Collaborative Research: Resilience and adaptive capacity of arctic marine systems under a changing climate (RACArctic)

Project description

Executive Summary

This project will synthesize information from completed and ongoing regional studies conducted by three member countries (Japan, USA, Norway) to examine how variability and changes in advection, temperature, ocean acidity and ice dynamics in the Subarctic to Arctic transition zone may affect future marine ecosystems of the Pacific and Atlantic Arctic. In particular, we are interested in how fish populations and their prey respond to, and may adapt to, natural and anthropogenic changes in the Arctic and how their responses are expected to affect existing and future fisheries, subsistence harvests, and the socio-economic systems that depend upon them. Input from a variety of stakeholders who directly or indirectly depend on living marine resources will be solicited to identify issues of concern, including threats and opportunities, across member countries. We will also review the ability of current management frameworks in each country to adapt to anticipated changes and new challenges as identified in our synthesis of research findings and stakeholder inputs. The strengths and weaknesses of management institutions will be identified and will be compared across countries in terms of their resilience and their capacity to adapt to anticipated challenges associated with global warming and ocean acidification. This review and analysis will serve to lay the foundation for developing best practices for building resilient institutions with respect to data collection needs, scientific capacity, and policy frameworks.

The proposed syntheses of scientific findings and stakeholder inputs, and the evaluation of management frameworks, will be achieved through a series of three workshops, with one workshop planned in each member country. These workshops will draw on the expertise and working relationships that have been developed in large part through the International Ecosystem Studies of the Subarctic Seas (ESSAS) program. As part of ESSAS, investigators have examined the physical, chemical and biological exchanges between the Subarctic and Arctic and their ultimate fate. This work is ongoing and ESSAS is sponsoring theme sessions on advection at this year's upcoming science meetings of the International Council for the Exploration of the Sea (ICES) and the North Pacific Marine Science Organization (PICES). Previous comparisons of the southeastern Bering Sea and the Barents Sea (Hunt and Megrey, 2005; Whitehouse et al., 2014), as well as comparisons of the Chukchi Sea and the Barents Sea (Hunt et al., 2013), have been undertaken through ESSAS, focusing on the general characteristics of these systems. Among other aspects, the dynamics of fish and shellfish populations have also been compared across Subarctic systems by one of the ESSAS working groups, highlighting the importance of climate variability in driving tropho-dynamic interactions in these systems (Mueter and Dawe 2012). More recently, ESSAS hosted a workshop on the ecology of Arctic gadids (*Boregadus saida* and *Arctogadus* spp.), which are key prey species in the Subarctic to Arctic transition zones and in the Arctic Ocean. The proposed project will build on and extend these efforts. To our knowledge, this is the first international project that draws on similar and complimentary research programs across the Pacific and Atlantic Arctic to assess the resilience and adaptive capacity of Arctic marine systems, with an emphasis on fishery systems, and including both biological and socio-economic subsystems.

We will meet project goals by reviewing and comparing key scientific findings from national programs, soliciting input from and engaging stakeholders during each of the workshops, and progressively synthesizing the relevant information to achieve an overall synthesis. Workshops will involve the lead PIs and key Partner PIs from each country, as well as stakeholders from the seafood industry, from Arctic communities that depend on these marine ecosystems, and from the agencies responsible for managing living marine resources in these regions. Together we will provide an assessment of the resilience and adaptive capacity of individual fish, fish populations, fisheries, fishery-dependent communities, and

management institutions in the face of future climate change. In addition to peer-reviewed publications, we will prepare short summaries for specific stakeholder groups (industry, managers, fishing communities), as well as the general public.

User groups are an integral part of the proposed project and will be engaged at each step to help identify the most critical challenges facing Arctic marine ecosystems in a changing climate. Users will also be directly involved in reviewing and synthesizing relevant scientific findings, emerging challenges, the threats and opportunities arising from these challenges, and the capacity of society to respond to these challenges. This engagement of relevant stakeholders will help insure that project outcomes are directly relevant to the management of living marine resources in the Arctic for the benefit of northern peoples and nations.

In selecting team members for the project, we have strived to achieve a balance among natural scientists, economists, and social scientists within each member country, while drawing on past and current international collaborations among investigators. The proposed international collaboration adds value by providing for a comparative approach to reach our study goals, including an evaluation of the potential for ecological shifts, fisheries expansion and resilience of dependent communities. An additional benefit arises from enhanced international collaboration on Arctic fisheries issues, including the identification of future research and monitoring needs at an international level. Our team includes scientists who have extensive experience working in interdisciplinary and transdisciplinary research projects. All PIs were involved in one or more interdisciplinary project in the Arctic, involving physical and biological oceanographers, plankton ecologists, fishery biologists, seabird and marine mammal biologists, economists, and social scientists. Several PIs directly connect to stakeholders through membership in teams which routinely provide scientific advice to natural resource managers. In sum, we believe that we have assembled a team that is uniquely qualified to bring the best available science to bear on critical issues facing Arctic marine ecosystems in a changing climate, and to effectively communicate results to managers and society at large, thereby improving the ability of managers and society to meet emerging opportunities and challenges.

Background

Increasing CO_2 in the atmosphere has raised global mean temperatures since the late 19th century with the Arctic being one of the most rapidly warming regions of the world (Stocker et al., 2013). Rapid warming has reduced recent summer sea-ice extent in the Arctic Ocean to record low levels. Winter sea-ice conditions differ between the Atlantic and Pacific sectors of the Arctic. Ice extent in the Barents Sea has undergone large, long-term fluctuations and is currently in a period of rapid decline, while the Bering Sea had record ice extent in recent years (2007-2013), following a warm period with very little ice in the early 2000s. These regional patterns of variability likely reflect large-scale natural forcing superimposed on a global warming trend (Litzow et al., 2014).

