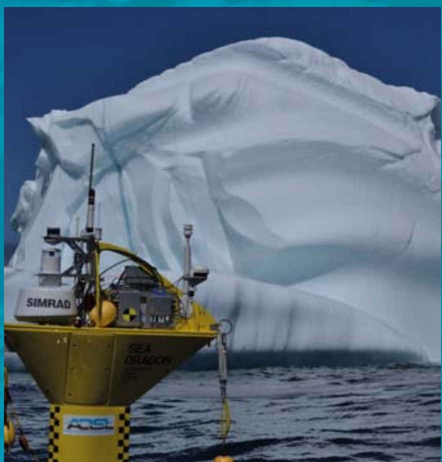


THE BAFFIN BAY OBSERVING SYSTEM

Title: The Baffin Bay Observing System (BBOS)

Authors: Søren Rysgaard & BBOS committee

Layout: Tinna Christensen, Aarhus University, Silkeborg

Financial support: xxxxxxxxxx

Number of pages: 32

Front page photo: Martin Fortier

Photo this page: xxxxxxxxxxxxxx

BBOS – Temporary Steering Committee:

Alain Leclair (alain.leclair@polar.gc.ca)

Alfred Jacobsen –regional advisor (aerj58@gmail.com)

Andrew Stewart (Andrew.Stewart@dfo-mpo.gc.ca)

Anne Barker (anne.barker@nrc-cnrc.gc.ca)

Brad DeYoung (bdeyoung@mun.ca)

Carl Bøggild (cegb@nanoq.gl)

Charlotte Havsteen – ICE-PPR, Denmark (cwh@fcoo.dk)

Christopher Debicki (cdebicki@oceansnorth.ca)

Craig Lee (craig@apl.washington.edu)

David Barber (David.Barber@umanitoba.ca)

Dorthe Dahl-Jensen (ddj@nbi.ku.dk)

Douglas Wallace (Douglas.Wallace@Dal.ca)

Garry Heard (Garry.Heard@drdc-rddc.gc.ca)

Jackie Dawson (jackie.dawson@uottawa.ca)

John Mortensen (jomo@natur.gl)

Katherine Wilson (katherine.wilson@canada.ca)

Bronwyn Keatley (Bronwyn.Keatley@dfo-mpo.gc.ca)

Kim Juniper (kjuniper@uvic.ca)

Lene Holm (leho@natur.gl)

Louis Fortier (Louis.Fortier@bio.ulaval.ca)

Luke Copland (luke.copland@uottawa.ca)

Marcel Babin (Marcel.Babin@takuvik.ulaval.ca)

Maribeth Murray (murraym@ucalgary.ca)

Marie-Noëlle Houssais (marie-noelle.houssais@locean-ipsl.upmc.fr)

Martina Loebl (martina.loebl@awi.de)

Mary Ellen Thomas (MaryEllen.Thomas@arcticcollege.ca) - regional advisor

Niels Andersen (na@space.dtu.dk)

Nigel Hussey (nehussey@uwindsor.ca)

Paul Briand (paul.briand@canada.ca)

Søren Rysgaard (Rysgaard@umanitoba.ca)

Stephanie Meakin (smeakin@inuitcircumpolar.com)

Trevor Bell (tbell@mun.ca)

CONTENT


North Pole
Norwegian Sea
Norway
Greenland Sea
UK
Russia
Lincoln Sea
Arctic Ocean
Ellesmere Island
Alert
Kalaallit Nunaat (Greenland) (Denmark)
Iceland
Bering Strait
Arctic Circle
Alaska (USA)
Beaufort Sea
Banks Island
Resolute (Qausuittuq)
Baffin Bay
Davis Strait
Inuvik
Victoria Island
Baffin Island
Dawson
Yukon
Great Bear Lake
Foxe Basin
Iqaluit
Labrador Sea
Atlantic Ocean
Whitehorse
Northwest Territories
Nunavut
Hudson Strait
Yellowknife
Baker Lake (Qamanittuaq)
Newfoundland and Labrador
Pacific Ocean
Fort Nelson
Great Slave Lake
Ungava Bay
Nain
Kuujjuaq
British Columbia
Fort McMurray
Lake Athabasca
Hudson Bay
Churchill
Prince George
Alberta
Saskatchewan
Reindeer Lake
Churchill Falls
St. John's
Edmonton
Manitoba
Newfoundland
James Bay
Sept-Îles
Saint-Pierre and Miquelon (France)
Vancouver Island
Kamloops
Calgary
Lake Winnipeg
Sandy Lake
Vancouver
Saskatoon
Quebec
Prince Edward Island
Victoria
Charlottetown
Regina
Winnipeg
Ontario
Fredericton
Québec
Halifax
United States of America
Thunder Bay
Montréal
Nova Scotia
Ottawa
New Brunswick
Canada – Political
International boundary
International boundary (disputed)
370 km Exclusive Economic Zone (EEZ) boundary
Provincial/territorial boundary
Alberta Province/territory
Ottawa National capital
Regina Provincial/territorial capital
Kamloops Other locale
Lake Superior
Toronto
Lake Michigan
Lake Huron
Lake Ontario
Lake Erie
Scale
0 250 500 750 1 000 km
Atlantic Ocean

THE BAFFIN BAY OBSERVING SYSTEM (BBOS)

1 PROJECT SUMMARY

Baffin Bay is one of the most productive marine systems in the northern hemisphere and represents an important connection between the Arctic Ocean and the North Atlantic. Baffin Bay is also an Inuit homeland and an important site for cultural resources and coastal interactions. Climate change is occurring particularly rapidly in the region and long-term, and large-scale integrated studies are needed to understand the cascading effects from physical changes to the environment, ecosystems, and social, economic, and geopolitical conditions. In addition, to operate safely and responsibly in this seasonally ice-covered region there is a need for significantly improved weather, ice hazard and environmental forecasting.

A BBOS team has been established consisting of ten Canadian universities and ten international universities/research institutes forming the first ever University Network focused around a single collaborative world-class bay-wide observatory. Moreover, partnership has been established with various technology providers and users. These includes Inuit organizations, communities on both sides of Baffin Bay, government ministries and agencies, defence, shipping and marine based companies, industry, coastal and offshore fisheries and colleges. Universities and their partners will contribute separate components to the observatory infrastructure, based on their institutional strengths.

The Baffin Bay Observing System encompasses an area from the Lincoln Sea to the Labrador Sea. It will be the global first *integrated baywide environmental observation system, that will enable a sustained year round, near real-time observation of the atmosphere, ice, land and ocean at the scale of an entire ocean basin*. BBOS will include field stations, vessels, extensive field instrumentation, community-based technologies and a data centre. Two hubs will be used to coordinate and organize BBOS, one located in Iqaluit, NT and one in Nuuk, Greenland. BBOS will provide the temporal and spatial long-term data needed to improve our understanding of this data poor region and at the same time provide the basis for modelling exercises of expected future conditions.

Offshore surface and deep water sensors will monitor ocean temperature, salinity and circulation, water chemistry, biological activity, and sea ice and iceberg drift, while near-shore observatories in and adjacent to coastal communities will provide data on water quality, riverine coastal domain, biological activity, sea ice thickness, glacier activity, sea state, and vessel traffic. Underwater instrument platforms will be equipped with hydrophones (passive acoustics) to support the region wide study of marine mammal and fish behaviour and its relationship to environmental variables, such as temperature, salinity, tidal cycles, marine productivity, and anthropogenic noise. Acoustic modems will be used on surface craft, underwater vehicles, and on moorings for data communication enabling near-real-time data updates. Commercial and government-operated vessels will carry standardized sensor packages that report key ocean and atmospheric variables in real time in order to increase the data availability for operational predictions of weather, ice, and ocean-related conditions.

A network of shore-based marine field sites will support coordinated process studies and multi-use of data by a diverse group of academic, government, and industry researchers and northern communities. In addition, coastal and offshore marine research will be conducted using research vessels from Canada, Denmark/Greenland, US and Europe in collaboration with the commercial fishing fleet, tourism vessels and the Canadian, US and Danish Navies. Data collected by mobile platforms (surface vehicles and underwater gliders), autonomous oceanographic moorings, automated ice motion trackers, volunteer observing ships, and satellites will complement observations from fixed cabled observatories on the seabed at coastal and deep water locations. Shore-based climate measurements, GPS recorders, and radar stations will provide meteorological, ice, and ocean data to support studies of sea ice formation and melt, as well as ice hazards. In addition, continuous environmental data acquisition by these remote shore stations will help improve weather and environmental forecasting for the region.

Working closely with communities and regional organizations, the Inuit need for observational data supporting adaptation and decision-making will be identified. Community members will be equipped with, and trained on, portable field equipment and mobile computing technologies in order to collect critical data on snow and sea ice thickness, seawater properties, marine species activities, and the measurement of other coastal zone environmental variables including those prioritized by the Inuit as part of an integrated Community Based Monitoring (CBM) system. Data from all marine and coastal sensors will be integrated, hosted, and served openly to all users via national and international repositories. CBM data will be managed in partnership with communities and with cyber-infrastructure support from the Arctic Institute of North America.

2 INTRODUCTION

The Arctic is frequently at the forefront of international public and government interest because of its sensitivity to climate change. On average, the temperature on the Earth's surface has increased by 0.9°C since 1880, but rates of temperature increase in some parts of the Arctic have reached more than three times this level (IPCC, 2013). Most of the warming observed over the past 50 years can be attributed to human activities and particularly to the burning of fossil fuels. Recent studies conclude that warming in the Arctic since 1980 has been twice as much as the rest of the globe and that in 2005-2016 the Arctic had the highest average temperatures since records began in 1840 (SWIPA, 2017). Records of increasing temperatures, melting glaciers, reductions in extent and thickness of sea ice, thawing permafrost, and rising sea level globally all provide strong evidence of recent warming in the Arctic. Atmospheric and ocean circulation patterns create regional variations, with some areas warming more than others and a few areas even showing a cooling; but for the Arctic as a whole, there is a clear warming trend.

