A COLLABORATIVE INTERNATIONAL RESEARCH PROGRAM ON THE COUPLED NORTH ATLANTIC-ARCTIC SYSTEM

Science Plan

Developed from a Workshop held in

Arlington, VA

14-16 April 2014

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Executive Summary

This North Atlantic-Arctic science plan is derived from an international workshop held in April 2014 with support from the National Science Foundation Division of Ocean Sciences and the European Union (EU). The workshop was designed to facilitate development of a core vision for advancing the next phase of research on the North Atlantic-Arctic system and strengthening international collaborations within and between the EU and North America. The recommendations that emerged were motivated by the desire to identify critical research questions that will advance understanding of the North Atlantic-Arctic system and implications for human communities, with particular focus on:

- ***Gateways:*** Implications of changes in communication (atmosphere and ocean) between the Arctic and the North Atlantic, as well as between the shelves and the open ocean for biogeochemical cycling, marine ecosystems and their services
- ***Circulation:*** Role of large-scale (e.g., AMOC) and sub-meso- to mesoscale (e.g., eddies, fronts) processes in different parts of the North Atlantic-Arctic system, effects of changing atmospheric circulation patterns, associated effects on biogeochemistry and ecosystem structure and function, and impact of Atlantic circulation changes on the Greenland ice sheet
- ***Bloom dynamics:*** Interactions between physical, biogeochemical, and ecological marine processes involved in the initiation, evolution, and termination of blooms, and associated sensitivities to climate and circulation changes
- ***Sustainable fisheries:*** Collective impacts of fishing pressures, climate, and ocean circulation changes on key North Atlantic fisheries, including the interactions with lower trophic levels and ecosystem restructuring resulting from these activities
- ***Marine ecosystem health:*** Sensitivity of marine biodiversity and ecosystem resilience to climate and circulation changes
- ***Prediction:*** Development, validation, and application of advanced earth system models (climate-atmosphere-ocean-ecosystem) able to capture the adaptive nature, evolution, and resilience of key biogeochemical and ecosystem players; thereby furthering our ability to predict future changes and inform decision-making

The research plan that emerged for the North Atlantic-Arctic systems combines sustained *in situ* observational and monitoring networks, integrated modeling studies, and innovative process studies to address questions focused on important issues that lie at the interfaces between atmosphere, ocean (including ecosystems), cryosphere, and human systems, and are driven by climate processes and socio-economic-policy concerns as:

- ➢ What are the critical dynamic processes and feedbacks driving variability and change in the North Atlantic-Arctic climate system? And how will a changing Arctic cryosphere influence ocean-atmosphere-ice interactions, thereby influencing biogeochemical processes and ecosystem structure?
- ➢ How will biogeochemical processes of shelf and open ocean waters of the North Atlantic and Arctic respond to changes in climate and increasing human pressures?
- ➢ How will marine ecosystem structure and function respond to environmental change in climate, ocean physics, biogeochemistry, and human pressures?

➢ What are the interactions between humans and a changing North Atlantic-Arctic marine system, considering perspectives of human health and well being and informing sustainable management practices?

This North Atlantic-Arctic science plan was developed with a view toward building a basin-scale multinational collaboration to advance observational and forecasting capacity and developing sound basin-scale management strategies to ensure long-term socioeconomic wellbeing. The immense geographic scale, interconnectivity of the regional components, scope of key science issues and environmental challenges facing the North Atlantic-Arctic region calls for a coordinated international multidisciplinary research program.

1. Introduction

1.1. Scientific Rationale

The North Atlantic Ocean, its connection to the Arctic Ocean, and its shelf seas (Fig. 1) are crucial for the ecological, economic, and societal health and resilience of both North America and Europe. This region also plays a critical role in the global climate system as a significant reservoir of heat, fresh water, and carbon dioxide, as well as through its ability to transport these over large meridional distances and exchange them freely with the atmosphere. The Atlantic Meridional Overturning Circulation (AMOC) figures prominently in this respect (Srokosz et al., 2010), and the North Atlantic accounts for nearly one quarter of the global marine uptake of anthropogenic CO_2 (Sabine et al., 2004; Sanders et al., 2014). Recent observations also suggest that increasingly warm Atlantic waters of subtropical origin that come in contact with Greenland's marine-terminating outlet glaciers play an important role in the ice sheet's increased mass loss and contribution to global sea level rise (Straneo et al. 2013).

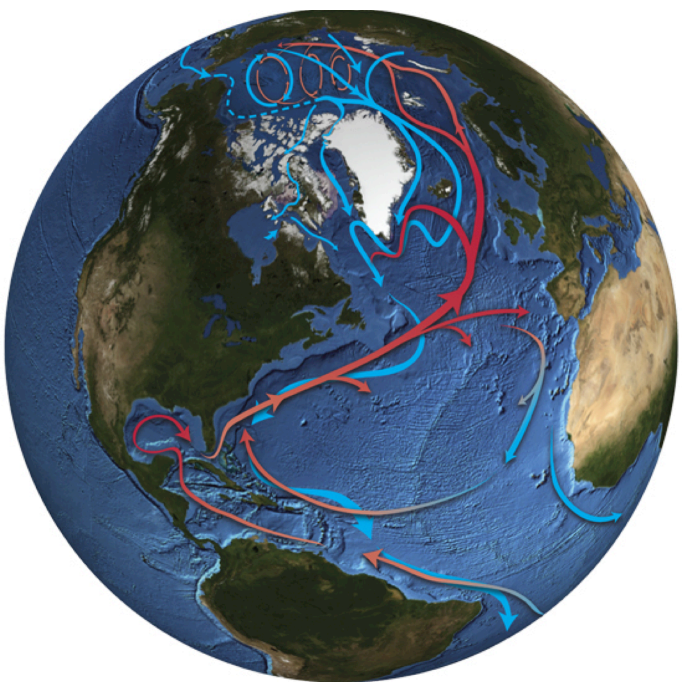

Figure 1. Map of the North Atlantic and Arctic Oceans showing major currents, gyres, and exchange pathways (Illustration by E. Paul Oberlander, Woods Hole Oceanographic Institution). This map is for illustration purposes only and is not intended to reflect the geographic boundaries of an international North Atlantic-Arctic research program.

Furthermore, this system provides habitat supporting some of the largest exploited fish stocks on the planet (Trenkel et al., 2014) with a potential to generate USD$17 billion compared to its current production of nearly USD$1 billion; a difference that is attributed to economic mismanagement of the stocks which are under pressure from exploitation and climate change (Merino et al., 2014; St. John et al., 2014).

Evidence that climate change is strongly affecting the structure and functioning of the marine environment is mounting (e.g., Beaugrand et al., 2002; Drinkwater et al., 2003; Edwards and Richardson, 2004; Richardson and Schoeman, 2004; Doney et al., 2012; Greene et al., 2013), and projected impacts suggest more dramatic changes in ecosystem productivity and services will occur in our lifetime (e.g., Orr et al., 2005; Doney et al., 2009). Recognition that the North Atlantic Ocean's carbon pump operates in a "non-steady-state" and its clear influence on climate brings into question the system's continued ability to compensate for increasing atmospheric CO_2 levels and the viability of its renewable resources such as fisheries (Sabine and Tanhua, 2010).