Future reductions in sea ice and associated changes in productivity (Jeffries and Richter-Menge, 2013; Wassmann, 2011) likely will affect marine fish in the Subarctic and Arctic. Anticipated changes include fish movement from the Subarctic to the Arctic and changes in local productivity and abundance. The nature and magnitude of such effects will depend on the sensitivity and adaptive capacity of the affected species (Hollowed et al., 2013), and will differ among species and habitats (Sigler et al., 2011; Stabeno et al., 2012b). These changes are of interest because 1) existing fisheries around the Arctic rim will be affected (Hollowed and Sundby, 2014; Kjesbu et al., 2014; Mueter et al., 2011); 2) some species may support future fisheries in areas that were of little commercial interest so far (Hollowed et al., 2013); and 3) Arctic marine fishes play a fundamental role in the transfer of energy to seabirds and marine mammals (Bluhm and Gradinger, 2008), which provide a livelihood for many Arctic residents.

In addition to warming, ocean acidification (OA) is also particularly pronounced in high-latitude regions (Yamamoto-Kawai et al., 2013). Continued sea-ice loss is likely to result in aragonite undersaturation (Yamamoto-Kawai et al., 2009), which could lead to direct impacts on calcifying organisms as waters become corrosive to their shells (Bednarsek et al., 2012).

Much of the variability in the Subarctic to Arctic transition zones is tied to the advection of warmer waters towards the Arctic. Variability in advection, in turn, is linked to large-scale climate patterns (Danielson et al 2014, Skagseth et al., 2008). Transport into the Arctic is highly variable (Woodgate et al., 2012; Skagseth et al 2008) but how this variability interacts with or is impacted by global warming is poorly understood.

Variability in advection and temperature affects primary production and lower trophic levels (Wassmann, 2011), as well as the fish, seabirds and mammals. It is uncertain whether the productivity of the Arctic Ocean and adjacent seas will increase or decrease as the ice retreats. However, primary production on seasonally ice-covered shelves is likely to increase with a longer ice-free season (Mueter et al 2009; Arrigo and van Dijken, 2011; Slagstad et al., 2011; Hirawake et al., 2012). To what extent the additional production may become available to fish and other consumers is not known. Community structure of phytoplankton also varies with timing of sea ice retreat (Fujiwara et al., 2014), with unknown impacts on higher trophic levels.

Warmer temperatures also allow fish to expand their ranges, affecting the trophic dynamics in newly colonized areas, e.g. Atlantic cod (*Gadus morhua*) in the Barents Sea, which have benefited from enhancing feeding opportunities and precautionary harvests (Kjesbu et al 2014). In contrast, early ice retreat and warm summer sea surface temperatures in the Bering Sea reduced preferred zooplankton prey (Coyle et al., 2011; Hunt et al., 2011; Heintz et al., 2013), leading to substantial declines in walleye pollock (*Gadus chalcogrammus*) following a series of unusually warm years. Although stock biomass has recovered in recent years due to more favorable conditions, walleye pollock are likely to decline in a warming climate (Mueter et al., 2011; Ianelli et al., 2011).

Harvest control rules for fish stocks were developed to cope with historical ranges of variability; however, as the climate changes, stocks maybe pushed beyond these historical ranges. Similar challenges arise from the expansion of fish stocks into formerly ice-covered waters and the potential establishment of new stocks in the Arctic (Hollowed et al., 2013).

Below we summarize some of the surveys and research programs relevant to the objectives of the proposed project. In particular, we highlight projects affiliated with the Ecosystem Studies of the Subarctic Seas (ESSAS) program. This international regional program under the IGBP project IMBER (Integrating Marine Biogeochemistry and Ecosystem Research) has recently focused on the role of advection between the Subarctic and Arctic regions and will be holding theme sessions on this topic at the upcoming ICES and PICES meetings. The lead PIs (Drinkwater, Mueter, and Saitoh) are co-chairs of ESSAS and most Partner PIs were or are investigators on ESSAS-affiliated projects.

Annual fisheries and ecosystem surveys are conducted on the Southeast Bering Sea shelf, providing information on the abundance and biology of commercial fish stocks and the broader ecosystem. The recently completed Bering Ecosystem Study/Bering Sea Integrated Ecosystem Research Program (BEST/BSIERP) has improved our understanding of the importance of wind forcing in the Bering and Chukchi seas (Danielson et al., 2012; Danielson et al., 2014), the role of ice in the Bering Sea food web (e.g. Aguilar-Islas et al., 2008; Cooper et al., 2012; Hunt et al., 2011; Sigler et al., 2014) and climate effects on commercial fish stocks (Mueter et al., 2011; Wilderbuer et al., 2013), fisheries (Haynie et al., 2013; Pfeiffer and Haynie, 2012) and subsistence-based communities (Fienup-Riordan and Rearden, 2010; Huntington et al., 2013a; Huntington et al., 2013b).

While there is large variability in winter ice extent on the Southeast Bering Sea shelf, the northern Bering Sea and Chukchi Sea will remain seasonally ice-covered (Stabeno et al., 2012a), limiting the northward expansion of demersal fish. Nevertheless, earlier ice retreat and reduced summer ice over the shelf and deep Canada Basin have brought profound changes to these marine ecosystems, which have been the focus of a number of recent studies, including several ESSAS-endorsed projects:

- ***Catastrophic reduction of sea-ice in the Arctic Ocean – its impact on the marine ecosystems in the polar region*** focuses on the western Arctic Ocean and aims to understand 1) temporal changes in primary production and the biological pump; 2) the physiological response of marine plankton to ocean acidification; and 3) the response of marine ecosystems and the biological pump to rapid sea-ice reduction in the Arctic Ocean. Observations, culture experiments and ecosystem models are yielding new insights into lower trophic level variability. Eddies appear to be an important mechanism driving changes in biogenic fluxes associated with seasonal ice extent and recent increases in eddy occurrence may have contributed to increased biogenic fluxes (Watanabe et al., 2014). Also, dissolution of shells of calcifying zooplankton has been documented. Results from this Japanese study will contribute to the proposed project by providing information on the dynamics of plankton communities in a changing Arctic.
- ***Ecosystem studies on the Arctic Ocean declining sea ice*** (ECOARCS/GRENE) examines ecosystem changes associated with sea-ice reduction in the Pacific Arctic. Hydrographic surveys by the R/V Mirai (JAMSTEC), TS Oshoro Maru (Hokkaido University) and various ice-breakers were carried out with international collaboration. Year-round moorings were deployed to obtain hydrographic, chemical and biological data, including under the ice during winter. The project also uses bio-logging and monitors large areas of the Arctic Ocean via satellite throughout the year. Results from ECOARCS support the proposed project by contributing a better understanding of both horizontal and vertical fluxes, and of the responses of plankton communities to observed variability in the Arctic. Results from both Japanese projects will be published in a special issue of an international scientific journal.
- The ***Arctic Ecosystem Integrated Survey (Arctic Eis)*** conducted comprehensive fisheries and ecosystem surveys in the northern Bering Sea and the US Chukchi Sea in 2012 and 2013, providing an unprecedented baseline for the distribution, abundance, and biology of plankton, fish, and shellfish in the Pacific Arctic. Analyses are examining biological responses to contrasting environmental conditions in the 2 years. The U.S. Arctic Eis project contributes new information on the biology and dynamics of fish populations in the northern Bering Sea and Chukchi Sea beyond the range of current fisheries, information critical to understanding the responses of fish populations to physical and lower trophic level variability.
- Numerous, more focused process studies and census activities have been conducted in the Pacific Arctic in recent years (Arrigo et al., 2014; Bluhm et al., 2010; Cai et al., 2012; Dunton et al., 2014; Grebmeier and Maslowski, 2014), the results of which will be reviewed, synthesized, and integrated with more recent information and with information from the Atlantic Arctic in the context of our objectives.

In the Northeast Atlantic region, annual fisheries and ecosystem surveys of the Barents Sea have been conducted jointly by Norwegian and Russian scientists since the 1970s. Recently, these surveys have extended north as reduced ice has allowed sampling of more stations along the northern slope and east to the Kara Sea. Monitoring of variability of ocean acidification (OA) is being carried out in the Norwegian and Barents seas. In addition, numerous research programs have examined the physical oceanography, biogeochemistry, phyto- and zooplankton dynamics, dynamics of fish, seabird, and marine mammal populations, and fisheries systems in the Barents Sea. The region of interest also includes Fram Strait and vicinity, which together with the Barents Sea, forms a key part of the Atlantic Arctic gateway connecting

the Subarctic to the Arctic. Results from past and ongoing projects will be used for the comparisons with the Pacific Arctic sector and for the overall synthesis. These include:

- **NESSAS** (Norwegian component of the Ecosystem Studies of Sub-Arctic Seas) (2005-2008) quantified the impact of climate variability on the structure and function of the marine ecosystem of the Barents Sea and adjacent waters to predict ecosystem responses to possible future climate change and their possible economic impact (Drinkwater, 2011). New insights were achieved on the role of large-scale atmospheric forcing on the ecosystem at periods of decades to multiple decades. Comparative studies with the Bering Sea revealed increased primary productivity under declining sea-ice and general poleward movement of zooplankton and fish during warm conditions. Game theory was used to explore economic consequences of changes in fish stocks. Offshore fleets would likely follow shifting fish populations northward while the inshore fleet would likely switch to new species moving in from the south. These NESSAS results will contribute to the present project by determining the biological response to natural and anthropogenic forcing.
- **NESSAR** (Norwegian component of the Ecosystem Study of Subarctic and Arctic Regions), a Norwegian IPY project (2007-2010), investigated ocean fronts between warm, salty Atlantic waters and cold, fresher Arctic waters in the Barents and Norwegian seas. It revealed that such fronts are not intense biologically productive regions, but are biological boundaries between distinct ecosystems (i.e. species) with some cross-front exchange. NESSAR results will contribute to the present project in determining how frontal positions will be modified under climate change and their impact on species distributions.
- The objectives of **FishExChange** (Expected Change in Fisheries in the Barent Sea) (2007-2010) were to evaluate the effect of climate change in the Barents Sea and adjacent areas on distribution of fish stocks and to evaluate what effect this will have on the division of national fish quotas and economical consequences for the fisheries. It developed a gridded database of physical variables and geographical distribution of catches of several species back to the 1970s. Using past relationships between distributions and physical variables, along with downscaled climate scenarios, future distribution maps were produced. These were then used to determine likely changes in landed values by species and fishery sector, costs of fishing and net revenues, fleet structure and geographical pattern of landings, and whether existing agreements on shared fish stocks will need to be changed. The results from FishExChange will be used to compare and contrast spatial distributional changes with those in the Pacific Arctic and the database will be used to further explore relationships between fish stocks and climate variables.
- **BarEcoRe** (Barents Sea Ecosystem Resilience under global environmental change) investigated (2010-2013) how the Barents Sea ecosystem will respond to anticipated changes in climate and human pressures. These investigations revealed how the system has responded to such perturbations in the past and what can make it more resilient to future perturbations. In the central Barents Sea, fish and benthos communities have responded similarly to environmental gradients driven by changes in the location of the polar front separating Atlantic from Arctic waters. The northeastward displacement of the polar front under warming has led to concomitant shifts in the distributions of biological communities. Assessment of resilience based on structural properties of the Barents Sea ecosystem revealed a variety of complex geographical patterns. These suggest that resilience is achieved in different ways for different regions and biological communities. This project will provide valuable information towards determining ecosystem resilience within both the Atlantic and Pacific sectors of the Arctic.
- **CLIFFIMA** (Nordic Network:" CLimate Impacts on Fish, Fishery Industry and MAnagement in the Nordic Seas", (2010-2014) is an inter-disciplinary/transdisciplinary melting pot for natural, social and economic scientists and a forum between scientists and managers. They have developed future ecosystem scenarios including invasive species and shifted spatial fish distributions. These are used to assess potential effects of more robust and flexible harvest

strategies, effects on industries and local communities, energy consumption related to spatial changes in fish distribution and ways in which fishing fleets can reduce greenhouse gas emissions. The results from this network will be used to address future changes in fish populations, their likelihood of moving into the Arctic and the socio-economic implications.