Geopolitics is shifting and the Arctic is becoming an important area of new and sometimes contested economic, legal, and governance perspectives related to maritime activities and environmental management (Newton et al., 2016). Decreasing summer sea ice has led to a growing global interest in establishing new, shorter, and more profitable shipping routes through the Arctic, and in developing Arctic resources including offshore oil and gas, mining and fisheries (Pizzolato et al. 2014, 2016). For Canada and Greenland/Denmark, there are enormous possibilities along with many challenges and obligations, and for Inuit in both nations the potential benefits stemming from a changing Arctic are weighed against risks to the environment, to critical subsistence and commercial species, to important cultural practices, and to community and individual well-being.

The Lincoln Sea - Baffin Bay - Davis Strait - Labrador Sea corridor (hereinafter simplified to just Baffin Bay) is a central ecological hub shared between Canada and Greenland/Denmark. Massive southward flows of freshwater, sea ice, and glacial ice converge along the coasts of both Canada and Greenland affecting natural and anthropogenic processes operating throughout Baffin Bay and along its shores. The North Water Polynya (NOW, Pikialasorsuaq), located at the northern limit of Baffin Bay, is one of the most productive marine systems in the northern hemisphere, and Inuit (and their predecessors) have occupied the region and utilized the NOW and other waters of Baffin Bay for roughly 5000 years. The climate of Baffin Bay is shaped by the Greenland Ice Sheet to the east (>1,000,000 km^2 of glacier ice), Canadian ice caps to the west (>100,000 km^2 of glacier ice), and the Arctic Ocean to the north (>10,000,000 km^2 of sea ice in winter). Today, exploitation of non-renewable (e.g, minerals, oil and gas) and renewable resources (fisheries), marine transportation, and tourism are experiencing rapid growth in the area.

Many Arctic animals, such as polar bears, seals, walruses, and seabirds, rely on marine biological productivity and on the presence of sea ice, both of which are highly dependent on climatic conditions. New and young sea ice forms are becoming a more prevalent feature in the Arctic as the icescape transitions from one dominated by multiyear ice to one of primarily first-year sea ice (Kwok, 2007; Maslanik et al., 2011; Gearheard et al. 2013, Barber et al., 2015). Reduced ice thickness and increased open water conditions in the Arctic favour phytoplankton blooms below sea ice (Rysgaard et al. 1999; Boetius et al. 2013, Mundy et al. 2009) whereas a shorter ice covered season may reduce the productivity of sea ice algae and the ice-associated ecosystem. Although much remains to be understood, recent studies provide evidence of how climate change has already resulted in clearly discernable changes in Arctic ecosystems and fisheries (Post et al., 2009; Wassmann et al. 2011; Gérin-Lajoie et al. 2016).

Arctic indigenous communities have shaped their cultural, social, and economic activities around the sea, ice, and landscapes of the north. They now face uncertainties and unexpected challenges because of the concurrent forces of climate change and globalization. They are finding weather less stable and predictable, and are affected by changes in wind, snow, sea ice, icebergs, and glacial discharge. In addition, long-range transport of pollutants and the increase of ultraviolet radiation reaching the Earth's surface as a result of the thinning of the ozone layer have negative effects on humans, animals, and plants in the Arctic. Finally, the ability of Arctic populations to manage the impacts of climate change will be greatly affected by political, legal, and socioeconomic factors such as growing populations, urbanization, industrial development, altered shipping patterns and ice-breaking activities, and self-determination rights. Arctic people need access to a host of local and regional data and information to adapt to climate changes and to make decisions on future development.

Climate change and the combination of increased global demand for resources in an ecologically sensitive and significant region demonstrate the urgent need for long-term data collection and committed collaboration among science, government agencies, the private sector, policymakers, and the communities surrounding Baffin Bay. These data and information needs are also global; the bay is also an area of critical water mass exchange between the Arctic and the North Atlantic. This interconnectivity underlies the support expressed in the 2013 Galway Statement on Atlantic Ocean Cooperation, which calls for broad international cooperation to "*increase our knowledge of the Atlantic Ocean and its dynamic systems - including interlinks with the portion of the Arctic region that borders the Atlantic*". By modulating the fluxes and configuration of ice and freshwater in Baffin Bay, the changing Arctic climate will affect ecosystem services regionally and in the western North Atlantic, as well as globally. River discharge has increased and the volume of Arctic glaciers and sea ice has radically declined in recent decades. Iceberg calving and accelerated melting and discharge of glaciers and the Greenland Ice Sheet are major contributors to global sea level rise. Changes in weather conditions and in the icescape of Baffin Bay including the release of numerous large icebergs and unpredictable ice hazards pose special challenges on an operational scale to safe transportation in the area.

3 RESEARCH OBJECTIVES

The overarching **vision** for the Baffin Bay Observing System is to develop an integrated environmental observation system, that will enable sustained year-round, near real-time observation of the atmosphere, ice, coast and ocean at the scale of an entire ocean basin (Baffin Bay). Human activities such as shipping will also be monitored. This observatory will be a unique platform for advancing our understanding of how global climate change affects the Atlantic sector of the Arctic system, and in turn how changes in the Arctic system affect the North Atlantic and beyond.

Why do we need an observing system? Climate change is occurring rapidly and has cascading effects from physical changes to the environment, ecosystems, and social, economic, and geopolitical conditions. In addition, there is a need to understand processes at the larger regional scales in order to understand local conditions. To operate safely and responsibly in any geographic region there is a need for improved weather, ice hazard, and environmental forecasting, which is currently inadequately developed for the Arctic.

Why in Baffin Bay? Climate change is opening up Baffin Bay for new activities, including increased shipping with increased risks for oil spills and search and rescue. Baffin Bay is one of the most productive marine systems in the northern hemisphere, including the North Water Polynya, and an important site for natural resources (fisheries, marine mammals, birds). It is an important link between the Arctic Ocean and the North Atlantic. It is also an Inuit homeland and important site for cultural resources and coastal interactions. The bay has limited data coverage both temporally as well as geographically.

Why now? The climate is changing rapidly; the Greenland Ice Sheet is melting with a further risk of sea level rise and a range of teleconnections to southern latitudes, e.g., changes that will affect meteorological, oceanographic, and biological conditions in the south. Increased access to the area could greatly augment the risk for regional accidents and environmental pollution while simultaneously enhancing local economic opportunities. The technology readiness level (TRL) of autonomous devices and communications is sufficient to allow for the capability to monitor the entire extent of Baffin Bay. Experience in operating such large infrastructures is now available. The potential for a broad international collaboration exists. Importantly, there is also reconciliation and collaboration with indigenous communities as they move towards self-determination.

What will be the societal benefit? Real-time and near real-time, high quality multi-use data from the Baffin Bay (i.e., Lincoln Sea to Labrador Sea), which will improve our understanding of this data poor region. This will deliver better weather, ice hazard, and environmental forecasting aimed at reducing risks and accidents. The BBOS will also deliver important sea state data for predicting an oil spill movement in icy waters and for aiding search and rescue operations. In addition, it will deliver better advice for fisheries and harvesters to support and inform a sustainable economies. It will provide a research infrastructure to support the Inuit in self-determination and enable new policy development. Finally, it will provide vital basic measurements for 'evidence based' research projects and policy development, and attract and increase collaboration between local, regional, and international investigators, stakeholders and regulators.

3.1 Inuit Leadership and Participation

A key objective for BBOS is to fully integrate Inuit participation and community research priorities into the project; community-based observing (CBM) is one of the main integrative research themes and approaches. It is our vision that Baffin Bay communities, supported by the BBOS network and regional Inuit organizations, will lead and manage CBM activities and be linked with other Arctic knowledge hubs and networks (e.g., CACCON, ELOKA). Inuit research, questions, and approaches identified through the CBM theme will complement and inform the research conducted under other themes within BBOS, including best practices in co-design and co-production (ITK, 2016). Several meetings on both sides of Baffin Bay have already taken place and plans are involving for joint collaboration and Inuit leadership of various components of the program.

This model of Inuit community participation and leadership in research would fully integrate Inuit knowledge, perspectives, and information needs in research design, implementation, and interpretation. It transcends typical project consultation on, and community engagement about, large science projects. Importantly, it demands that communities are afforded the time and opportunity to reflect on and discuss their own research priorities, and that they are given the support to address solutions-oriented research for proactive adaptation policies in their communities. The framework for such partnership in BBOS by Inuit communities and organizations will take time to initiate and operationalize, but in due course will be an important ground breaking BBOS legacy, hopefully serving as best practice for future big-science Arctic initiatives, including those spearheaded by Inuit themselves.

3.2 Industry and Government Involvement

BBOS is a network that will be driven by the needs of end users and scientifically based. This framing ensures that scientific efforts have utility that enables both the development of globally and locally relevant science, while also providing support for decision-making, risk reduction, economic development and resource sustainability. Working directly with industry and government partners from the outset will help to guide network investigations and will also enhance knowledge mobilization and uptake of scientific discoveries. This approach will facilitate fundamental private-public partnerships and enable leveraging of funding aimed at developing innovative ice navigation, ocean sensing, and co-management and decision-making opportunities. This framework will break down the barriers between scientific measurements and policy often associated with large scientific endeavours, paving the way for innovation and collaboration. This will make the region a global science-policy leader in Arctic oceans management

3.3 Primary Research Areas

A. The Polar Climate System

Many of the natural physical processes occurring in the polar atmosphere and oceans are of profound significance in controlling the global climate, thereby affecting livelihoods across the world. Future changes in climate mean that many of these processes may be modified in intensity or effect, with the impacts being felt most strongly for the local residents and operators in Baffin Bay, with such changes also having global importance. Understanding polar processes in a global context will therefore benefit people, policy and businesses well beyond Baffin Bay.

The main project objectives in relation to the polar climate system will address:

- The role that Baffin Bay plays in controlling transformations that occur between the Arctic and Atlantic Oceans.
- How changes in Baffin Bay have local, regional and global importance for people, policy and businesses.

Key questions to be addressed:

- What are the heat, freshwater, and carbon fluxes and the climate relevant system budgets?
- What are the impacts of freshwater into Baffin Bay on climate and ecosystems?
- What is the role of warm water input from the south in changing sea ice and glaciers?
- What are the key atmosphere-ice-ocean interactions?
- How do we improve forecasting and projections of future local, regional, and global climate?
- How do the changing polar climate systems affect lower latitudes through ocean and atmospheric circulation?