This interplay between climate, marine ecosystems and human activities fundamentally affects not only the North Atlantic-Arctic system, but also the entire earth system. Much scientific effort has been invested to build the existing knowledge base of this system, but it remains rudimentary in many aspects that are requisite to deliver predictive capacity and long-term forecasting. These are essential to addressing key scientific, environmental, governance, policy and societal challenges that we are already facing, and which are guaranteed to multiply in the near future. The pathway to understanding the North Atlantic-Arctic system, its role in climate and response to climate change, its impact on biogeochemical cycling, marine ecosystems, and dependent communities, and its potential for resilience depends critically upon augmenting available operational oceanographic services, developing observing and modeling capacity, and working more constructively and efficiently across disciplines.

The objective of this science plan is to outline a core vision for advancing the next phase of research on the North Atlantic-Arctic system and strengthening international collaborations within and between the European Union (EU) and North America. The dynamic physical, biological, chemical and ecosystem processes of the North Atlantic-Arctic system operate across basins and international borders. This immense geographic scale, interconnectivity of the regional components, scope of key science issues and environmental challenges facing this region calls for a coordinated international multidisciplinary research program. Hence, this science plan was developed with a view toward building a basin-scale multinational collaboration to advance our observational and forecasting capacity and developing sound basin-scale management strategies to ensure long-term socioeconomic wellbeing.

1.2. International Agreements and Coordination

In February 2013, the EU-United States (US) Joint Consultative Group held a meeting on Science and Technology Cooperation, which focused on developing the knowledge and technologies that can foster economic growth, create jobs, and help solve shared challenges, such as in health, climate change and food security. To facilitate this process, the Group explored how to advance international cooperation in trans-Atlantic and Arctic marine, maritime, transportation, health and materials science research. This meeting represented an important step toward the Galway Statement on Atlantic Ocean Cooperation, an agreement that was signed at a follow-up international workshop *The Atlantic: A Shared Resource* in May 2013 between the US, EU, and

Canada to join forces on Atlantic research. The goals of this cooperative agreement are to better understand the Atlantic Ocean, promote the sustainable management of its resources, and study the interplay of the Atlantic Ocean with the Arctic Ocean, particularly with regard to climate change. This agreement recognizes that Atlantic research will be more effective if coordinated on a trans-Atlantic basis.

These international agreements have coincided with a move in the international global environmental change research community towards a new structure, Future Earth (http://www.futureearth.info), which is a 10-year international research initiative. Future Earth is being developed around themes that focus on: 1) observing, understanding, and projecting Earth and societal system trends, including important drivers, processes, feedbacks, and thresholds; 2) providing the knowledge for sustainable, secure and fair stewardship of food, water, health, energy, materials and other ecosystem services; and 3) understanding and evaluating strategies for governing and managing the global environment across scales and sectors, and transformations to move towards a sustainable Future Earth. These themes are consistent with the goals articulated in the Galway Statement. Future Earth intends to develop and facilitate coordinated international research because it is recognized that making advances with the major issues facing science and society, such as climate change, requires resources and expertise that transcend what is available in individual countries or organizations.

1.3. Workshop Approach

A key suggestion from the scientific workshop in Galway was to convene a series of trans-Atlantic workshops to evaluate the basis for, and feasibility of, a jointly funded competitive research program. Given the scientific, social and economic importance of the North Atlantic-Arctic system and recognizing the need for coordinated international research, an international multidisciplinary planning workshop was held 14-16 April 2014 in Arlington, Virginia USA (Appendix 1). Participants included invited scientists from the U.S., Canadian and European research communities, as well as representatives from relevant national funding agencies (Appendix 1), with a mission to identify critical research questions that will advance understanding of the North Atlantic-Arctic system and implications for human communities, with particular focus on:

- ***Gateways:*** Implications of changes in communication (atmosphere and ocean) between the Arctic and the North Atlantic, as well as between the shelves and the open ocean for biogeochemical cycling, marine ecosystems and their services
- ***Circulation:*** Role of large-scale (e.g., AMOC) and sub-meso- to mesoscale (e.g., eddies, fronts) processes in different parts of the North Atlantic-Arctic system, effects of changing atmospheric circulation patterns, associated effects on biogeochemistry and ecosystem structure and function, and impact of Atlantic circulation changes on the Greenland ice sheet
- ***Bloom dynamics:*** Interactions between physical, biogeochemical, and ecological marine processes involved in the initiation, evolution, and termination of blooms, and associated sensitivities to climate and circulation changes

- ***Sustainable fisheries:*** Collective impacts of fishing pressures, climate, and ocean circulation changes on key North Atlantic fisheries, including the interactions with lower trophic levels and ecosystem restructuring resulting from these activities
- ***Marine ecosystem health:*** Sensitivity of marine biodiversity and ecosystem resilience to climate and circulation changes
- ***Prediction:*** Development, validation, and application of advanced earth system models (climate-atmosphere-ocean-ecosystem) able to capture the adaptive nature, evolution, and resilience of key biogeochemical and ecosystem players; thereby furthering our ability to predict future changes and inform decision-making

The plenary presentations and breakout groups (Appendix 1) focused on these questions and provided the basis for workshop discussions, the formulation of overarching science questions, and the science plan outlined in the following sections. Improved understanding will require:

- Targeted development of a sustained and coordinated observational effort for the North Atlantic-Arctic system that includes both in situ and remotely sensed data from a suite of ocean and land-based platforms, airplanes and satellites
- Time-series analysis and process studies
- Targeted experimental studies
- Development and application of synthetic modeling frameworks
- Socioeconomic research to explore feedbacks between human communities and the North Atlantic-Arctic system
- Research to explore response and sensitivity of the North Atlantic-Arctic system to management decisions

A consensus opinion of *The Atlantic: A Shared Resource* workshop in May 2013 was that rapid progress could be made by integrating current programs and infrastructure on a trans-Atlantic basis. This science plan emerging from the April 2014 workshop in Arlington, VA is intended to provide guidance for the development of new research initiatives that are compelling, feasible, cost-effective, and which will improve the understanding, and hence, the ability to monitor, predict and adapt to future changes in the North Atlantic-Arctic system. The translation of these science results to inform socio-economic issues, decision-making, management and policy is a program priority, as are directed efforts to work at the interface between natural and human sciences.

Targeting specific topics and locales for study, and developing international teams will mutually benefit scientists and funding agencies. It will improve international collaboration through better transfer of knowledge, expertise and facilities. Finally, such an approach will foster integration of disciplines, focus the development of conceptual and strategic frameworks, and clearly articulate research goals for the funding agencies and the general public.

2. Overarching Questions and Research Priorities

The physics, biogeochemistry, and ecosystem structure of the North Atlantic-Arctic system are inextricably linked by a set of complex processes and dynamics. The goal of the workshop was to identify key interdisciplinary links and knowledge gaps to help inform future research. Plenary talks and breakout sessions focused on how feedbacks between climate and circulation affect the biogeochemistry of shelf and open seas, food web dynamics, and community structure, which represent key links to humans via socioeconomics and human health. Within the following four disciplinary focus areas, workshop participants identified the most urgent questions and unknowns that currently limit our understanding and predictive capacity. These questions address important issues that lie at the interfaces between atmosphere, ocean, cryosphere, and human systems, and are driven by climate processes and socio-economic-policy concerns (Fig. 2).