- The **NUCCME** (Norway-US Climate Change and Marine Ecosystems) workshop held in Norway in May 2014 was a Norwegian-US collaboration together with CLIFFIMA-net. Its objectives were to examine future climate scenarios, how such projections can be used in fisheries management, and to determine the potential economic and societal consequences of climate change on the fishing industry and fishing communities in the two regions. Results from 11 forthcoming papers will be made available for the present project.
- A new strategic initiative on the Arctic Ocean Ecosystem (**SI_ARCTIC**) aims to develop a knowledge base on the state and variability of the present and future Arctic Ocean and to explore potential options for providing ecosystem-based advice in a changing climate. The initiative expands ongoing surveys into ice-free Arctic waters under Norwegian jurisdiction, providing new information on species distribution and abundance in the Arctic Ocean ecosystem, similar to the Arctic Eis project in the Chukchi Sea. Findings from these surveys will be available to assess the dynamics of fish populations in the Atlantic Arctic and compare results with the Pacific region.
- **OA$^{\text{STATE}}$** (Establishing the Current Status of ocean acidification in the Norwegian Arctic) and **SICCA** (The role of Sea Ice processes on Calcium Carbonate saturation levels) are projects within the OA Flagship at the Fram Centre (the High North Research Centre for Climate and the Environment) in Tromsø. They are investigating the effect of water mass composition, freshwater, and sea-ice dynamics on the ocean carbon chemistry and OA state, specifically the variability of the Polar outflow water originating from the Pacific. In the present proposed project we will compare and synthesize data from the Pacific water inflow through Bering Strait with data from the Fram Centre.

The proposed project builds on these and other research efforts. Biological responses, particularly at the upper trophic levels outside "traditionally" surveyed regions have only begun to be explored. More importantly, an understanding of the resilience of the ecological and social systems to projected changes in physical and chemical forcing and associated lower trophic level variability is often lacking. Therefore we propose to review and synthesize results from national programs to assess the resilience and adaptive capacity of these arctic marine systems in a changing climate, from both a natural and social science perspective. Specifically, our objectives are to:

(1) Review and synthesize the potential for changes in the physical and chemical oceanography under future climate using state-of-the-art models.
(2) Review and synthesize what is known about potential changes at the bottom of the food web, including: a) the supply of nutrients to surface waters; b) the impact of ocean acidification on calcifying organisms; c) the magnitude and seasonal timing of primary production; d) the distribution, abundance, and species composition of zooplankton; and e) the role of temperature changes and advection in these processes.
(3) Assess implications of these changes for fish populations and fisheries in the Subarctic to Arctic transition zone: How will the spatial distribution of fish change? What is the likelihood that new fish populations become established in the Arctic? What is the potential for new fisheries to develop outside of historical fishing areas? A similar objective was addressed by an earlier workshop (Hollowed et al 2013) and their conclusions will be revisited in light of recent and ongoing projects that have greatly increased the amount of available data on the spatial distribution and dynamics of Arctic fish populations.
(4) Assess the resilience of the Arctic marine ecosystem, in particular fish populations and their zooplankton prey, to changes in physical forcing and primary production.

(5) Identify key challenges, including threats and opportunities, for the fishing industry and for subsistence users arising from these anticipated changes.
(6) Evaluate the ability of scientific and management institutions to adapt to potential threats and opportunities and explore ways in which their resilience can be improved.

We anticipate a series of peer-reviewed papers encompassing ecological, management and social dimensions of the marine systems in the Pacific and Atlantic Arctic that will be broadly applicable to other Arctic areas as well as marine systems elsewhere.

Research plan
The synthesis we propose here focuses on the future of fish populations, the prey they depend upon, and the people that directly or indirectly depend on fish production. We focus on two Subarctic-to-Arctic transition zones, specifically the eastern Bering Sea and Chukchi Sea in the Pacific Arctic and the Barents Sea/Fram Strait in the Northwest Atlantic Arctic.

Figure 1: Physical geography of the Arctic with 10°C July isotherm (red line) and Subarctic-Arctic transition zones in the Pacific and Atlantic Arctic. The highlighted areas approximately encompass the areas investigated by relevant projects.

To achieve project goals we propose three workshops involving PIs from each country and stakeholders from the seafood industry, Arctic communities dependent on marine ecosystems, and agencies managing Arctic living marine resources. Workshops will be held in each country to maximize opportunities for regional stakeholder participation.

- An international workshop in Japan (year 1) will include project PIs from all member countries, other collaborators and regional stakeholders. Japanese stakeholders include major fishing companies (Nissui, Maruha-Nichiro), food supply companies (Arcs holdings, Otsuka holdings) and a fuel shipping company planning to use ice breakers in the Arctic (Shosen-Mitsui). In addition, we will invite members of fisher's associations, the regional fisheries management

council, and the Government of Hokkaido. Stakeholders from the US and Norway will be invited to foster exchanges among key stakeholders from each member country.

- A regional workshop will be conducted in Alaska (year 2) to maximize opportunities for engaging stakeholders from the most immediately affected coastal communities in the Bering Strait region, as well as representatives from the US fishing industry (pollock and flatfish fleets), the North Pacific Fisheries Management Council (see letter from Chris Oliver), the Bureau of Ocean Energy Management (letter from Catherine Coon), and the State of Alaska. In addition, we will work with the University of Alaska Marine Advisory Program to identify relevant stakeholders from coastal communities in the Bering Strait region.
- An international workshop in Norway (year 3) will include project PIs from all three member countries, collaborators and regional stakeholders. Norwegian stakeholders will include representatives of the offshore and inshore fishing industries, fisheries management, and mayors of affected coastal communities. Stakeholders from the US and Japan will also be invited.