B. The Cryosphere

The Greenland ice sheet and Canadian ice caps hold sufficient water to raise global sea level by more than six metres if they were to completely melt. The uncertain stability of these glacier systems, many of which are in areas of recent, rapid, climate change makes them uniquely vulnerable to both atmospheric warming and changes in ocean temperature and circulation. Sea ice is another profound feature of Baffin Bay that plays an important role in the control of physical and chemical exchanges between the atmosphere and ocean, as well as for living organisms. Sea ice and icebergs also present hazards to shipping, marine structures and Inuit use of marine areas.

In relation to the cryosphere, the main project objectives will address:

- Sea ice cover and polynyas.
- Release and uptake of greenhouse gases.
- Sea ice and iceberg impacts on shipping and marine activities and structures.
- Risks to coastal communities, coastal ecosystems, and assets.
- Climate change and mass loss of ice sheet leading to sea level rise.

Key research questions:

- What are the processes controlling glaciers and ice sheets and their links to global sea level, ocean circulation, climate, and ecosystems?
- What are the processes controlling sea ice distribution and evolution?
- How are permafrost and snow changing?
- What is the coupling between the cryosphere and other aspects of Baffin Bay? (e.g., glaciers, sea ice, permafrost, snow, freshwater runoff, energy, icebergs, ocean circulation, ecosystems, and climate).
- What is the best technology for monitoring the cryosphere?
- What are the primary community concerns in relation to the cryosphere? (e.g., safe travel over sea ice, drinking water quality, effect on marine ecosystems, etc)
- What are the implications of changing sea ice (and challenging ice conditions such as ridged ice) for shipping activities and offshore platforms

C. Marine Ecosystems

Marine ecosystems provide numerous services to society, including regulating services (such as climate and waste regulation), provisioning services (food, raw materials, biochemical, and genetic resources), cultural services (physical and mental health and well-being, community well-being, cultural identity, economic opportunities), and supporting services (nutrient cycling, primary productivity, carbon storage etc.). Many Arctic animals, such as polar bears, seals, walruses, and seabirds, rely on the marine biological productivity (fish, shrimp,

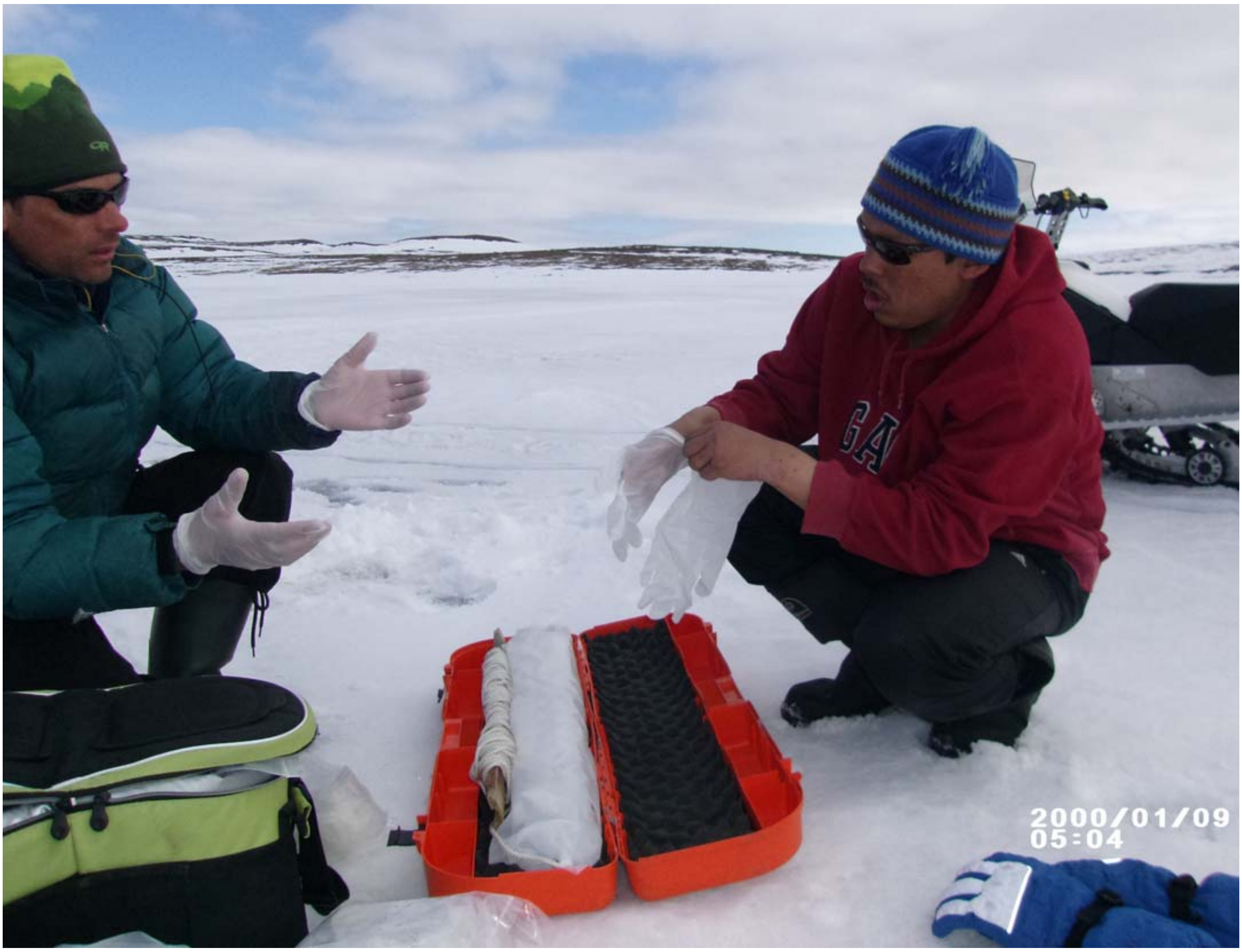
squid) and on the presence of sea ice, both of which are highly dependent on climatic conditions. In addition, commercial fisheries in the north are rapidly growing, species such as capelin, are moving northward, and shifting temperatures are impacting arctic cod productivity. Sea ice and oceanographic conditions in Baffin Bay are changing rapidly and we currently lack sufficient knowledge to understand the linkages between these changes and those in marine ecosystem function and production.

In relation to marine ecosystems, the main project objectives will address:

- Key physical and chemical drivers of biodiversity and ecosystem processes in the atmosphere, snow, sea ice, glaciers, ocean, and sea bottom.
- Spatial and temporal cataloging of biodiversity and food webs (e.g., coupling between coastal shallow water and deep water ecosystems).
- Implications of environmental change (physical and chemical drivers) and anthropogenic activities for biodiversity and ecosystem processes.
- Surveying, monitoring, and research efforts related to climate change and environmentally hazardous substances in Baffin Bay.

Key research questions:

- What are the defining Baffin Bay food webs; coastal to offshore, shallow to deep-water?
- What are the short and long-term changes in Baffin Bay food webs?
- How will Baffin Bay ecosystems adapt to climate changes?
- How vulnerable are Baffin Bay ecosystems to combined human and natural influences?
- How do we manage Baffin Bay coastal and marine living resources in a sustainable way?
- How does ocean acidification affect polar marine and coastal ecosystems?
- How are the nutrient exchanges between the Arctic and the Atlantic Ocean impacted by changing conditions?



D. Impacts of Contaminants

The increase in maritime operations and transport in Baffin Bay may result in an increased risk of oil spills and other transport related contaminant spills in ice-covered seas. This includes oil spills in Canadian or Greenlandic/Danish waters but also local effects of transportation from the Russian sector of the Arctic to Baffin Bay due to predominant sea ice circulation patterns. Long-range atmospheric transport and the bioaccumulation of contaminants in polar food chains, as well as increased UV radiation, have already been shown to have significant impacts on Arctic ecosystems and human and wildlife health affecting food security and food safety. Arctic and indigenous communities are expected to continue to experience such risks as animals change migration routes, hunting conditions become more difficult, and contaminant bioavailability may change in response to continued climate warming and sea ice retreat. New opportunities for economic development and community prosperity are unclear; for example, to what extent will people benefit from tourism, private sector enterprise, and natural resource development?

In relation to contaminants and development, the main project objectives will address:

- Effects of long-range contaminant transport and their bioaccumulation in Baffin Bay food chains.
- Risks to safe water supply and country foods.
- Increased economic activity and related hazards.
- Economic well-being and development of local communities.

Key research questions:

- How do natural and anthropogenic pollutants and contaminants currently affect Baffin Bay?
- What is the priority list of pollutants to monitor?
- How do we design optimal collection of information concerning contaminants? (e.g., automated instrumentation *vs.* human collectors.)
- What are the future contaminant scenarios and how do we improve monitoring and decision making to decrease their potential impact?
- How do we increase food security for northerners and the use of traditional food?

E. Sustainable Management of Resources

The circumpolar Arctic is predicted to garner investments ranging from 100bn CAD$ (Lloyds, 2012) to 300bn CAD$ (Synberg, 2013) over the next decade as climate change alters international shipping routes, improves access to renewable and non-renewable resources, and draws tourists to the region (also see Mikkola and Käpylä, 2013). Approximately 20% to 30% of untapped global petroleum resources are found in the Arctic, and oil exploration activities in Baffin Bay have recently increased. There are growing fisheries and tourism opportunities, and global warming will facilitate better access to both. Arctic and non-Arctic nations are investing in icebreaking capabilities and other infrastructure to explore these and other potential economic opportunities across the Arctic. This increased interest in the region, from both Arctic and non-Arctic states as well as the international business community will play an important role in the development of the region, but will also have significant impacts on the ocean and coastal environment and on Inuit and northern communities. For Canada and Greenland/Denmark, there are enormous possibilities along with many challenges and obligations that require both monitoring and policy attention. For Inuit on both sides to benefit from a changing Arctic, adaptation plans need to be developed that take into account risks to the environment, to critical subsistence and commercial species, to cultural practices, and to community and individual well-being.