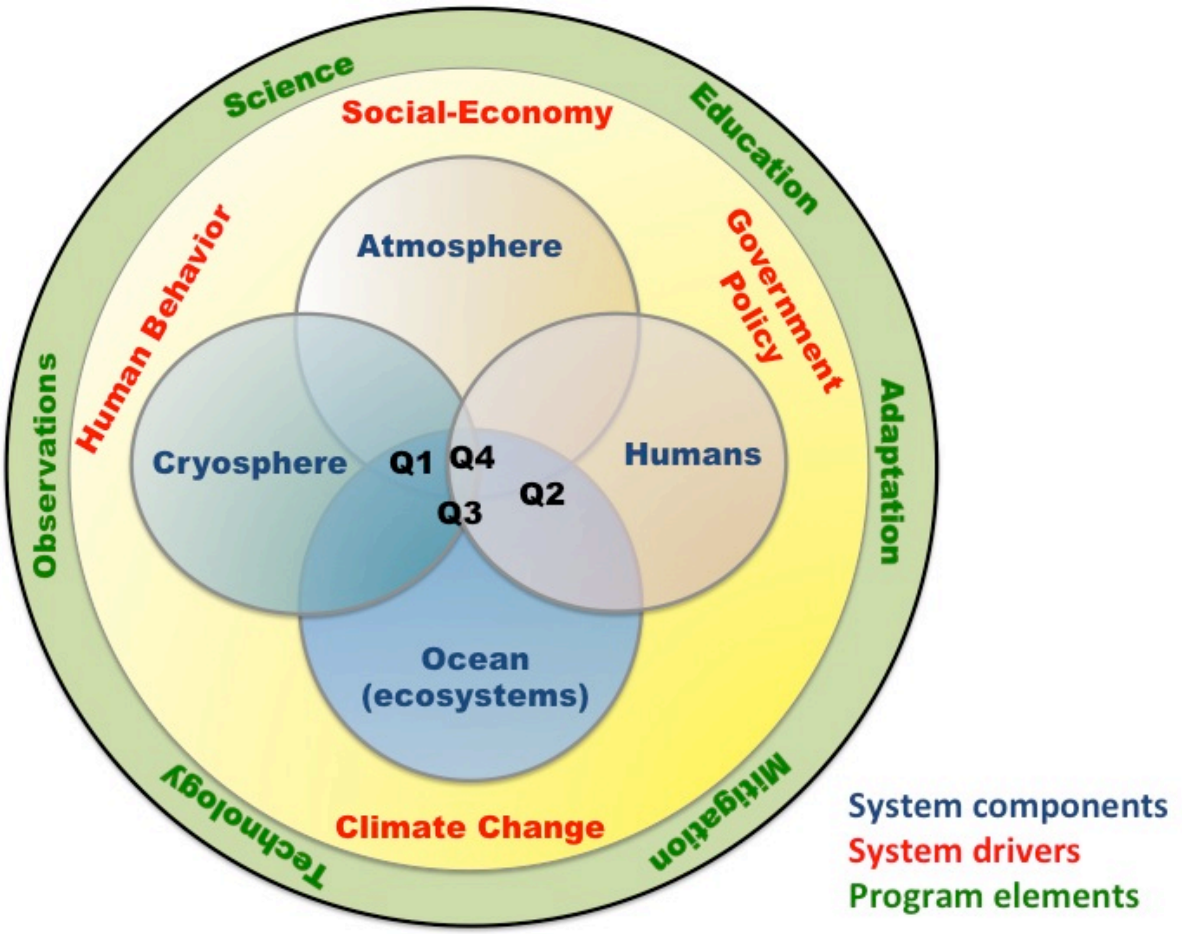

Figure 2. Diagram illustrating components of the North Atlantic-Arctic system, including system interactions (overlapping circles) and drivers (red), as well as key elements of an international multidisciplinary North Atlantic-Arctic program. The overarching research Questions 1-4 (Q1-4) presented in the science plan include aspects of all the system components and their placement on the diagram indicates the *key* systems involved.

2.1. Physical circulation and climate

Question 1: What are the critical dynamic processes and feedbacks driving variability and change in the North Atlantic-Arctic climate system? And how will a changing Arctic cryosphere influence ocean-atmosphere-ice interactions, thereby influencing biogeochemical processes and ecosystem structure?

Changes in climate from seasonal to centennial time scales are intimately linked to changes in atmospheric radiation and physical circulation, including changes in upper ocean density (e.g., upper ocean heat content, ice melt and freshwater runoff from Arctic rivers and discharge from the Greenland ice sheet), wind-driven surface currents, stratification, and eddy dynamics, which in turn affect biogeochemical cycling and ecosystem processes (see Chapters 2.2 and 2.3). The subpolar North Atlantic, a site of deep convection associated with the AMOC, provides one example of these changes. Nordic Seas Overflow Water and Labrador Sea Water are the primary water masses contributing to North Atlantic Deep Water (NADW), and changes in upper ocean density could affect the capacity for deep convection in these regions. Recent improvements in the spatial and temporal resolution and geographic coverage of ocean observations have resulted in a shift away from the classic conveyer belt paradigm and demonstrated the importance of local physical forcing such as winds and eddy fields in driving meridional transports of water masses and their properties, both at the surface and at depth (Srokosz et al., 2012).

Fischer et al. (2010) show that the reduction of overturning in the Labrador Sea, indicated by warming temperatures, may not be accompanied by a weakening deep western boundary current. However, recent data from RAPID-MOCHA (Rapid Climate Change-Meridional Overturning Circulation and Heat flux Array) at 26.5°N show a reduction in northward ocean heat transport, suggesting a weakening AMOC (Smeed et al., 2014). Linkages between deep ocean convection and AMOC transport variability in observations have been elusive. While subtropical/subpolar AMOC coherence appears rather weak on decadal time scales (Bingham et al., 2007; Wunsch and Heimbach, 2013), modeling studies strongly suggest that such a linkage emerges on longer time scales. Similarly, AMOC variability has been associated with dramatic climate (McManus et al., 2004) and ecosystem (Schmittner, 2005) changes in the paleo-record, but has not been directly observed on modern time scales. Warming and increased freshwater inputs at high latitudes are projected to continue stabilization of surface waters, with one likely consequence being reduced deep convection in the subpolar North Atlantic. However, there is still considerable uncertainty about the overall magnitude of an AMOC decrease, the resulting oceanic and atmospheric impacts, and how they might vary regionally.

In the Arctic, warming, sea ice loss, and fresh water accumulation in the Beaufort Gyre, a key atmosphere-ocean circulation feature that strongly influences Arctic climate has important implications for Arctic sea ice and ecosystems, as well as exchange with the North Atlantic. An anticyclonic circulation regime has dominated in this region for the past ~16 years, intensifying the buildup of fresh water in the gyre, but prior to that, periodic climatological shifts between anticyclonic and cyclonic circulation regimes have been observed. A shift to a cyclonic atmosphere-ocean circulation in the Arctic would release large amounts of the accumulated fresh water in the Beaufort Gyre to the North Atlantic, which could disrupt deep convection in the subpolar North Atlantic (Proshutinsky et al., 2012; Krishfield et al., 2014). The Arctic system is transitioning to seasonal sea ice cover, which will intensify seasonal variations in air-sea exchange, biogeochemistry, and ecosystem functioning; this could be particularly intensified in the inner coastal Arctic regions where the interactions between natural and human ecosystems are most apparent. Over a decade of observations (Steele et al., 2008) suggest that the focal point of sea ice retreat and subsequent upper ocean warming appears to be shifting from the Canadian sector of the Arctic to the Eurasian sector, and Overland and Wang (2013) project a complete loss of summer Arctic sea ice by mid-century. A weaker atmospheric circulation (i.e. a more meandering jet stream) could result in more extreme weather over the Arctic-North Atlantic boundary (Cassano et al., 2014), especially when effects of snow loss or increased water vapor and air-sea exchange on mid-latitude weather and cloudiness patterns are included. Finally, a more efficient transport of warm, saline water of subtropical Atlantic origin to the margins of the Greenland ice sheet may trigger dynamic changes and have a profound impact on its mass balance, freshwater discharge, associated freshening of and nutrient supply to the North Atlantic, and contribution to global sea level rise (Straneo and Heimbach, 2013).