Specific tasks are:

1) Review, synthesize and compare results from relevant research projects in the Pacific and Atlantic Arctic to summarize what is known about effects of variability in advection, temperature, ocean pH and ice dynamics on the growth, abundance and distribution of phytoplankton and ice algae, zooplankton prey, fish, and fisheries in the Subarctic-Arctic transition zone. Much of the work will be accomplished prior to the first (Pacific Arctic) and third (Atlantic Arctic) workshop. Key findings will be summarized and presented during the workshops to contribute towards an overall synthesis. The first workshop (Japan) will focus on integrating findings across multiple projects in the Pacific Arctic. The second workshop (Alaska) will review and summarize those findings for regional stakeholders and seek additional stakeholder input, while the third workshop (Norway) will focus on comparisons across the Pacific and Atlantic. Workshops will be structured to allow one or two days for presenting and discussing scientific findings, and approximately two days for addressing tasks 2 and 3, with additional time at the third workshop to begin writing synthesis reports.
2) Identify major issues and concerns of each stakeholder group and country. What are the major threats and opportunities associated with a changing climate? How are the ecosystem, management bodies, and communities positioned to deal with threats or exploit opportunities? What are the important research questions to understand and prepare for these threats and opportunities? A list of relevant questions will be prepared ahead of the workshop and distributed to stakeholders. While discussions at each workshop will focus on issues facing stakeholders in the host country, they will benefit from the engagement of stakeholders from other countries. Each workshop will build on the previous workshop(s), outcomes from which will briefly be summarized at the beginning of subsequent workshops.
3) Review the ability of current management frameworks in each country to adapt to likely changes identified in (1). The strength and weaknesses of management institutions will be explored and will be compared across countries in terms of their resilience and their capacity to adapt to anticipated challenges associated with global warming and OA. This will serve to lay the foundation for developing best practices for building resilient institutions. The analysis will lay out an action plan in terms of 1) data collection needs, 2) scientific resources and active research programs, and 3) policy frameworks. Prior to the final workshop, we will solicit input from a variety of reviewers in each country to identify the institutional challenges that may stand in the way of such an action plan.
4) Overall syntheses of key findings from (1) – (3) will be summarized for submission to a special issue in a peer-reviewed journal. In combination, these papers will provide an assessment of the resilience and adaptive capacity of individual fish, fish populations, fisheries, fishery-dependent communities, and management institutions in the face of future climate changes.
5) In addition to peer-reviewed publications, we will prepare short summaries for specific stakeholder groups (industry, managers, fishing communities) as well as the general public.

Interdisciplinarity, transdisciplinarity and complementarity of the team
Principal Investigators in each country include natural scientists, economists and social scientists who have extensive experience working in interdisciplinary settings. All PIs were involved in projects involving physical and biological oceanographers, biogeochemists, plankton ecologists, fishery biologists, seabird and marine mammal biologists, and others. Several projects, such as BEST/BSIERP, NESSAS, CLIFFIMA and the FRAM Ocean Acidification Flagship included natural scientists, economists and social scientists and took a transdisciplinary approach that is reflected in publications by multiple authors from the natural and social sciences (e.g. Huntington et al., 2013b).

Partner PIs were chosen to represent a broad range of disciplines from the physical sciences (oceanography) to biogeochemists, fisheries biologists, fisheries managers, economists, and social scientists. Partners will contribute to the review and synthesis of the regional programs by reviewing relevant project components and literature and contributing to writing. For the overall syntheses, Lead PIs will work closely with all Partner PIs to summarize and synthesize findings, including the scientific basis for observed and anticipated changes in Arctic marine ecosystems, threats and opportunities associated with climate change as identified by participants, and management responses. Based on these syntheses, we will aim to create a holistic, transdisciplinary assessment of the resilience of ecological and socio-economic systems in the Subarctic-Arctic transition zones.

The Japan Lead PI and overall project leader, Sei-Ichi Saitoh, serves as co- PI on the ECOARCS/GRENE project, along with Partner PI Takashi Kikuchi. Most Japanese Partner PIs were involved in ECOARCS/GRENE. Dr. Saitoh will work with other PIs to summarize relevant Japanese research activities in the Pacific Arctic. Partner PI Takashi Kikuchi, who served as lead PI for ECOARCS/GRENE, will synthesize relevant findings from the ECOARCS program and other relevant literature (e.g. Nishino et al., 2010; Itoh et al., 2014) with respect to anticipated changes in ice dynamics and physical features. Partner PI Yutaka Watanuki will take the lead in reviewing the role of sea bird distribution in marine ecosystem communities on the eastern Bering Sea shelf and in the Chukchi Sea and the consequences for their upper trophic level predators and predator-prey interactions (e.g. Kokubun et al., 2010; Toge et al., 2011). Partner PI Toru Hirawake, who served as the sub-lead PI for ECOARCS, will synthesize relevant new findings and available literature with respect to changes in primary productivity and phytoplankton functional groups (e.g. Fujiwara et al., 2011; Hirawake et al., 2012; Fujiwara et al., 2014). Partner PI Naomi Harada served as the lead PI for project "Catastrophic reduction of sea-ice in the Arctic Ocean – its impact on the marine ecosystems in the polar region" and as co-PI of ECOARCS. She will synthesize changes in the biological pump and phytoplankton assemblages associated with drastic sea-ice reduction and the physiological responses of marine phyto- and zooplankton to OA in the Pacific Arctic region, based on recent findings and available literature (e.g. Harada et al., 2012; 2014; Matsuno et al., 2013; Watanabe et al., 2014). Partner PI Mitsutaku Makino will review the impacts of climate change on existing fisheries to assess potential economic implications, building on relevant literature (e.g. Makino et al., 2011). Partner PI Hiroki Takakura will review the impacts of climate change on coastal communities in the Russian-Siberian region with respect to the marine ecosystem, based on relevant literature (e.g. Takakura, in press).