In relation to the management of resources, the main project objectives will address:

- Monitoring current use and engaging in projections of future use of the marine environment - i.e., shipping, tourism, fisheries, and mining activities.
- Monitoring human use impacts to sensitive coastal and shoreline areas.
- Undertaking complex risk analyses to identify hot spots and highly sensitive areas where enhanced policy and regulations could reduce ecological and cultural impacts.
- Improve navigational tools, ice forecasts, and data products for industry stakeholders aimed at risk and spills reduction.
- Identifying sustainable use thresholds of resources while maintaining the structure, functioning, and productivity of Baffin Bay ecosystems.
- Development and implementation of innovative co-management strategies for the Baffin Bay resources and shipping activity.
- Identifying innovative policy and regulatory mechanisms.

Key research questions:

- How can use and management of natural resources in Baffin Bay occur in a sustainable and safe way in the context of a changing climate and increased human activity?
- How can we best work with industry and other government agencies toward common goals such as risk reduction, improved forecasting, and enhanced data acquisition?
- What are the consequences of a changing environment for local and global food sources and food security?
- How can environmental consequences be minimized for extractive industrial activities in Baffin Bay and how can society maximize the benefits?
- How can Baffin Bay contribute to sustainable growth in the marine and maritime sectors and to a low carbon energy transition?

F. New Technologies and Innovation

Technology development is a key enabler for cutting-edge scientific research in the Arctic. Rapid technological developments have had the most profound results in advancing polar marine and cryosphere research given the very high cost of undertaking fieldwork in these locations (e.g., with icebreakers). Mitigating environmental impacts of climate change and development in sensitive Polar Regions will require new technologies and innovation to increase our observational capacity and reduce logistic costs. Baffin Bay will be the first regional observatory of its kind in the Arctic. The technology needs for the scientific research studies are multi-faceted and diverse in nature.

In order to achieve the project objectives, new technologies in the following areas will need to be developed:

- Vessel-based oceanographic and atmospheric measurement systems.
- Moored underwater observing systems.
- Robotic and drifting platforms for measurements operating over an extended area in ice-covered waters.
- Satellite platforms.
- Numerical modeling.
- Information and communications technologies.
- New risk analytics for evaluating human-environment interactions that are aimed at policy and decision-making.
- New forecasting approaches for dangerous and currently unpredictable ice conditions.

Key research questions:

- How do we establish effective partnerships between businesses, universities, research institutions, government agencies and Inuit partners in order to stimulate new technological development?
- How to integrate atmosphere-ice-ocean observatories?
- How to develop the best technology for a complex Arctic environment with remote data transfer, cabled and autonomous vehicles operating in highly variable conditions?
- How can we improve forecasting of high risk ice conditions in real time to end users?
- What new technologies can be created and used for improving marine navigation (enhanced e-charts or SMART charts etc.)?

3.4 Education and outreach

BBOS will create education, capacity building and outreach programs focusing on Arctic issues in cooperation with universities, high schools, industry, and communities on both sides of Baffin Bay. In particular, the goals are to 1) strengthen local education in collaboration with institutions in Canada, Greenland, Denmark and beyond, 2) stimulate growth in academic excellence among Inuit in environmental monitoring, 3) promote and develop cross-institutional and cross-disciplinary education programs. 4) Create mechanisms to attract young students from undergraduate to Ph.D. levels, and 5) to increase employment opportunities in public and private sectors locally and regionally. 6) investigate ways of transferring Inuit led education initiative in Greenland to those in Canada, including development of an Arctic university in Iqaluit.

4 PROPOSED RESEARCH INFRASTRUCTURE

A conceptual model for monitoring core components in the different subprograms across BBOS is illustrated below. (See Appendix A.1. for a list of measured parameters).

With reference to Figure 1, each sub-program is explained in the following: (1) Offshore surface and deep water sensors will monitor ocean circulation, water chemistry, biological activity, and iceberg drift, while (2) near-shore observatories in and adjacent to coastal communities will provide data on water quality, biology, sea ice thickness, glacier activity, sea state, human impacts to coastal areas, and vessel traffic. Underwater instrument platforms will be equipped with hydrophones to support the study of fish and marine mammal behaviour and its relationship to environmental variables such as temperature, salinity, tidal cycles, marine productivity and anthropogenic noise (from shipping, seismic activity, port construction, etc.). Acoustic modems will also be used on surface craft, underwater vehicles, and on moorings for data communication enabling near-real-time data updates. (3) Commercial and government-operated vessels will be partnered to carry standardised sensor packages that can report key ocean- and atmospheric variables in real time in order to increase the data availability for operational predictions of weather, ice, and ocean-related conditions and to improve navigational information. A citizen-based science approach will also be developed and encouraged among ship-based tourists, scientists, and commercial operators. Citizen science observations of Arctic wildlife, ice, and other human observations of natural conditions will be linked to the well-established national database 'Nature Watch' and can be used to validate, extend, and explain other sensor-based observations.

Strong industry partnerships will help enhance proposed opportunistic monitoring activities and will also help to ensure research is end-user driven and scientifically informed. (4) A network of shore-based marine field sites (including ice cap margins) will support coordinated process studies by a diverse group of academic, government and industry researchers and northern community members in Canada and Greenland/Denmark. In addition, marine research will be conducted using vessels owned by Canada, Greenland, and Denmark. Data collected by autonomous mobile platforms (airborne, surface vehicles and underwater gliders), autonomous oceanographic moorings, automated ice motion trackers, volunteer observing ships, and satellites will complement observations from fixed cabled observatories on the seabed at coastal and deep water locations. (5) Shore-based climate measurements, GPS recorders, and radar stations will provide meteorological, ice, and ocean data to support studies of sea ice formation and melt, as well as ice hazards. In addition, continuous environmental data acquisition by these remote shore stations will help improve weather forecasting for the region. (6) The comprehensive BBOS monitoring data-set collection will be used as ground truth calibration of remote sensing to provide a high spatial distribution of conditions in Baffin Bay and beyond. Data can also be used in order to enhance safety of navigation as well as supporting maritime operations like search and rescue.

Working closely with residents of local communities, Inuit needs for environmental data will be established. Community members will be equipped with and trained on portable field equipment and mobile computing technologies in order to collect critical data on snow and sea ice thickness, seawater properties, marine species activities, and the measurement of other coastal zone

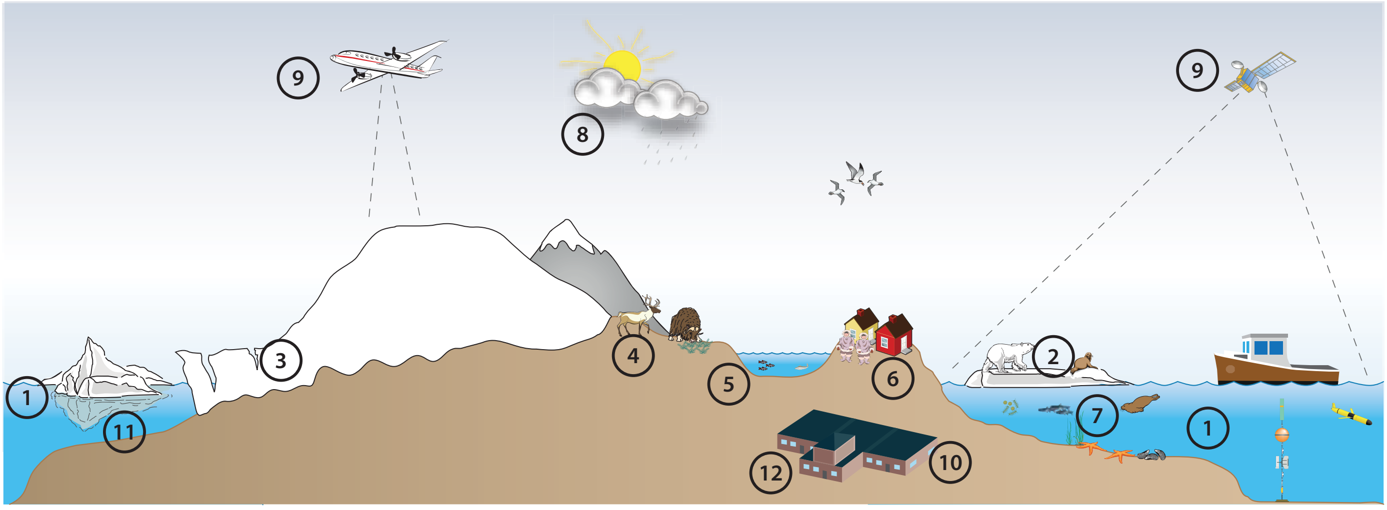


Figure 1. Conceptual model for core monitoring components in the different subprograms across BBOS. It will comprise field stations, vessels, extensive field instrumentation and community-based technologies. BBOS is an integrated baywide environmental observation system, that will enable a sustained year round, near real-time observation of the atmosphere, ice, land and ocean at the scale of an entire ocean basin (Baffin Bay). More information is provided in appendix.

environmental variables including those prioritized by the Inuit as part of an integrated Community Based Monitoring (CBM) system. Data from all marine and coastal sensors will be integrated, hosted, and served to all users and the public.

The Baffin Bay Observing System will be designed and built for an expected lifetime of 30 years. The marine technology sector will contribute many of the underwater and shore-based components for the Baffin Bay Observatory. These technologies will include seafloor nodes, sensor platforms, sensors and sensor packages, shore-based control equipment, and software for generating specialized data products. Companies participating in the Baffin Bay Observing System will be able to showcase their ocean technologies in an Arctic setting, where ocean monitoring represents a future market. The BBOS will extend this demonstration to the challenging Arctic coast where remote monitoring is often the only option for situational awareness and long-term environmental management. **The total integrated budget for the BBOS is still under development but is in the order of $170M; to be distributed across the Canadian BBOS network**. International network and collaboration partners are described in section 8, page 25.