An improved understanding of key physical oceanic and atmospheric processes in the North Atlantic-Arctic and important feedbacks with biogeochemistry and marine ecosystems will require multi-platform observations and monitoring, paleoclimate and process studies, and continued development and improvement of state-of-the-art earth system models (ESMs). During the workshop, the following high-priority areas were identified for studies of the physical circulation and climate of the North Atlantic-Arctic system. An overarching question for each of these areas is the extent to which current (or planned) observing systems provide sufficient information to address these topics in a satisfactory quantitative manner, or whether fundamental observational gaps prevent this at the present time.

Atmosphere and climate

What is the impact of changing northern atmospheric circulation patterns and cloud cover on ocean mixing, oceanic fluxes, and physical and biogeochemical property distributions? What is a role of marine aerosols in changing the radiative forcing and energy fluxes between ocean and atmosphere?

Lateral exchanges

Can we refine existing measurements of large-scale ocean fluxes to balance the time-varying budgets of mass, heat and fresh water, with particular focus on 1) exchanges between the North Atlantic and Arctic (e.g., flows through Fram Strait, Canadian Arctic Archipelago, etc.), including size, time scales, and impacts on sea ice coverage, biogeochemistry, and marine ecosystems; 2) deep water flows across sills; 3) exchanges between the continental shelf (e.g., boundary currents) and the basin interior; and 4) heat delivery and fresh water drainage from Greenland's marine-terminating outlet glaciers?

Deep circulation

How has AMOC varied and changed in the past and present, and what should we expect for the future? What have been/will be the associated impacts on productivity, biogeochemistry, and climate? What are the key pathways linking the deep Arctic basins and the Nordic Seas, as well as pathways for spreading of deep waters throughout the interior of the Atlantic basin, and what was the past stability of these pathways (e.g., Galaasen et al., 2014; Mokeddem et al., 2014)?

Freshwater impacts

What is the role of Atlantic-origin waters in melting of marine terminating Arctic glaciers, increased freshwater input, and related changes in Arctic fjord ecosystems? In the face of an accelerating hydrologic cycle and fresh water input from melting sea ice and discharge from the Greenland ice sheet, what are the relative contributions of freshwater exports through gateways (e.g., Fram Strait vs. the Canadian Arctic Archipelago) and their respective impacts on dense water formation in the subpolar North Atlantic?

Smaller-scale circulation, stratification, and shelf-basin interactions

What is the role of mixed layer eddies in re-stratification of the high latitude upper ocean? How do physical dynamics of the marginal ice zone feed back on the climate system and how do they affect biogeochemical cycling, productivity, and timing of blooms in the high latitude ocean? What are the key processes driving shelf-basin exchange and what are the dominant spatial and temporal scales governing these exchanges? For example, how do seasonally ice-covered shelf-basin exchanges impact distributions of physical, chemical (e.g. nutrients) and biological (e.g. carbon)?

Sea ice loss

Is the recent decline in sea ice coverage unprecedented? How will continued thinning and loss of sea ice impact air-sea fluxes, downstream ice and nutrient exports, and marginal ice zone dynamics? What are the implications for biogeochemistry, productivity, and marine ecosystem structure and function?

Regional sea level distributions

What is the partitioning of regional sea level change into steric contributions, fresh water input from Arctic rivers and mass loss from the Greenland ice sheet, redistribution through ocean dynamics, and what are the relative roles of decadal natural variability versus secular changes in sea level?

2.2. Biogeochemistry of shelf and open ocean waters

Question 2: How will biogeochemical processes of shelf and open ocean waters of the North Atlantic and Arctic respond to changes in climate and increasing human pressures?

The North Atlantic represents one of the key regions for the uptake of anthropogenic carbon via the functioning of the solubility and biological carbon pumps. An improved understanding of the physical and biogeochemical exchanges and transports between the subpolar North Atlantic and Arctic Oceans, as well as the processes modifying the magnitude of the influence of these two pumps, is needed. In particular, linking surface processes to deep processes across these basins is critical to understand the effects of changing stratification and circulation on carbon, oxygen, nutrient, and trace metal transport in the deep ocean, which affects the return of these properties to the surface, thus impacting global productivity patterns. The exchange with continental shelves/shallow seas is part of this larger transport pattern as is the continental shelf carbon pump. The exchange between the basins and the shelves is essential for improving our understanding of how changes in one basin (e.g., changes in Arctic sea ice) may affect other regions (e.g., changes in macro- and micronutrient levels and distributions, productivity, etc.), and for constraining and evaluating process-based and predictive models.

The biological Argo floats that are being deployed in the North Atlantic, Greenland and Norwegian Seas, which will provide long-term continuous measurements of oxygen, nitrates, acidity, fluorescence and backscatter from surface to ~2,000 m, will significantly expand current ship-based and autonomous ocean observing efforts in this region and are likely to revolutionize our understanding of ocean biogeochemistry. Six priority areas were identified for studies of the biogeochemistry of the North Atlantic-Arctic system that incorporate aspects of shelf-ocean exchanges and links to ecosystems and social science.

Basin-scale processes

What is the degree of connectivity between the basins of the North Atlantic-Arctic and their connection to the global ocean? What are the scale of fluxes, exchanges and variability, including past variations of heat, freshwater, nutrients, carbon, trace metals, and oxygen? What are the impacts on productivity and longer-term carbon uptake and storage in both regions? What is the role of cross-shelf exchange on ecosystems around the Arctic and North Atlantic basins? What are the main pathways of oxygen transport within the North Atlantic basin, and how sensitive is the supply of oxygen to the deep ocean to potential changes in near-surface exchange and deep convection? What is the long-term variability of uptake of anthropogenic CO_2 in the North Atlantic-Arctic region?

Local to regional processes

What is the role of submeso- to mesoscale marine (e.g., eddies, stratification, mixing, riverine supply, ice cover) in driving productivity and biogeochemical fluxes? Will changes of ice-cover in the Arctic Ocean induce trapping of nutrients in deep Arctic Basins and a decrease of the supply of nutrients to shelf and slope-water ecosystems along the Canadian and US continental margins? Will the export of newly acidified waters along the northwestern Atlantic continental margin have impacts on life in the deep ocean?

Seasonal cycle

How does the phenology and magnitude of seasonal variations in marine and atmospheric physical forcing affect ecosystem production and biogeochemical fluxes?