The US Lead, Franz Mueter, also serves as lead PI on the Arctic Eis project, along with Partner PI Mike Sigler. All US PIs were involved in BEST/BSIERP. For the current project, Mueter will summarize evidence for changes in fish distributions associated with changes in temperature, advection, and abundance. Building on earlier work (Hollowed et al., 2013; Mueter and Litzow, 2008), he will work with other PIs to assess the likelihood of fishes expanding into the northern Bering Sea and Chukchi Sea and for changes in the abundance of local populations. Mike Sigler, who also served as the lead PI for BSIERP, will synthesize relevant findings from the BEST/BSIERP program with respect to anticipated

changes in ice dynamics and ice-associated communities (plankton, seabird, mammals), based on BSIERP contributions and other relevant literature (e.g. Sigler et al., 2010; Sigler et al., 2011; Sigler et al., 2014). Partner PI George Hunt will take the lead in reviewing the role of advection in regulating zooplankton communities on the eastern Bering Sea shelf and in the Chukchi Sea and the consequences for their upper trophic level predators and predator-prey interactions, building on ongoing efforts to understand zooplankton and predator-prey dynamics in the Subarctic-Arctic transition zone (Hunt et al., 2011, Hunt et al. In Review, Hunt et al., In Prep). Partner PI Alan Haynie will review the impacts of climate change on existing fisheries to assess potential economic implications, building on work conducted under BEST/BSIERP and other relevant literature (Haynie and Pfeiffer, 2012; Haynie et al., 2013; Ianelli et al., 2011; Pfeiffer and Haynie, 2012). Partner PI Henry Huntington will review the impacts of climate change on coastal communities in the Bering Strait region with respect to the marine ecosystem, based on BEST/BSIERP results and other relevant literature (e.g. Huntington et al., 2013a; Huntington and Moore, 2008; Huntington et al., 2013b).

The Norwegian Lead PI, Ken Drinkwater, headed the NESSAS and NESSAR projects and undertook a synthesis of the former (Drinkwater, 2011). He will take the lead in summarizing and synthesizing the Norwegian ecosystem results with input from the physical, chemical and biological Partner PIs. He will also take a leading role in the determining natural variability at decadal and multidecadal scales and their interaction with anticipated anthropogenic climate change, both in the Atlantic and Pacific sectors. Partner PI Randi Ingvaldsen, lead on the SI_ARCTIC project, will provide input on the fluxes between the Subarctic and Arctic and the circulation in the Barents Sea and Fram Strait. Partner PI Jan Erik Stiansen, lead on the FishExChange, NorExChange, and CLIFFIMA-net projects will spearhead the discussions on the effects of climate and climate change on spatial distributions of fish. The environmental-fish database will be used to explore additional spatial relations to determine the fish responses to climate variability and change. Partner PI Melissa Chierici is an expert on ocean acidification and co-leads the SICCA project within the Fram Centre. She will work together with Dr. Harada of Japan to determine how the pH of the Arctic and Subarctic oceans will change and their potential effect on the ecosystem. Partner PI Arne Eide was involved in the EU-funded projects ATP (Arctic Tipping Point) and ACCESS (Arctic Climate Change, Economics and Society). He will provide input on climate change impacts on Arctic fisheries and the economic effects on the fishing industry and fisheries-dependent communities. He will also deal with governance issues and how they can support the fishing industries under climate change. Partner PI Alf Håkon Hoel will be responsible for questions regarding fisheries management and international relations.

PIs will present key findings from initial reviews at the first workshop in Japan, as well as brief summaries at the other workshops. After the last workshop, all PIs will work together with PIs from the other countries to achieve a holistic synthesis of climate change impacts on the marine ecosystem of the Subarctic-Arctic transition zone, ranging from effects on temperature, circulation, and ocean chemistry to effects on phytoplankton communities, zooplankton prey, fish and shellfish, seabirds and mammals, and effects on the people that harvest marine resources commercially or for subsistence.

Added values resulting from the consortium that could not be provided by the individual projects include (1) integration of social sciences and stakeholders in assessing climate change impacts on arctic marine ecosystems; (2) comparative analyses that would not be possible without international collaboration: this includes comparisons of different project within the same region (US, Japan) and comparison across regions (Pacific vs Atlantic); (3) enhanced international collaboration on Arctic fisheries issues; (4) identification of future research and monitoring needs at an international level.

Project Management Plan

We define the roles of the overall lead coordinator and national coordinators as follows:

Overall lead coordinator: Sei-Ichi Saitoh
The lead coordinator is responsible for promoting the project nationally and internationally in collaboration with the other national coordinators (Mueter, Drinkwater), coordinating national activities, including meetings and workshops, and integrating the overall outcomes from international project meetings.

National coordinators (Sei-Ichi Saitoh, Franz Mueter, Ken Drinkwater)
The national coordinators are responsible for organizing the meetings and/or workshops in their respective countries, coordinating contributions to the international meetings from Partner PIs and from other collaborators, and summarizing the meeting's findings. Together they will ensure the comparative and synthesis studies are carried out in a consistent and scientific manner, scientific papers are published and stakeholder summaries produced.

The project structure (Figure 2) reflects the linkages and close coordination among the PIs from three nations and between scientists and stakeholders, with the overall Lead PI and the national leads serving to integrate scientific findings with stakeholder inputs and any emerging research, management and policy recommendations. Our two target regions in the Subarctic-Arctic transition zones of the Atlantic and Pacific sectors (Figure 1 in section 10), will be the focus of three workshops in Norway (Atlantic focus) and in Japan and Alaska (Pacific focus). However, integration and comparisons across regions and nations will occur throughout the project. The three Lead PIs, Saitoh, Mueter and Drinkwater, are also co-chairs of ESSAS, a regional program under the IMBER project. ESSAS has been involved in Arctic-Subarctic interactions during the past 2 years, hosting a number of past and upcoming workshops and theme sessions with a focus on the role of advection. The results of these will be used in the synthesis of the present proposed project. ESSAS and many of the PIs have experience in conducting comparative ecosystem studies including in Arctic regions. Many of them have worked closely together in carrying out investigations and seeing the work completed through to publication. This bodes well for a successful collaboration in the proposed project. Partner PIs from the different countries also cover a range of disciplines with disciplinary overlap between nations to ensure adequate comparisons. Also, all of the PIs have experience working with interdisciplinary and transdisciplinary research teams and cover both the natural and social sciences. Stakeholders in the three countries represent the fishing industries, food supply companies, a fuel shipping company, regional management bodies, governments and/or coastal communities.