5 USERS

BBOS will be designed from a multi-use perspective. National and international science communities, Inuit, government agencies, business and local operators from both sides of the bay will be central users of the facility. BBOS will be designed in collaboration with industry (ship operators, fisheries, tourism, and resource development) and Inuit in such a way that output will be accessible and understandable for both specialized and general users. The engagement of stakeholders in the scientific achievements of BBOS will foster an environment in which knowledge mobilization and knowledge translation can directly support decision-making. Inuit Circumpolar Council (ICC), local policy makers, industry stakeholders, and self-governments will form a consultative team, bringing both traditional knowledge and co-management of resources to bear on science-to-policy integration in both Canada and Greenland/Denmark and beyond. Local, regional, national, and international bodies with co-management responsibilities will be partners in the program from the outset to ensure that the design meets expected information requirements and policy outputs, and that outputs are delivered to pertinent users responsible for resource management and development in this region of rapid environmental change and globalization. Finally, BBOS will play an important role in educating the new generation of multidisciplinary researchers who will be prepared to continue the dialogue and development of cross-disciplinary, cross-cultural, and cross-institutional decision support.

6 EXPERIENCES AND BENEFITS

The Arctic represents both a challenge and an opportunity to Canada, Greenland/Denmark, and the Arctic Council member states particularly and to all countries of the world in general. A 'third ocean' is rapidly becoming available for development, but this fragile environment requires stewardship. The BBOS team has the scientific excellence needed, the international networks in place, and the leadership skills to make data collection and analysis for this region a unique contribution to the global issue of Arctic climate change. The BBOS consortium will leverage world-class scientific and engineering knowledge with private sector talent and expertise working along the discovery-innovation continuum to the benefit of Canada, Greenland/Denmark, the Arctic, and indeed the world.

The BBOS team has also demonstrated a strong commitment to research training, community engagement, and outreach of science. The team has been instrumental in developing the 'Community Based Monitoring', the 'Schools on Board', and 'Schools on Tundra' programs. During the international polar year (IPY) Circumpolar Flaw Lead System Study (IPY-CFL) project, BBOS team members contributed significantly to the global IPY Education Outreach and Communication (EOC) agenda by integrating Artists on Board, International Schools on Board, and an international media competition with the World Federation of Science Journalists into an active research agenda. Copland, University of Ottawa, has been the North American leader of the Canadian-US-Norwegian GlacioEx project for the past five years, which has enabled the exchange of up to 20 faculty and graduate students per year in areas of Arctic science. Dawson, University of Ottawa, chairs an international social impacts and policy working group for the World Meteorological Organization's Polar Prediction Project (YOPP - i.e. 10-year focused international effort to improve prediction and forecasting in polar regions). Many of our faculty interact extensively with local, national, and international media (TV, radio and print), with policymakers, Inuit co-management organizations, Senate committee hearings, policy workshops, Canadian Arctic Sovereignty, ADM committees, and industry (oil companies, hydroelectric utilities, mining companies, and marine transportation companies). The team also works extensively with Inuit research collaborators, including publication of a book entitled *Two Ways of Knowing: Merging Science and Traditional Knowledge During the Fourth International Polar Year (Barber and Barber, 2009).* In addition, Rysgaard's ASP team have been instrumental in building up natural science courses for local high school students and local university students as well as international students in new education buildings (funded by private donors) in Nuuk, Greenland. These courses are now occurring year round, the number of students is increasing, and the new facilities will have space for 40 students. The goal is to make a full natural science university degree in 'Arctic system science' and to collaborate and coordinate local education and research activities across Baffin Bay.

The BBOS team has exceedingly strong training environments due to the critical mass of excellence housed within the team and through our partnerships nationally and internationally. The BBOS team will take advantage of unique training programs developed under the ASP partnership (www.asp-net.org) where international exchanges are an important part of the training. More than 130 graduate students already share curriculum, engage in discipline specific field schools and travel between Canada, Denmark, and Greenland laboratory environments. Faculty and staff in the ASP Centres already teach in each other's programs and coalesce to contribute to at least two field schools and four professional development-training courses per year. The ASP Student Association coordinates these activities through leadership elected from University of Manitoba, Greenland Institute of Natural Resources and Aarhus University.

BBOS will also integrate several other teaching/training initiative including NSERC CREATE (Collaborative Research and Training Experience) programs, the UQAM led ArcTrain (Arctic Training) involving eight Canadian Universities, the University of Bremen, and the Alfred Wegner Institute in Germany; the UOttawa led RemoteEx project on remote sensing of the cryosphere (funded for 2017-2020 by the Norwegian Centre for International Cooperation in Education), involving four Canadian universities, the University of Oslo, University Centre in Svalbard and Alaska Geological Survey; and the UM-led NSERC i-AMS (industrial development of the Arctic Marine System) proposal involving seven Canadian Universities, four Federal departments, and eight private sector companies. BBOS will strongly engage with the Nunavut Research Institute (NRI), Arctic College, and Transport Canada to promote, enhance, and foster capacity building and training of Canadians living in the north. This model of fluid Highly Qualified Personnel (HQP) engagement across the BBOS consortium is already in place and has strong metrics of success – over 530 students trained over the past five years; 110 holding academic positions in Canada, 85 in Europe, 25 in Asia, approximately 130 past students working in Industry and roughly 80 more in various levels of government, both in Canada and abroad. Another 70 past students hold positions in non-government organizations. We expect our trainees will take up positions within the areas of environmental engineering, geophysics, physical and chemical oceanography, hydrocarbon exploration, oil spill detection, oil in ice mitigation, marine transportation, mining, and remote sensing, as well as in policy development, policy integration, and management. Employment opportunities accrue from the environmental engineering, ocean science and technology companies, marine transportation, fisheries, oil and gas industry, government regulatory agencies, and academia.

Examples of benefits from BBOS:

- Technology – benefits to companies and users.
- Risk reduction and mitigation of environmental and cultural impacts.

- Better data – for a wide range of consumers including individuals, communities, and managers.
- Improved knowledge – promoting safer operations, better and sustainable economies (transport, fisheries, and industry).
- Employment – improved opportunities for individuals and better employees for business.
- Capacity building and Training – better opportunities for all users.
- Better integration between science and traditional knowledge.
- International – sharing and coordination leading to a more efficient return on observing investments.
- Global – better understanding of climate change in the Arctic and connections to the North Atlantic.
- Situational awareness – providing improved safety and security aspects and better search and rescue capabilities.

7 MANAGEMENT

The University of Manitoba have led the development of this BBOS network concept paper in partnership with nine other Canadian universities (Memorial, Dalhousie, Laval, Ottawa, Calgary, Windsor, Alberta, Carleton, and Victoria) and ten international universities/research institutes (Alfred Wegener Institute, Germany; French National Center for Scientific Research, France; University of Copenhagen, Denmark; University of Aarhus, Denmark; Technical University of Denmark; Geological Survey of Denmark and Greenland; Danish Meteorological Institute, Greenland Institute of Natural Resources, University of Washington, USA; University of Tromsø, Norway) forming the first ever University Network focused around a single collaborative world-class bay-wide observatory. Partnerships have been established with the various providers and users of the type of technology and science envisioned within the BBOS program. These include Fisheries and Oceans Canada (including Canadian Coast Guard), Environment and Climate Change Canada, Defence Research and Development Canada, Danish Defence Center for Operational Oceanography, Indigenous and Northern Affairs, Natural Resources Canada, National Research Council of Canada, Transport Canada, the Canadian Space Agency, CanNor, national and international shipping and marine based companies (Fednav, NEAS, Group Desgagnés, Adventure Canada, others) Nunavut government ministries, Nunavut Arctic College, Inuit Taparit Kanatami (ITK), the Inuit Circumpolar Council (ICC), Ocean's North Canada, coastal and offshore fisheries in Baffin Bay (NOAHA, Royal Greenland, KNAPK) the World Wildlife Fund (WWF), and communities on both the Baffin and Greenland sides of Baffin Bay. Universities and their partners will contribute separate components to the observatory infrastructure, based on their institutional strengths.

We have set up a temporary management model for the BBOS initiative and foresee a multi-sector management model with primary centres in Iqaluit, NT and Nuuk Greenland. Community based centres will be networked to the central management centres. The BBOS organization will be operated as an interdisciplinary center without walls and established through collaborations between participating Canadian, Danish/Greenlandic and international institutions.

The BBOS organization will consist of a Steering Committee ('Right'/'Stakeholders'), a Secretariat, Coordination group, and sub-programs. The overall Steering Committee will consist of representatives from the right/stakeholders and representatives from the main science institutions involved. The Steering Committee will be responsible for the overarching strategy and oversee the work carried out by the Secretariat and the Coordinating Group.

The BBOS Secretariat will follow the Network of Centres of Excellence (NCE) framework with a scientific director, an executive director, a board of directors and a research management committee. The central secretariat will provide provide support to ensure a good coordination of activities within BBOS. A database management team will be established to investigate the best way to implement, operate and maintain a central BBOS database and data portal. This will be coordinated with already existing data management systems. In short, BBOS will: 1) process and archive data on the common variables according to scientifically sound and well-documented standard and forms, 2) serve data on common variables in real time and delayed mode, 3) enable efficient access to data on the common variables and derived products.

The BBOS Coordination Group consists of the scientific and executive directors, a database manager, sub-program leaders and one logistician from each of the BBOS long-term multidisciplinary monitoring sites. The Coordination Group contributes to the development of the five-year BBOS strategies, is responsible for coordinating fieldwork activities, and facilitates cross-institutional initiatives.

Leaders from the participating institutions shall lead the BBOS sub-programs: Subprogram 1, Subprogram 2, Subprogram 3, Subprogram 4, etc. (see Appendix A.1. for list of monitored parameters). These subprograms are not necessarily classical science themes, but can cover broader ranges of disciplines for the benefit of local, regional, national, and international questions. The subprogram leaders contribute to the BBOS strategy and will be responsible for ensuring high scientific standards through cooperation with relevant experts from other institutions. We will use this efficient management model in the startup phase. The management model will of course develop as the project evolves.