Vertical and lateral exports

What are dominant controls (e.g., ecosystem structure, grazing, ballasting, size spectrum, physical and biological aggregation/disaggregation, canyon flows and cascading) on the magnitude and fate of vertical and lateral export of organic matter between sympagic-pelagic-mesopelagic-benthic systems? Can we quantify differences in carbon fluxes across the temperature gradient between Atlantic- and Arctic-origin waters?

Elemental ratios

What are the key processes (e.g., preferential remineralisation, denitrification, nitrogen fixation, luxury consumption, atmospheric deposition) that drive and rectify decoupling of elemental ratios?

Marine ecosystem pressures

How do/did climate drivers (e.g., warming, wind-fields, cloud cover, mixing, fresh water input, ocean acidification) and anthropogenic pressures (e.g., mesopelagic fishing, eutrophication, atmospheric deposition, pollution) influence marine ecosystems and biogeochemistry, both today and in the past?

2.3. Food web dynamics and community structure

Question 3: How will marine ecosystem structure and function respond to environmental change in climate, ocean physics, biogeochemistry, and human pressures?

There are several studies that demonstrate the potential for major biogeographic shifts of key food web organisms and biogeochemical fluxes stemming from environmental change in coupled North Atlantic-Arctic ecosystems. Five major factors drive biogeographic shifts, and are expected to cause major changes in the coming decades, including:

- Changes in availability of limiting resources such as habitats and nutrients
- Changes in circulation that alter population connectivity
- Physiological tolerances of individual taxa to different environmental conditions (e.g., temperature, pH, etc.)
- Changes in trophic interactions, including timing of events and loss or introduction of key species
- Resource exploitation (e.g., fisheries extractions)

Effectively monitoring and detecting these changes will require an improved baseline understanding of key organisms in the marine food web, including physical and biogeochemical habitat preference, range of physiological tolerance, capacity to adapt to changing conditions, including response to individual and multiple stressors.

Biological responses vary greatly, depending on specific drivers, and may range from changes in abundance and dominance of single species, to large community shifts arising from local extinction and species adaptive potential. These changes raise questions of whether reshuffling matters – how relative dominance and addition of new species affect ecosystem function and persistence of species; the influence of genetic diversity on adaptability; and the impact of alteration of food web interactions. Poor knowledge of the role of biodiversity and issues of unknown species and unrecognized sibling species limit inference on how species and ecosystems are responding to ongoing change. Four priority areas were identified for food webs and community structure:

Resolving food web variability and trophic linkages

Can fishing pressure result in new and/or altered trophic cascades by restructuring the food web? What are the consequences for carbon flux from the upper ocean to the mesopelagic and deep-sea systems, and what roles do organisms from different trophic levels (plankton, mesopelagic and soft-bodied invertebrates, fish, etc.) play in these vertical fluxes? Does changing plankton size structure influences trophic and elemental transfer, and how do these changes influence the food webs of the North Atlantic-Arctic system?

Estimating event timing

What is the importance of sub-mesoscale physical processes in early re-stratification of the winter mixed layer and subsequent initiation of the North Atlantic spring bloom? What are the controls of species succession during events, grazing dynamics, upper ocean export, seed populations, bloom phenology and top down pressures in the North Atlantic-Arctic system?

Clarifying biogeography changes and their consequences

How will biogeography, life history, and behavior be influenced by environmental changes in North Atlantic-Arctic ecosystems, and how will these changes impact food webs? How do the life history strategies of key species vary geographically in the North Atlantic-Arctic system?

Defining multi-scale effects

What are the effects of coupled multi-scale physical processes on the structure of North Atlantic-Arctic food webs? How can we scale up information about the smaller-scale biophysical interactions that take place within a small patch of a heterogeneous bloom system to achieve an improved predictive understanding of bloom dynamics as a whole? What is the role of the middle trophic levels (mesopelagic and soft-bodied invertebrates) in the structure and function of North Atlantic-Arctic marine food webs?

2.4 Linking social and natural sciences

Question 4: What are the interactions between humans and a changing North Atlantic-Arctic marine system, considering perspectives of human health and well being and informing sustainable management practices?

Obtaining a balance between societal challenge-driven and basic research-driven science is a key issue for the success and community support of a North Atlantic-Arctic initiative. Linking the science-based overarching questions (Q1-3) with the overarching societal challenge-driven research (Q4) is critical to implementation of the initiative and the development of collaborative proposals, and will require efforts to communicate and/or re-brand basic research outcomes in terms that are more directly tied to human well being (e.g., food security). The overarching question considers two-way interactions between human pressures and the North Atlantic-Arctic system. With the recognition that ocean-human interactions are more directly experienced in coastal systems, this question includes anticipated physical, chemical, and biological challenges in both coastal and open ocean systems. A critical component of linking social and natural science is communication of basic research to policy makers and the general public in a societal challenge context, which can build upon existing marine educator networks that already translate marine research to policy, as well as engaging society at large.

The North Atlantic-Arctic system is and will continue to be influenced by multiple natural and anthropogenic drivers, including natural decadal-scale climatic shifts (e.g., North Atlantic Oscillation), warming, acidification, sea ice loss, coastal population growth and subsequent pollution and land use change, etc. Scale is a critical issue when addressing the interactions between human communities and marine systems. While some of these drivers and their associated impacts and feedbacks can be studied on a basin scale, others can best be addressed locally or regionally via collaborative interdisciplinary process studies. Furthermore, the issue of time scale is particularly important when discussing marine ecosystem and human responses to different pressures (i.e. "press" vs. "pulse" disturbances). Working effectively at this interface requires that disciplines and research approaches (observations, modeling, process studies, etc.) be integrated from the very beginning. This plan addresses the full cycle of:

> **PRESSURES:** Natural and anthropogenic pressures for ecosystem change (e.g., warming, acidification, sea ice loss, fisheries, maritime activities, geopolitical drivers)
>
> **RESPONSES:** Ecosystem response to pressures (e.g., changing food webs and biogeographic boundaries, invasive species introduction and proliferation, increasing storm frequency and intensity)
>
> **IMPLICATIONS FOR SOCIETY**: Implications of changing ecosystems across different human groups, including low-income or fragile populations (e.g., changes in fishery target species and food security, pathogens, shellfish poisoning from harmful algal blooms, coastal flooding and storm damage, changes in leisure and recreation habits with implications for human health)

Four near-term priority areas that link human communities to the North Atlantic-Arctic system were identified:

Shifting biogeographic boundaries
What are the implications of shifting biogeographic boundaries for human populations (health, social, cultural, economic, etc.)? Climate- and human-driven changes in heat distribution, biogeochemistry, nutrient and oxygen levels will impact marine food web structure and dynamics, species distribution, and long-term fitness and adaptation. As a result, human systems will experience changes in how they interact with the marine system (e.g., new fishery target species, introduction of new invasive species) and will need to develop effective adaptation and mitigation strategies.

Increasing resource exploitation
What are the feedbacks between human communities and marine ecosystems, including the geopolitics and dynamics of demand for natural resources? Can we anticipate increasing resource exploitation (e.g., expanded/changing shipping lanes, offshore energy exploration, mesopelagic fisheries, aquaculture)? Can we develop tools and methods to better quantify, understand and model tradeoffs between human wellbeing (socioeconomic, cultural, health) and marine ecosystem health? What are the most effective institutional frameworks for supporting this research?