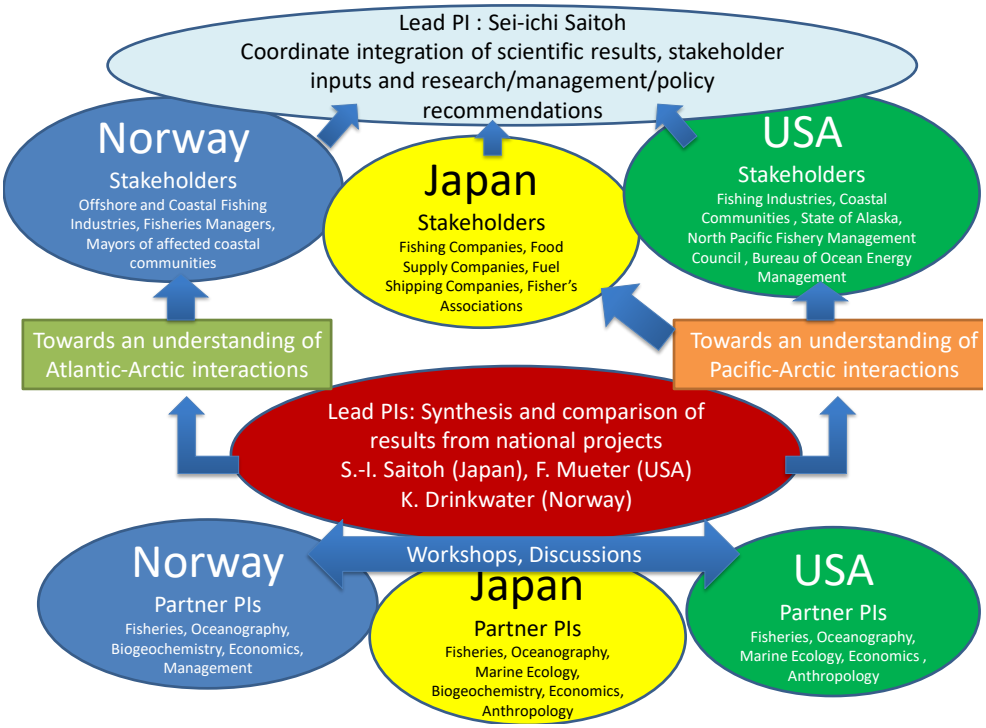

Figure 2: Project structure and linkages among Lead PIs, Partner PIs and stakeholders in the three member countries

The project will run for three years during which we plan the following activities (Figure 3).

- Three international project meetings will be held at which PIs from all three countries will attend. These meetings will take place in Japan, Alaska and Norway, respectively. When possible, these project meetings will be held in conjunction with ESSAS Annual Science Meetings, or in association with other international Arctic related meetings.
- All PIs will participate in mandatory mid-term and end-of-term meetings of the Belmont Forum.
- Research and writing will occur throughout the project period to review and synthesize research findings in preparation for project meetings.
- Comparative analyses and synthesis activities will be agreed to and outlined during the first international meeting in Japan. Activities during year 2 and 3 include synthesizing overall findings for publication, with draft manuscripts completed by the end of the project period.
- Workshop reports with a summary of outcomes will be published following each of the international project meetings.
- A final report on the overall project including the results will be published in the fall of 2018. Scientific papers and stakeholder summaries will also be completed at this time. The latter will evaluate the potential sustainability of Arctic Marine Ecosystems under climate change and will provide recommendations to both the fishing industry and northern communities to overcome any potential problems they might encounter.

Timeline

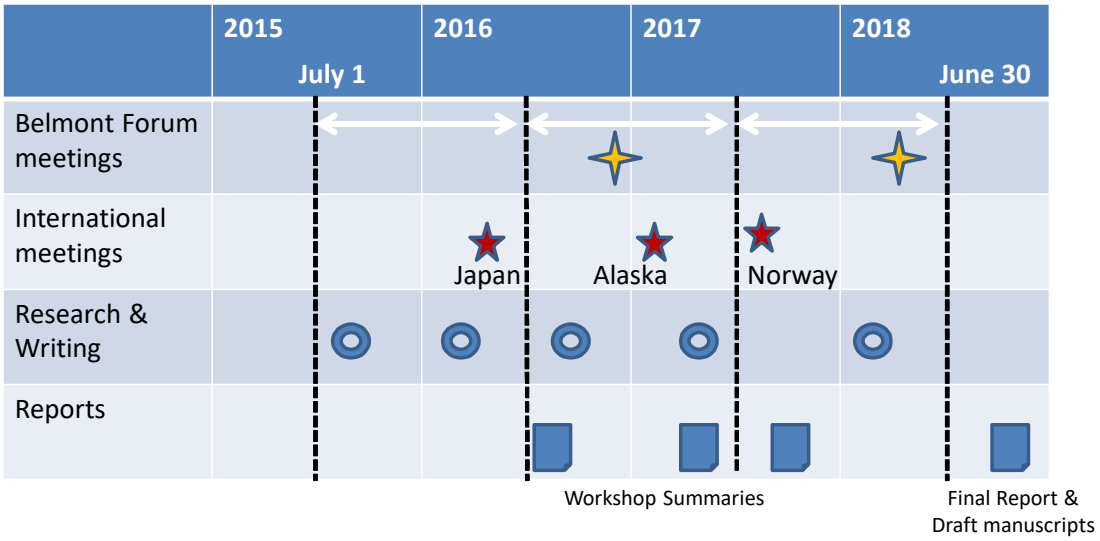

Figure 3: Timeline of the project from 2015 to 2018

Detail timeline of activities:

Year 1 (July 1, 2015 - June 30, 2016)

- Each country will hold a kick-off meeting in Year 1 and will hold a second meeting during this period if considered necessary to coordinate national activities. These may be held using web conference software or video conferencing facilities if funding is unavailable to hold direct face-to-face meetings.
- For the first international project meeting, held in Japan during spring 2016, Japanese stakeholders will be invited to attend. We will publish a report summarizing outcomes of this meeting by June 2016.
- Lead PIs will coordinate ongoing review and synthesis activities in each country and will disseminate tentative results through the ESSAS website.