BBOS has been designed as a bay-wide observatory that will be operated year round. It will comprise a science hub in Iqaluit/Nuuk, field stations, vessels, extensive field instrumentation and community-based technologies. Full-time staff will be based in the science hub, and in field stations. Technical staff will be responsible for operations and management of the overall facility, as well as logistics (user access) and coordination, activity scheduling, shipping, maintenance, and overseeing operational staff. Funding for technical and operations support staff will come from university sources and potentially through partnership with CHARS, Polar Continental Shelf Program, Danish/Greenlandic, European, and US funding bodies. Scientists, students, and technical staff conducting studies as part of BBOS, conducting laboratory work, or using the field stations, will be accommodated locally (room and board). There will be annual maintenance and cycling of BBOS moorings (5-10 year replacement cycle). This work will be undertaken using the Canadian coast guard ship Amundsen, European icebreakers where possible, coastal ships, and via partnerships with industrial shipping and tourism companies.

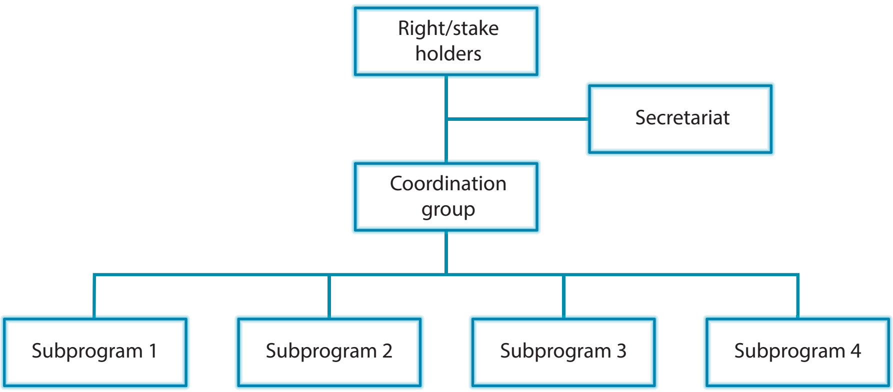


Figure 2. Temporary management model for BBOS. The BBOS organization will be operated as an interdisciplinary centre without walls and established through collaborations between participating Canadian, Danish/Greenlandic and international institutions.

8 INTERNATIONAL NETWORK AND COLLABORATION PARTNERS

The BBOS team has incubated, with other private sector companies, and Federal, Provincial and Territorial governments, a coordinated national network of Arctic marine science. This began 15 years ago with federally-funded networks such as Marine Baysys, North Water Polynya, Canadian Arctic Shelf Exchange Study (CASES), Sea-Ice Environmental Research Facility (SERF), Churchill Marine Observatory (CMO), Collaborative Mercury Research Network (COMERN), International Polar Year–Circumpolar Flaw Lead System Study (IPY-CFL), the ArcticNet Networks of Centres of Excellence (NCE) and the MEOPAR (Marine Environmental Observations Prediction and Response) NCE. Due to the high cost of Arctic science and the need for major infrastructure (icebreakers, aircraft, and remote camps), it was also necessary to establish highly coordinated international networks. Significant international collaboration began with the IPY-CFL system study (2006-2011). The IPY-CFL project evolved into collaborations with several international Arctic networks including: SEARCH (USA), ARCTOS (Norway), DEFROST (Europe), CHINAIR (China) and IAPP (pan-Arctic).

As a CERC at the University of Manitoba, Prof. Rysgaard was instrumental in the development of the Arctic Science Partnership, which began in 2012. ASP fully integrates the Arctic research at the University of Manitoba, the Greenland Institute of Natural Resources, Aarhus University in Denmark, Lund University in Sweden, University of Tromsø, Norway, and the Alfred Wegener Institute in Germany. The ASP was formed to study the impact of the changes in the Arctic; the mechanisms behind these changes; and consequences of these changes on people living both within and outside of the Arctic. ASP fosters a critical exchange of knowledge and provides scientists with a joint logistical platform, drawing on the numerous facilities administered by each institution, including research vessels, field stations, technical support staff, laboratories, and a common graduate level curriculum. We have used our ASP network as the framework to marshal the consortium for BBOS, expanding the ASP collaboration to Norway, Germany, United Kingdom, USA, Japan, Korea, China, France, Finland, Iceland and Sweden. BBOS thereby assures a strong Canadian commitment to the Arctic scientific cooperation under the framework of the transatlantic Ocean Research Alliance between Europe, the United States and Canada, launched with the *Galway Declaration*.

Our international collaborators bring an estimated $1.3B CDN in capital funding for new icebreakers, coastal research vessels, mooring programs and research stations in Greenland. To illustrate this, the University of Aarhus has just completed Station North, to be used extensively in our program, at a cost of $13.4M donated from the Villum Foundation. In addition, the Aage V Jensens Foundation has donated $12M to new joint ASP education facilities in Nuuk. Denmark/Greenland provides several coastal research vessels, one of which (the *Sanna*) was completed in 2013 ($9.5M). A new Danish Navy Vessel (*Lauge Koch*), designed to support science, will be brought online in 2018 ($80M). Investments in our own Canadian Arctic infrastructure both now (CCGS *Amundsen*, Alexandra Fiord Base, the Nunavut coastal vessel *Nuliajuk*) and in the near future (e.g., The CMO facility in Churchill, the Canadian High Arctic Research Station (CHARS) and the new research icebreaker *John G. Diefenbaker*) will support Canadian contributions to BBOS. University of Manitoba has received significant levels of funding ($31M over the past 7 years) from on going partnerships with oil and gas companies (Imperial Oil, Exxon, Chevron, Shell and BP), from Manitoba Hydro, Hydro Quebec, environmental consulting companies (KGS group, Stantec, Kavik-Stantec, C-CORE, Golder), Canadian Science and Technology companies (e.g., MDA, C-CORE, ASL), various federal departments (DFO, ECCC, INAC, and NRCan) and non-governmental organizations (WWF, PEW Charitable Trusts, and private Foundations).

Université Laval: Université Laval boasts a tradition for academic excellence and benefits from a well-established infrastructure for Arctic research. Over the past 50 years, UL scientists have developed a diversity of expertise in northern research (ocean and land, ecology, engineering, health, humanities). Led by Université Laval, ArcticNet is Canada's Network of Centres of Excellence that brings together scientists from 32 universities with their partners in Inuit organizations, northern communities, government, and industry to help Canadians face the impacts and opportunities of climate change and globalization in the Arctic. ArcticNet has deployed the icebreaker CCGS Amundsen annually since 2002 to monitor Canadian Arctic seas. Jointly managed by the Canadian Coast Guard and Université Laval, the CCGS Amundsen is Canada's dedicated research icebreaker that provides Canadian researchers and their international collaborators unprecedented access to the Canadian Arctic Ocean. Québec-Océan mobilizes Québec researchers to develop excellence in oceanographic research and training, pooling scientific equipment, technical expertise, and intellectual and financial resources from its members. Québec-Ocean is pursuing its ambitious program on the function and integrity of Arctic and subarctic marine ecosystems of ice-covered seas under climate change and provides support to the operation of CCGS Amundsen. Centre d'études nordiques (CEN: Centre for Northern Studies) is one of North America's leading research centres of excellence for the study of high latitude climate, landscapes, aquatic environments, vegetation and wildlife. CEN manages an array of Northern research stations and automated environmental stations. Université Laval will coordinate the contribution of ArcticNet, Amundsen, Québec-Océan and CEN to INTAROS, an emerging European large-scale project on integrated Arctic observation system (H2020, BG-09-2016). Finally, Laval has recently launched Sentinel North (CFREF), a 98 M$ worth initiative on new optical technologies for health and environment in the north.

Memorial and Dalhousie are developing the Ocean Frontiers Institute with a focus on marine ecosystems of the Northwest Atlantic. Together they are also developing new technology for ocean observation in the sub-polar Atlantic with a focus on gliders, underwater and wave, and new mooring technology – SeaCycler – capable of long-term real-time monitoring of the open ocean. They are active partners in the Overturning of the SubPolar North Atlantic Program (OSNAP) that is measuring the deep meridional overturning circulation of the North Atlantic. They are co-leads on the NSERC CCAR project Vitals that is making measurements and modeling air-sea gas exchange in the Labrador Sea. Memorial is a partner with the EU AtlantOS project that is seeking to enhance and integrate ocean observations in the North Atlantic and are also partners in the EU funded BlueAction with a focus on enhancing ocean observation in the Sub-Polar Atlantic. Dalhousie also has significant capacity for big data analytics and in processing AIS (automatic information system) shipping data which requires extensive handling. BBOS will benefit from Canada's existing Arctic shipping research groups which are predominantly at Dalhousie, Memorial and University of Ottawa. These groups already work in close partnership considering their rich and diverse areas of expertise.

The University of Ottawa has major partnerships and joint project agreements with many northern-focused federal government departments and Canadian shipping companies, including Transport Canada (Network of Expertise for Transportation in Arctic Waters), Canadian Ice Service (iceberg drift and deterioration and ship-ice interaction), Geological Survey of Canada (glacier mass balance, glacier velocity mapping), Defence Research and Development Canada (iceberg tracking and development of cold-resistant time-lapse camera systems), National Research Council (ice island drift, ship navigation technologies, and forecasting pressured/ridged ice) Canadian Coast Guard (establishment and implementation of the Northern Marine Transportation Corridors), Fednav (forecasting pressured ice and monitoring ice thickness), and Adventure Canada (remote site assessments and shoreline impact monitoring). These collaborations include the appointment of government scientists as adjunct professors, the co-supervision of graduate students, in-kind berths on vessel voyages, and fundamental linkages to policy and decision makers to ensure science-based policy uptake. The in-kind contributions of satellite and field data, ship berths, and FTE's from government partners provide uOttawa with >$1.5M/yr of support to graduate student and researcher projects. UOttawa also has a strong track record of consulting on glacial ice hazards for the offshore oil and gas industry, including C-CORE, Canatec, Coastal Frontiers Corporation, Shell, Exxon and Imperial Oil; as well as consulting on ship navigation, regulation and policy development for government agencies (Transport Canada, Coast Guard, DFO, NRC, Government of Nunavut), land claim organizations (IRC), and industry partners (Fednav, Adventure Canada). Academic collaborations with Carleton University (Water and Ice Research Laboratory) provides access to their iceberg drift database and extensive measurements of ice island deterioration, while collaboration with University of Maine enables coordination of field studies with one of the main groups currently measuring iceberg-ocean interactions on the Greenland side of Baffin Bay.