Extreme weather and environmental events
Can we quantify and predict the risks of extreme weather and environmental events, their subsequent impacts on marine ecosystems and coastal communities, and the role of marine ecosystems and their habitats in mitigating these? Warming and increased moisture content in the atmosphere hold the potential for more intense and frequent storm events, which are damaging to coastal infrastructure and communities. Human activities involving energy production (nuclear, offshore oil and gas exploration, deep sea mining) and transportation are high risk and can result in accidents that pose serious threats to the environment and human populations. How can we more effectively monitor extreme events? Can we develop

vulnerability indices for marine ecosystems and human communities? How can we better communicate risk and uncertainty to the public and incorporate it into decision-making? Can we better protect and enhance elements of coastal marine ecosystems to dampen the intensity of extreme weather and environmental events?

North Atlantic-Arctic carbon pump
How will the North Atlantic-Arctic biological carbon pump efficiency (in sensu Volk and Hoffert, 1985) change in shelf and open ocean settings? What are the implications for food web structure, human activities (e.g., fisheries), and management strategies (e.g., carbon quotas)? What are the economic and societal implications of the trade-offs between different ecosystem services? We need to develop a quantitative understanding of human pressures on marine ecosystems, particularly with regard to fisheries extractions (mesopelagic fisheries, higher trophic levels) and associated impacts on carbon cycling and food web structure. Exploration of this link between fisheries and carbon cycling will require the development and application of coupled biogeochemical-fisheries models.

2.5 Research tools and approaches

With regard to research tools and approaches, there were several recommendations that were common across disciplines:

1) Retrospective analysis and synthesis (e.g., Greene et al., 2013) based on available monitoring and scientific data sets (e.g., European Marine Observation and Data Network [EMODnet], EU Data Collection Framework [DCF], Global Earth Observation System of Systems [GEOSS], Joint Global Ocean Flux Study [JGOFS], North Atlantic Bloom Experiment 2008, Continuous Plankton Recorder [CPR] surveys, Ocean Observatories Initiative [OOI], Overturning in the Subpolar North Atlantic Program [OSNAP], GEOTRACES, national and international databases on higher trophic levels such as International Council for the Exploration of the Sea [ICES], Arctic Observing Network [AON], linked German Alfred Wegener Institute-HAUSGARTEN and Norwegian Polar Institute-Fram Strait Observatories). These resources can provide

- critical constraints on model parameterizations;
- critical tests of physical and biogeochemical model performance;
- assessment of the observational capacity to address the needs for model validation;
- historical context for environmental changes to inform future process studies that focus on key unknowns surrounding bloom phenology, the carbon pump, food web dynamics, biogeochemical cycling, and freshwater fate and impacts in the North Atlantic-Arctic region; and
- data for validation of simulation activities

2) High-resolution coupled models that provide the basis for projecting changes and effects for the next 20 years, as well as regionally based, end-to-end ecosystem modeling systems that provide an approach to link climate to all trophic levels including human interactions and implications (e.g., socio-economic systems)

3) Formal model-data integration and synthesis frameworks, including data assimilation techniques to test and improve models and obtain basin- and global-scale budgets of key biogeochemical variables

4) Cost-effective, sustained, long-term measurement programs (including land-, ocean-, satellite-, and aircraft-based programs, such as OSNAP, OOI, ICESat, Argo, IceBridge) to support interdisciplinary research on the North Atlantic-Arctic system across a wide range of space and time scales (e.g., European Strategy Forum on Research Infrastructures [ESFRI], OceanScope, A Framework for Ocean Observing, A Canadian Contribution to an Integrated Atlantic Ocean Observing System [IAOOS, see Wallace et al., 2014]), including focused 'Sentinel Sites/Areas' where sustained observations and a series of science activities and industry-oriented measurement programs can be combined

5) Development of novel integrated sensors (e.g., NeXOS) and biological measurement approaches (e.g., eco-sensors, bio-logging tags)

6) Development of paleo-data sets (and incorporation of paleo-data in models) to explore past freshwater forcing, ocean circulation, sea ice extent, etc. and associated biogeochemical and marine ecosystem impacts, as well as calibration and validation of new paleo-proxies via modern process studies and observational platforms

7) Comprehensive ecosystem studies that provide more than just a snapshot of a biogeochemical flux or a small part of the food web, and are conducted over sufficient time intervals to develop a baseline understanding of the physics, thus providing the necessary dynamic context for biogeochemical and ecosystem observations; examples of high priority process studies include (but are not limited to):

- Subpolar North Atlantic and Arctic bloom dynamics
- Physical interaction between the ocean and the Greenland Ice Sheet and impacts on regional biogeochemistry and ecosystems (e.g., Heimbach et al., 2014)

8) Diagnostic tools to measure and monitor marine ecosystem health, including:

- Universal guidelines on observational coverage (temporal and spatial scales, scaling up), common reference points, uncertainty, etc. are needed to develop effective and comparable basin-scale marine ecosystem metrics
- Indicators to assess long-term fitness and adaptation potential; in addition, they must relate to, and be easily translatable into implications for ecosystem services and human welfare

9) Collection of social and economic data sets and development of forecasting models (e.g., computable general equilibrium, or CGEs) to estimate social, demographic, and economic impacts of policies and resource exploitation in different regions, including the mapping of decision processes across different countries to help researchers understand the scale at which decisions and impacts can be perceived beyond the reach of physical diffusion

3. Crosscutting Research Topics

Throughout the discussions at the workshop, participants identified research topics that cut across disciplines (Chapter 2, questions 1-4) and would benefit from trans-Atlantic collaborative research investigations. Potential research topics discussed at the workshop are described below, though please note that these are only provided as examples and are not meant to be exclusive or prescriptive. Each is linked to several of the topical research areas highlighted at the beginning of this plan (e.g., gateways, sustainable fisheries, bloom dynamics) and address aspects of the four research questions). A common thread running throughout these research topics that ultimately serves as an overarching goal of an international research program is, ***"providing the scientific basis for the sustainable delivery of ecosystem services in the changing coupled North Atlantic-Arctic system."*** This theme connects each of the topical research areas, allows optimization for national needs, lends itself to comparative studies in different regions, and fosters the international coordination that is required for cross-basin synthesis.

3.1. Changing biogeographic distribution and population dynamics of key ecosystem players and exploited populations

What are the drivers resulting in changes in spatial and temporal distributions? Comparative studies that span latitudinal ranges are needed to understand the biogeographic distributions of fish stocks and potential changes to these distributions. For example, the same fish species occur in the Norwegian and Irminger Seas, and estimates of the stock sizes and corresponding environmental and biogeochemical conditions for these are part of ongoing research and assessment programs.

To address this important research area and identify mechanisms of cause and effect in biogeographic shifts, process studies are needed that focus on trophic linkages and implications of changing bloom dynamics (in time and space) for these fish stocks, including links to ocean circulation and stratification (including freshwater inputs and changing sea ice cover), extreme weather events, and biogeochemical cycles.