Year 2 (July 1, 2016 - June 30, 2017)

- Each country will hold one or two organizational meetings or workshops in Year 2 to coordinate national activities using face-to-face meetings, web conference software or video conferencing facilities.
- The second project meeting will be held in Year 2 in Alaska, if possible in conjunction with the ESSAS Annual Science Meeting. This meeting will have a regional focus and will primarily include US PIs and stakeholders with at least some international participants (Partner PIs and stakeholders) from the other member countries. We expect to meet in early 2017 with a summary report to be completed by June 2017.
- Lead PIs will coordinate ongoing review and synthesis activities in each country and will disseminate tentative results through the ESSAS website.
- All PIs participate in the mid-term meeting of the Belmont Forum.

Year 3 (July 1, 2017 - June 30, 2018)

- Each country will hold one or two organizational meetings or workshops in Year 3 to coordinate national activities using face-to-face meetings, web conference software or video conferencing facilities. This will include an overall synthesis meeting in spring 2018 that may include Partner PIs from other countries as needed.
- The third international project meeting will be held in Year 3 in Norway, if possible in conjunction with the ESSAS Annual Science Meeting. Partner PIs from all member countries and Norwegian stakeholders will attend this meeting but will have had earlier input during national meetings in years 1 and/or 2. We expect to meet in fall 2017, with a summary report to be completed by early 2018.
- Each country will hold at least one national meeting or workshop following the international project meeting to continue the synthesis and writing activities.
- Lead PIs will coordinate the progress in their respective countries and will continue to disseminate results and advancements on the website.
- All PIs participate in the end-of-term meeting of the Belmont Forum.

Year 4 (after July 1 2018)

- We will publish final reports in summer or fall 2018 in accordance with requirements of the national funding agencies and the Belmont Forum.

Other required reports and documentation will be prepared in accordance with requirements of the national funding agencies and the Belmont Forum.

The above activities, which will bring together natural and social scientists with stakeholders from the fishing industry, regional management bodies, governments and coastal communities, will assess whether the biological, management and socio-economic systems have the resilience and adaptive capacity to cope with anticipated changes.

Impact, engagement and dissemination plan

User groups for this proposed research (fisheries managers, policy makers, fishing industry representatives, community representatives) will be an integral part of the planning and research throughout the project. Stakeholders from each member country will participate in the international meetings to identify key concerns and questions that they would like answered. Where possible, users will be invited to obtain and/or provide relevant data. They will also be strongly involved in the preparation of brief summary material to ensure it is easily understood by the target audience and is on target to answer the agreed to questions. The project will benefit the above named stakeholder as well as other scientists and the interested public. These benefits include:

- Increased awareness of the scientific basis for projecting future changes in Arctic Marine Ecosystems
- Improved understanding of how Arctic Marine Ecosystems are anticipated to change in the future under a changing climate, including the expected resilience of the ecosystems in both the Atlantic and Pacific sectors of the Arctic and Subarctic
- Better understanding and appreciation of the likely adjustments, risks and opportunities for fisheries in the changing Arctic and Subarctic regions
- Adaptation strategies for the fishing industry and northern communities
- Improved basis for decision making for ecosystem-based fishery management

Data collected as part of the associated projects will be sent to and archived in the national data centres of the respective countries in a timely manner. Scientific results will be disseminated to the research community through peer-reviewed publications and at international meetings such as the PICES and ICES Annual Meetings, the biennial Ocean Sciences Meeting, the ESSAS Open Science Meeting, the

annual Arctic Frontiers Conference, the Arctic Science Summit Week, and others. Presentations of the results at scientific meetings will be made at several of these meetings between 2016 and 2018. Manuscripts for scientific publication will be produced before or by the end of the project and all are expected to be published within a year of the end of the project as part of a special issue of a major, open-access international scientific journal. This will include papers on the ecosystem, fisheries management and socio-economics.

Key findings and written summaries will be disseminated to managers and policy makers at national and international levels. At the national level, individual investigators will communicate results through their service on various advisory bodies and involvement in other Arctic science, management, or policy forums. For example, Franz Mueter and George Hunt serve on the Scientific and Statistical Committee of North Pacific Fishery Management Council (NPFMC), one of eight US regional management councils responsible for managing fisheries in Alaska's offshore waters including the Arctic; Mike Sigler (as co-chair) and Alan Haynie serve on the Bering Sea Fisheries Management Plan Team of the NPFMC. Jan Erik Stiansen is part of the Arctic Fisheries Working Group of ICES and Alf Håkon Hoel and Randi Ingvaldsen have been involved in the Barents Sea Ecosystem Management Plan. Sei-Ichi Saitoh and Mitsutaku Makino serve on the Fisheries Committee of the Science Council of Japan, which is responsible for recommendations on world fisheries and the food supply chain. These connections will ensure that relevant results will be directly communicated to key managers and stakeholders during regular meetings that are open to the public and are typically attended by a broad group of stakeholders.

Additionally, a summary of findings will be disseminate to other interested stakeholders and the broader public through brochures that will be available at regional meetings such as the Arctic Marine Science Symposium in Anchorage, Alaska, the Arctic Frontiers Conference in Trømso, Norway, and other regional meetings in which various stakeholders typically participate. Materials will also be made available through the ESSAS website to insure dissemination to an international audience. Media will be alerted to the research and highlights will be made available to the electronic and print media throughout the project to ensure that they are available to a wide audience quickly. Additional efforts will be made to disseminate findings both regionally and through international organizations that focus on Arctic issues such as the Arctic Council and the International Arctic Science Committee (IASC).