The University of Victoria owns and hosts Ocean Networks Canada (ONC), a not-for-profit society established in 2007. ONC operates cabled ocean observatories without an equivalent nationally or globally. The innovative cabled infrastructure supplies continuous

power and Internet connectivity to hundreds of subsea instruments from coastal to deep-ocean environments and in the Arctic. These observatories collect data needed to address pressing scientific and policy issues. ONC's sophisticated data management system, Oceans 2.0, monitors and controls the observatory infrastructure, receives and archives ocean data from across Canada, conducts automated QA/QC, and creates and delivers data products globally. ONC's Innovation Centre leverages the observatories to develop products and services, and accelerate the advancement Canada's marine technology industry. In the Arctic, ONC's Canadian partners include the Department of Fisheries and Oceans (ice buoy data archiving), MEOPAR (ocean acidification initiative), Polar Knowledge Canada (Safe Passage sea ice study), Nunavut Arctic College (marine sensor training course), Defence Research and Development Canada (Arctic observing system programs), Oceans North Canada (marine mammal monitoring), Ocean Tracking Network (real time fish tracking) and the Arctic Research Foundation (logistic support). Internationally, ONC is a full partner in the Integrated Arctic Observing System (INTAROS), participates in the Future Earth Coasts/IMBER working group that is developing a pilot study on climate change and community security in Baffin Bay, and partners directly with several member nodes of the European Marine Seafloor and water-column Observing System (EMSO-ERIC) program, including Smart Bay (Galway), EMSO-Açores (Ifremer, Brest) and OBSEA (ICM-CSIC, Barcelona). Other international partnerships include the University of Alaska Fairbanks (community observing programs), Jacobs University Bremen (deep-sea crawler vehicles), the University of Toulon (marine mammal monitoring), and the British Antarctic Survey (benthic ecology studies).

The University of Windsor and Dalhousie and Department of Fisheries and Oceans are active partners heading up the Arctic component of the Global Ocean Tracking Network Program (OTN - http://oceantrackingnetwork.org) a major CFI/NSERC initiative to monitor marine species movements (fish to marine mammals) in the context of a changing environment. This initiative which currently services approximately 140 fixed moorings across inshore and offshore environments of Baffin Bay (Capital cost of ~$14,000 per mooring = ~$2,000,000 invested with operating cost currently funded at $1.4 million until 2018) involves diverse stakeholders, from local Inuit communities developing inshore fisheries to the offshore commercial fishing industry (NOAHA - Nunavut Offshore Allocation Holders Association) and is supported by the Government of Nunavut, CanNor and NGOs such as WWF. All data are currently archived through the OTN public access database.

The Arctic Research Centre, Aarhus University, Denmark (ARC) was founded in 2012 and was initiated by a major contribution to Arctic research, investing approximately $20M for a five year startup period. The centre has received its second funding period 2016-2021. The centre bridges all the faculties at the university: science and technology, health, arts, business and social sciences, and brings together more than 250 scientists. The scientific goal of the ARC is to strengthen interdisciplinary Arctic research, with a particular focus on Greenland and surrounding waters. Furthermore, the centre will disseminate this knowledge to local Arctic actors through targeted communication activities and run a new Arctic education programme in natural science in Nuuk, Greenland. The university also operates the Zackenberg Research Station, the Daneborg Research Station, and the Villum Research Station Nord in northeast Greenland.

The Geological Survey of Denmark and Greenland (GEUS) operates the Greenland ice sheet monitoring programme (PROMICE) and the glacier part of the Greenland Ecosystem Monitoring (GEM) providing observations of the freshwater contribution to the Baffin Bay from the ice sheet through iceberg discharge and meltwater runoff. GEUS is a central theme-lead partner in the 20-nation EU-project INTAROS building an integrated Arctic Observation System and engaged in the ESA Climate Change Initiative for Ice Sheets. GEUS is the key advisor for the authorities in Greenland with regard to oil and gas exploration, while working closely with the industry on research and consultancy. GEUS has expertise in relevant issues for BBOS such mapping of seabed instability and mass flow deposits as natural geohazards and seafloor habitat mapping in support of sustainable marine ecosystem management.

The Centre for Ice and Climate at the University of Copenhagen operates a base EGRIP on the North East Greenland Ice Sheet monitoring where a deep ice core will be drilled through the ice stream. The project will investigate the full ice stream to understand the mass loss form ice streams. The project is international and has a logistic budget of 70 mill DDK ($12 MCAD) and a scientific budget of the same size. The Centre for Ice and Climate, consisting of 50 researchers (professors, PostDocs and Phds) also have a significant group that models the mass loss of the Greenland Ice Sheet as well as global sea level changes. The University of Copenhagen also owns and operates the Arctic Station on Disko Island in West Greenland (budget of ca. 450.000 DKK per year). The station is facing Disko Bay and the Davis Strait and facilitates a wide variety of scientific research through monitoring (part of the Danish project Greenland Ecological Monitoring) and research projects. The Arctic Station can lodge about 26 scientists, has laboratory facilities and a library and owns a Research Vessel 'Porsild'). The research vessel is mainly used for marine research projects in the Disko Bay and surrounding fjords. The Danish Center of Excellence CENPERM (Center for Permafrost) at the University (annual budget ca. 10 mill DKK) is using the station as a basis for their field experiments. These experiments are all focused on the impact of changing permafrost on the terrestrial and coastal environments, and try to estimate the sediment and nutrient fluxes between the ice and the marine environment.

The Greenland Institute of Natural Resources (GINR) is situated in Nuuk, Greenland, and consists of meeting rooms, offices, laboratories, education facilities, various field stations, ship (Paamiut), vessels (Sanna), several smaller boats, boat house and skidoos etc. The institute work year round in Greenland waters and especially in Baffin Bay/Davis Strait. Long-term oceanographic, environmental and fisheries surveys are an important part of the work at the institute that gives advice to the Greenland Self Government on climate change, harvest and fishery. The institute has 75 employed and an annual budget of $18 MCAD, of which half is from external research projects. All work is carried out in and around Greenland.

9 REFERENCES

Barber, D. G., Hop, H., Mundy, C. J., Else, B., Dmitrenko, I., Tremblay, J.-E., Ehn, J. K., Assmy, P., Daase, M., Candlish, L., Rysgaard, S. (2015) Selected physical, biological and biogeochemical implications of a rapidly changing Arctic Marginal Ice Zone. Progress in Oceanography. 139:122-150.

Boetius, A., Albrecht, S., Bakker, K., et al., 2013. Export of algal biomass from melting Arctic sea ice. Science 339(6126): 1430-1432. doi: 10.1126/science.1231346.

Gearheard, S. F., Holm, L. K., Huntington, H., Leavitt J. M., Mahoney, A. R., Opie, M. (2013) The meaning of ice: People and sea ice in three Arctic Communities. Hanover, New Hampshire: International Polar Institute Press, 2013. ISBN 978-0-9821703-9-7.

Gérin-Lajoie, J., Cuerrier, A., Collier, L. S. (2016) "The caribou taste different now". Inuite Elders observe climate change. Published by Nunavut College Media, www.nacmedia.ca, Box 600 Iqaluit, NU, X0A 0H0. ISBN 978-1-897568-39-2.

IPCC 2013. Fifth Assessment Report - Climate Change 2013.

ITK (2016) Inuit Tapiriit Kanatami submission to the Naylor panel for Canada's fundamental science review.

Kwok, R. 2007. Near zero replenishment of the Arctic multiyear sea ice cover at the end of 2005. Geophysical Research Letters 34, doi: 10.1029/2006GL028737.

Lloyd's (2012). Arctic Opening: Opportunity and Risk in the High North. London: Chatham House, p. 29. http:// www.lloyds.com/~/media/Files/News%20and%20Insight/360%20Risk%20Insight/Arctic_Risk_Report_20120412.pdf

Maslanik, J., Stroeve, J., Fowler, C., et al., 2011. Distribution and trends in Arctic sea ice age through spring 2011. doi: 10.1029/2011GL047735.

Mikkola, H. and Käpylä, J. (2013). Arctic Economic Potential; The need for a comprehensive and risk-aware understanding of Arctic dynamics. FIIA Briefing Paper 127. April 2013. The Finnish Institute of International Affairs. http://www.fiia.fi/en/publication/337/arctic_economic_potential/

Mundy, C. J., et al. (2009), Contribution of under-ice primary production to an ice-edge upwelling phytoplankton bloom in the Canadian Beaufort Sea, Geophys. Res. Lett., 36, L17601, doi:10.1029/2009GL038837.

Newton, Robert, Pfirman, Stephanie, et al., 2016. White Arctic vs. Blue Arctic: A case study of diverging stakeholder responses to environmental change, Earth's Future 4: 396-405. doi: 10.1002/2016EF000356.

Pizzolato, L., Howell, S.E.L., Derksen, C., Dawson, J., and Copland, L. (2014). Changing sea ice conditions and marine transportation activity in Canadian Arctic waters between 1990 and 2012. Climatic Change, 123(2), 161-173.

Pizzolato, L., Howell, S., Dawson, J., Laliberte, F., and Copland, L. (2016). The influence of declining sea ice on shipping activity in the Canadian Arctic. Geophysical Research Letters, 43(23), 12,156-12,154.

Post, E., Forchhammer, M. C., Bret-Harte, S., Callaghan, T. V., Christensen, T. R., Elberling, B., Fox, T., Gilg, O., Hik, D. S., Ims, R. A., Jeppesen, E., Klein, D. R., Madsen, J., McGuire, A. D., Rysgaard, S., Schindler, D., Stirling, I., Tamstorf. M., Tyler, N, J. C, van der Wal, R., Welker, J., and Wookey, P. J. (2009). Ecological dynamics across the Arctic associated with recent climate change. Science 325:1355-1358.

Rysgaard, S., Nielsen, T. G., Hansen, B.., (1999). Seasonal variation in nutrients, pelagic primary production and grazing in a high-Arctic coastal marine ecosystem, Young Sound, Northeast Greenland. Marine Ecology Progress Series 179:13-25

SWIPA 2017. Snow, Water, Ice, Permafrost in the Arctic. AMAP report to be published in 2017.

Synberg, K. (2013). Russia and the Arctic. In Baltic Rim Economies: Special Issue on the Future of the Arctic, no. 2, 27 March 2013, p. 5. http://www.utu.fi/fi/yksikot/tse/ yksikot/PEI/BRE/Documents/2013/BRE%202-2013%20web. pdf.

Wassmann, P., Duarte, C. M., Agusti, S. and Sejr, M. K. (2011), Footprints of climate change in the Arctic marine ecosystem. Global Change Biology, 17: 1235–1249. doi:10.1111/j.1365-2486.2010.02311.x.

A Appendix

A.1 BBOS components

1. Weather, climate and atmosphere

Standardized automatic weather stations with sensors for measuring 1; air temperature and humidity, 2; wind speed and direction, 3; solar radiation, 4; air pressure, 5; precipitation, 6; SW↓, LW↓, SW↑, LW↑ radiation, 7; ultraviolet index.

2. Ice sheet and glaciers

Standardized automatic ice sheet weather stations with sensors for measuring 1; air temperature and humidity, 2; wind speed and direction, 3; solar radiation, 4; air pressure, 5; precipitation, 6; SW↓, LW↓, SW↑, LW↑ radiation, 7; ice flow, 8; hydraulic ablation, 9; surface level, 10; ice temperature. Annual freshwater input from ice sheet melt and iceberg discharge, GPS tracking of icebergs and islands.

3. Sea ice

Standardized ice mass balance buoys (fixed and moving) with sensors for measuring 1; air temperature and humidity, 2; wind speed and direction, 3; solar radiation, 4; air pressure, 5; SW↓, LW↓, SW↑, LW↑ radiation, 6; sea ice and snow depth, 7; sea ice temperatures, 8 ice drift speed and direction, 9; surface water temperatures.

4. Ocean and fjords

Standardized fixed position moorings for measuring profiles of 1; temperature, 2; conductivity (for salinity measurements), 3; pressure, 4; currents speed and direction, 5; backscatter, 6; ice draft, 7; waves, 8; passive acoustics, 9; dissolved organic material (CDOM), 10; fluorescence (Chl a), 10; radiance (PAR), 11; O_2, pH, pCO_2, NO_3^-. Moving platforms such as ocean gliders, crafts and autonomous underwater vehicles (AUVs). Ship based coastal and offshore sections across major gateways. Moving platforms will measure parameters above and bathymetry mapping.

4. Marine ecosystems

Standardized fixed positions for measuring 1; Composition of indicator species (ice, pelagic and benthic), 2; vertical sinking flux (total matter, organic matter, carbonate, pigments, C and N, 3; nutrient conditions in water column, 4; annual growth of macrophytes and key bivalve species (somatic and reproductive), 5; breeding success of selected bird colonies, 6; monitoring of marine mammals (photo ID and hydrophones) acoustic monitoring and tags for fish detection, regional scale movement studies, 7; monitoring juvenile fish egg and larvae, 8; Ship based coastal and offshore sections across major gateways.

5. Contaminants

Standardized fixed positions for measuring 1; legacy (e.g., mercury and organohalogens) and emerging (e.g., oil and associated hydrocarbons) contaminants, 2; Monitoring the main pathways: a) atmospheric transport; b) oceanic transport; c) biological transport; d) riverine; e) permafrost and coastal erosion; f) glacier melts; g) marine shipping and resource development. Ship based coastal and offshore sections across major gateways.

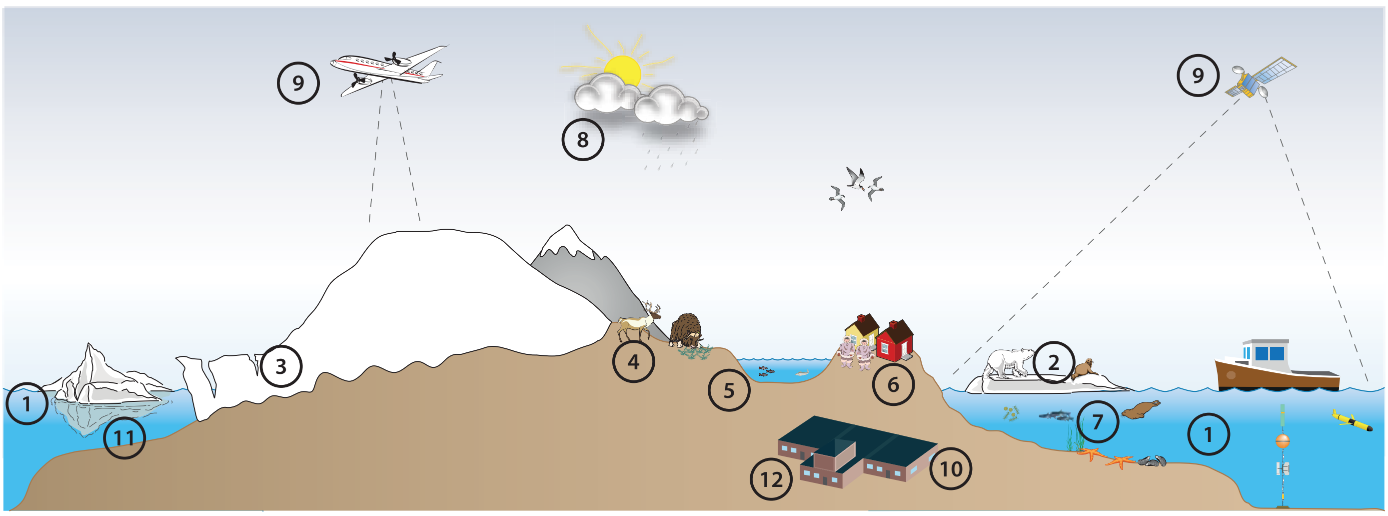


Figure 3. Conceptual model for core monitoring components in the different subprograms across BBOS. It will comprise field stations, vessels, extensive field instrumentation and community-based technologies. BBOS is an integrated baywide environmental observation system, that will enable a sustained year round, near real-time observation of the atmosphere, ice, land and ocean at the scale of an entire ocean basin (Baffin Bay).

6. Sustainable Management

Standardized fixed positions for measuring ship traffic (shore based AIS and automated data processing techniques). Remote sensing and UAV monitoring of long-term marine and coastal impacts and risks from human activities. Smart sensor packages for opportunistic monitoring on commercial and government vessels. Development of citizen science platforms (apps) for human observations. Development of new forecasting technologies for ship-ice risk mitigation and improved ice navigation technologies. Develop of systems for the co-management of resources in the context of a changing climate and increased human activity.

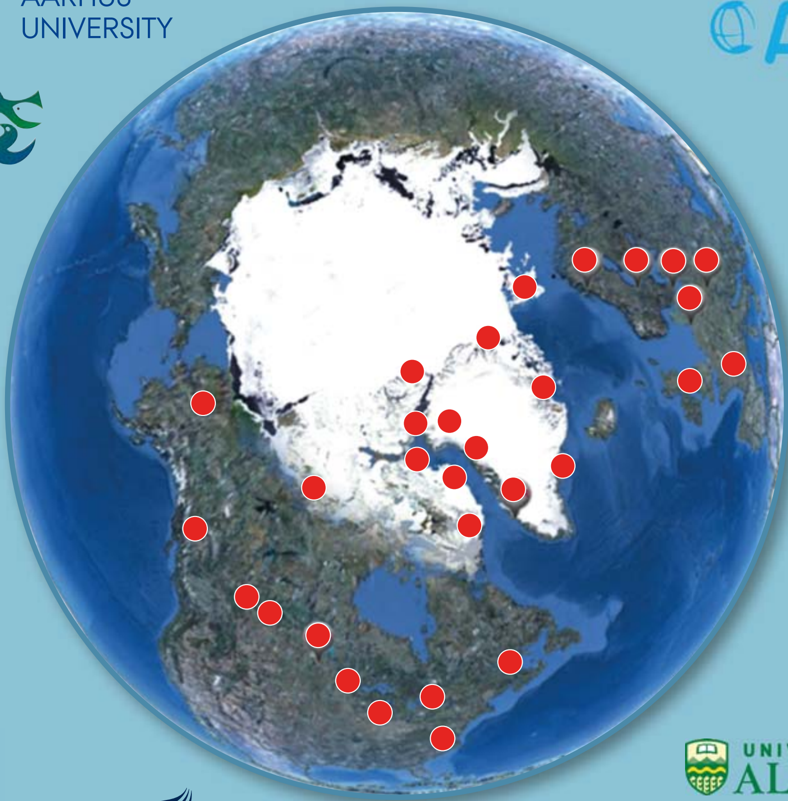
7. New technologies

Development new technology for measuring physical, chemical and biological components across the atmosphere-ice-ocean system. These will include 1; new sensors, 2; vessel based instrumentation (air & ocean), 3; moored underwater systems, 4; robotic platforms, 5; drifting platforms, 6; satellite platforms, 7; manned and unmanned aircraft, 8; surface based vehicles, 9; numerical modeling, 10; information and communication technologies – near real time outputs, 11; new methods for forecasting weather and pressured ice, 12; new ways to establish strong partnerships between business, universities and Inuit partners.

Figure 4. Schematic diagram of the locations of the overall BBOS infrastructure e.g. research bases, moorings, gliders/AUV systems, cable observatories, climate stations and community based monitoring.

THE BAFFIN BAY OBSERVING SYSTEM

www.asp-net.org



University of Manitoba

Aarhus University

AWI

ASP Arctic Science Partnership

University of Victoria

Canada

Université Laval

Nunavut Arctic College

INUIT

University of Copenhagen

UNIS

GEUS

Dalhousie University

Aalborg University Denmark

University of Alberta

UiT

Memorial University

DTU Technical University of Denmark

dépasser les frontières

University of Calgary

DMI

University of Southern Denmark

W

Ocean Networks Canada

uOttawa