3.2. Physics, biology and biogeochemistry of the North Atlantic-Arctic carbon pump

How will the solubility and biological carbon pumps be influenced by climate-driven changes in temperature and circulation? The North Atlantic-Arctic region plays an important role in the global carbon cycle for two main reasons. First, the subpolar North Atlantic includes multiple sites of dense water formation and deep convection, and is therefore a key driver of the solubility pump. Second, with an annual spring bloom that constitutes one of the most conspicuous features in satellite global ocean color, the biological pump is particularly active as well (Ducklow and Harris, 1993). The AMOC enhances the efficiency of the global biological pump by injecting low-preformed-nutrient waters (North Atlantic Deep Water, or NADW) into the deep ocean (Ito and Follows, 2005; Schmittner and Galbraith, 2008). Freshening due to melting ice could lead to increasing stratification, which in turn may decrease the rate of deep water formation and thus slow the solubility pump. Increasing stratification could reduce wintertime mixed layer depths, thereby reducing the nutrient supply that fuels the spring bloom and weakening the biological pump. On longer (millennial) time scales, a weakened AMOC would reduce biological pump efficiency due to decreased injection of low-preformed-nutrient NADW at depth. These changes will be communicated to the global ocean via the overturning circulation currently being monitored as part of programs like OSNAP and the Fram Strait Observatory. This and other existing international observing assets in this region are largely focused on ocean physics, but could provide baseline infrastructure from which to investigate the collective physical, chemical, and biological impacts of climate change in modulating carbon uptake, biological pump function and associated connections to the global carbon cycle.

3.3. Phytoplankton bloom dynamics and implications for North Atlantic-Arctic food webs

What are the consequences of changes in phenology and magnitude of phytoplankton blooms? Developing an improved understanding of the ecology that supports the biological carbon pump discussed in Chapter 3.3 is essential. Many unknowns and poorly constrained rates require process level understanding, with increased focus on linkages between euphotic and twilight zones, shelf and open ocean settings, and across the sub-arctic region. Process studies such as *Bridging productivity regimes in the Arctic Ocean* (CarbonBridge), the *North Atlantic Bloom Experiment* (NAB08), and *Carbon flux and ecosystem feedback in the northern Barents Sea in an era of climate change* (CABANERA, 2003-2006) have advanced our understanding of the initiation (physics, biogeochemistry, etc.) of spring blooms that sustain entire food webs, but as highlighted in Section 2.3, much more research is needed to understand what controls the timing and spatial patterns of bloom events, species succession during events, changes in plankton size structure, seed populations, and the relative roles of top down (e.g., grazing) vs. bottom up (nutrient availability) pressures. A combination of in situ and satellite-based observations, as well as models of the appropriate scale (i.e. eddy-resolving) will be critical in advancing research on bloom dynamics. Given new and existing OSNAP observing infrastructure, bloom dynamics and associated productivity in the Nordic Seas are especially ripe for international process research.

3.4. Increasing freshwater input and a changing Arctic cryosphere

How will changes in freshwater input influence ecosystem dynamics and the functioning of the physical and biological carbon pumps? As a result of increasing fresh water input from Arctic rivers, melting sea ice, and increased mass loss of the Greenland ice sheet, water mass transport and connectivity among basins are changing in the North Atlantic-Arctic region, affecting surface heat balance and stratification, biogeochemistry, event timing, community composition and trophic size structure, charismatic megafauna distributions, fisheries, etc. Monitoring freshwater inputs, particularly in regions undergoing rapid changes, is needed to quantify freshwater impacts on circulation (e.g., deep water formation, stratification and eddy formation in shelf systems, etc.) and biogeochemistry (e.g., nutrient ratios, oxygen, carbon and trace metal distributions, air-sea fluxes, etc.). Process studies that couple changes in ocean physics and biogeochemistry with marine food webs and the provisioning of ecosystem services (fisheries, transportation, etc.) will provide a more complete picture of how increasing freshwater in the North Atlantic and Arctic Oceans will play out for marine ecosystems and the human communities that depend upon them.

3.5. Feedbacks between mesopelagic food webs and biogeochemistry and response to earth system changes

What is the role of the mesopelagic community in the functioning of the biological carbon pump and biodiversity? Changes in temperature, freshwater input, nutrients and population connectivity in the coupled North Atlantic-Arctic system, as well as human extraction of marine resources, will influence mesopelagic foods webs and biogeochemical processes. Changes in climate will affect the ontogenetic migrations of zooplankton and fish, which will influence mesopelagic food webs and biogeochemical processes. Variations in the timing and extent of deep convective mixing will result in different sinking fluxes of particulate and dissolved material, which will have cascading effects on mesopelagic food webs, carbon export and nutrient and trace metal cycling. Addressing these important changes will require process studies that focus on the pathways of particulate and dissolved material exchanges and associated feedbacks with mesopelagic organisms. Furthermore, it will be critical to assess and quantify the impacts of these changes on key ecosystem services (carbon sequestration, biodiversity, fisheries) in the pelagic and mesopelagic zones of the North Atlantic-Arctic system.

4. Program Coordination and Planning Suggestions

4.1 Mechanisms to promote collaboration

Linking international research efforts and programs from the outset is the most efficient way to address key scientific questions in the North Atlantic-Arctic region, since it offers opportunities to leverage resources, strengthen scientific community building across disciplines and nations, and facilitate two-way transfer of knowledge and methodological approaches. Mechanisms for promoting collaboration include:

- Synchronize timing of activities to avoid missing opportunities
- Facilitating international research collaborations among US, EU, and Canadian PIs
- Coordinating with other relevant activities (e.g., OSNAP, US AMOC, AON, NASA-proposed process studies, and other relevant US, EU, and Canadian agency-funded activities)
- Linkage of social and natural sciences from the outset
- Joint funding strategies and firm commitment among various funding entities to make joint programming happen on a synchronized time line (e.g., Belmont Forum, international bilateral agreements)
- Dedicated collaborative US, EU and Canadian postdoctoral programs
- Coordination at the international level through global environmental change research platforms (e.g., Future Earth), programs and networks (e.g., Integrated Marine Biogeochemistry and Ecosystem Research [IMBER] Project, Surface Ocean-Lower

Atmosphere Study [SOLAS], US (interagency) Study of Arctic Environmental Change [SEARCH], International Study of Arctic Change [ISAC], Arctic in Rapid Transition [ART], Ocean Tracking Network [OTN], The Greenland Ice Sheet-Ocean interaction [GRISO] Network, etc.)
- Developing strategic partnerships with the private sector

4.2 Integration and coordination

Effective implementation of the Science Plan that maximizes opportunities for funding and makes efficient use of all available resources (expertise and infrastructure) requires a coordinated multidisciplinary approach from the outset. Field campaigns and process studies should be carefully planned to maximize use of ship time and ensure fully integrated data sets, including the collection of relevant physical, biological, chemical, and geological samples that provide the necessary temporal and spatial constraints to address important research questions. This requires coordination and integration across project components and international community (individual national programs). Many national programs are ongoing or in the planning phase (Appendices 2-4) and leveraging the intellectual resources, facilities, and human capital already invested in these would enhance and strengthen a North Atlantic-Arctic research program.

Establishment of a EU-US-Canada project office and an international science steering committee will ensure communication, coordination and implementation across the program components and provide a central focal point for links to national programs. A project office would oversee coordination and a science steering committee would provide a structure for discussing and focusing scientific ideas and approaches. Experiences from international global change programs show clearly the importance of these programmatic structures, especially for implementation and coordination of multi-national field studies. Funding for a central project office and steering committee should be provided through contributions from national funding agencies. Another key aspect of coordination will involve the management and archival of North Atlantic-Arctic data sets and establishment of common data formats and quality control criteria to facilitate working across disciplines and nations.

Another important element of an integrated Arctic-North Atlantic research program is focused workshops, particularly for the design of monitoring, survey and field studies; for design and analysis of modeling results; and for harnessing integration of natural and social science efforts. A further requirement from the outset is funding for communication, outreach, and education that support the understanding and dissemination of new scientific insights and research results.

4.3 Data access

Open and timely exchange of observations, associated data products and a data policy, research findings, and model results are critical to the success of this North Atlantic-Arctic Science Plan. Investments in information management for observational and model data need to be included from the start of the program and be agreed upon by all participating nations.

4.4 Program measures of success

Metrics to assess success are an important part of the development of any research. Potential success metrics for the North Atlantic-Arctic program can be established in terms of new resources developed, scientific advances, predictive capability, observational capability, data sets and availability, and capacity building and educational outreach. The definition of success metrics should be incorporated into the initial program planning and implementation.

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Appendix 1. North Atlantic-Arctic Planning Workshop Documents

A Planning Workshop for an International Research Program on the Coupled North Atlantic-Arctic System

April 14-16, 2014
Hilton Arlington, Arlington, VA

WORKSHOP AGENDA

MONDAY, APRIL 14

7:30-8:30 Breakfast (Hilton Arlington)

8:30-8:40 **Welcome** (Eileen Hofmann, ODU; Heather Benway, OCB)

8:40-9:00 **Introduction and overview** (Eileen Hofmann, ODU; Michael St. John, Danish Technical Univ.) – 15 minutes to talk, 5 minutes for questions

9:00-10:15 **Opening remarks from agency representatives**

- **EU Representative** (James Gavigan)
- **NSF** (Roger Wakimoto, Debbie Bronk)
- **NASA** (Paula Bontempi, Eric Lindstrom)
- **NOAA** (Craig McLean)
- **DOE** (Renu Joseph)
- **Canada Representative** (Alain Vezina, Doug Wallace, Paul Myers)

10:15-10:30 Break

10:30 **Plenary talks** (*speaker)**:** These talks will include 45 minutes total for presentation and 5 minutes for questions.

10:30-11:20 **Human implications and management strategies in the coupled North Atlantic-Arctic system** (Melanie Austen*, Plymouth Marine Laboratory; Angel Borja, AZTI-Tecnalia; Jon Hare, NOAA Northeast Fisheries Science Center)

11:20-12:10 **North Atlantic bloom dynamics: Insights from an interdisciplinary, multi-platform process study** (Mary Jane Perry*, Univ. of Maine; Eric d'Asaro*, Univ. of Washington, Craig Lee*, Univ. of Washington)

12:15-1:15 Lunch (Hilton Arlington)

1:15-2:05 **Rapid changes in Arctic biogeochemistry and marine ecosystems** (three 15-minute talks)

Primary productivity (Patricia Matrai*, Bigelow Laboratory)
Nutrient fluxes (Jean-Éric Tremblay*, Laval Univ.)
CO_2 fluxes and biogeochemistry (Jeremy Mathis*, NOAA/PMEL)

2:05-2:55 **Large-scale circulation in the North Atlantic-Arctic system: Past and present** (three 15-minute talks)
Atlantic Meridional Overturning Circulation (Susan Lozier*, Duke Univ.)
Arctic circulation **(**Michael Steele*, Univ. of Washington)
Insights from the paleoceanographic record of deep circulation in the North Atlantic and Arctic Oceans (Jerry McManus*, Lamont-Doherty Earth Observatory)

2:55-3:00 **Break down into smaller groups** (see breakout list in meeting folder)

3:00-4:00 **Breakout Session 1: Overarching interdisciplinary science questions**
Goal: *To gather participant feedback and refine overarching questions*

- What is the mechanistic link between climate and circulation in the North Atlantic-Arctic system, and what are the physical, biological, and biogeochemical implications of future changes in climate and circulation?
- How will biogeochemistry of shelf and deep waters of the North Atlantic and Arctic respond to climate change and increasing human pressures?
- How will marine ecosystems and associated biodiversity respond to changes in ocean physics and chemistry?
- How will marine ecosystem changes impact the health and well being of human populations, and what scientific information is most critical for developing sustainable management practices that will help human populations adapt to changes in the coupled North Atlantic-Arctic system?

4:00-4:15 Break

4:15-5:30 **Breakout Session 2. Relevant international activities and resources**
Goal: *To compile information on relevant ongoing or upcoming observing campaigns, research activities, etc.*

- **U.S.**
- **European Union**
- **Canada**

5:30-7:30 Welcome reception hosted by EU Delegation (Hilton Arlington)

TUESDAY, APRIL 15

7:30-8:30 Breakfast (Hilton Arlington)

8:30-9:30 **Breakout reports and discussion from day 1**

9:30-10:20 **Mesoscale and submesoscale dynamics in the North Atlantic-Arctic system** (three 15-minute talks)
- ***Mesoscale and submesoscale physical-biogeochemical interactions in the North Atlantic*** (Dennis McGillicuddy*, Woods Hole Oceanographic Inst.)
- ***Arctic*** (Craig Lee*, Univ. of Washington)
- ***Modeling shelf seas dynamics, ecosystems, and ocean-shelf coupling in the North Atlantic and Arctic*** (Jason Holt*, National Oceanography Centre)

10:20-10:40 Break

10:40-11:30 **Marine ecosystem health and biodiversity** (Paul Snelgrove*, Memorial Univ. of Newfoundland; Michael Fogarty, NOAA Northeast Fisheries Science Center)

11:30-12:20 **Developing our predictive capacity**
- ***Theory and models of marine ecosystems*** (Mick Follows*, Massachusetts Inst. of Technology; Mike Heath, Univ. of Strathclyde)
- ***Arctic climate and sea ice projections*** (Wieslaw Maslowski*, Naval Postgraduate School)
- ***AMOC perturbation experiments*** (Andreas Schmittner*, Oregon State Univ.)

12:20-1:30 Lunch (Hilton Arlington)

1:30-5:30 **Breakout session 3: Research foci in coastal and open ocean settings – Knowledge gaps and future needs**
Goal: *To identify specific high-priority research areas under each subheading that are needed to advance our holistic understanding of the North Atlantic-Arctic system*
- Physical circulation and climate
- Biogeochemistry
- Food web dynamics and community structure
- Ecosystem health and biodiversity
- Human implications, management, and adaptation strategies

3:00-3:30 Break

6:30-9:00 Workshop dinner (Hilton Arlington)

WEDNESDAY, APRIL 16

7:30-8:30	Breakfast (Hilton Arlington)
8:30-9:30	**Breakout 3 reports**
9:30-12:30	**Breakout session 4: Research tools and approaches** **Goal:** *To identify highest-priority needs in each of these categories for addressing research foci above* • Integrated observations and monitoring • Modeling and prediction • Process studies • Management and decision support
10:15-10:45	Break
12:30-1:30	Lunch (Hilton Arlington)
1:30-2:30	**Agency remarks**
2:30-3:15	**Breakout 4 reports**
3:15-3:30	Break
3:30-5:00	**Science Plan Outline discussion and next steps**
5:00	Adjourn

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A Planning Workshop for an International Research Program on the Coupled North Atlantic-Arctic System

April 14-16, 2014
Hilton Arlington, Arlington, VA

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