norwegian Research Centre
OFI	Ocean Frontier Institute
PCO2	Partial Pressure of Carbon Dioxide
PMEL	Pacific Marine Environmental Laboratory
ROMS	Regional Ocean Modeling System
SCOR	Scientific Committee on Ocean Research
UK	United Kingdom

UN Decade	United Nations Decade of Ocean Science for Sustainable Development
UNEP	United Nations Environment Program
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment