OCS Study
BOEM 2018-017

Synthesis of Arctic Research (SOAR): Physics to Marine Mammals in the Pacific Arctic

Final Report

US Department of Commerce
National Oceanographic and Atmospheric Administration
Final, 13 June 2018

DISCLAIMER

This study was funded, in part, by the US Department of the Interior, Bureau of Ocean Energy Management, Environmental Studies Program, Washington, DC, through Interagency Agreement Number M11PG00034 with the US Department of Commerce, National Oceanic and Atmospheric Administration, Office of Oceanic and Atmospheric Research. This report has been technically reviewed by BOEM and it has been approved for publication. The views and conclusions contained in this document are those of the authors and should not be interpreted as representing the opinions or policies of the US Government, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.

REPORT AVAILABILITY

To download a PDF file of this Alaska OCS Region report, go to the US Department of the Interior, Bureau of Ocean Energy Management, Environmental Studies Program Information System website and search on OCS Study BOEM 2018-017.

This report can be viewed at select Federal Depository Libraries. It can also be obtained from the National Technical Information Service; the contact information is below.

US Department of Commerce
National Technical Information Service
5301 Shawnee Rd.
Springfield, VA 22312
Phone: (703) 605-6000, 1 (800) 553-6847
Fax: (703) 605-6900
Website: http://www.ntis.gov/

CITATION

Moore, S.E., Stabeno, P.J., Sheffield Guy, L.M., Van Pelt, T.I. 2018. Synthesis of Arctic Research (SOAR): Physics to Marine Mammals in the Pacific Arctic. US Dept. of the Interior, Bureau of Ocean Energy Management, Alaska OCS Region, Anchorage. OCS Study BOEM 2018-017, 61pp.

Synthesis of Arctic Research (SOAR)

Physics to Marine Mammals in the Pacific Arctic

FINAL REPORT — June 13, 2018

Prepared for: Environmental Studies Program
Alaska Outer Continental Shelf Region
Bureau of Ocean Energy Management
3801 Centerpoint Drive Suite 500
Anchorage, Alaska 99503

Authors:

Dr. Sue E. Moore
NMFS/Science & Technology
7600 Sand Point Way NE
Seattle, WA 98115
Sue.Moore@noaa.gov
206-526-6889

Dr. Phyllis J. Stabeno
OAR/Pacific Marine Environmental Laboratory
7600 Sand Point Way NE
Seattle, WA 98115
Phyllis.Stabeno@noaa.gov
206-526-6453

Lisa Sheffield Guy
ARCUS
3535 College Road, Suite 101
Fairbanks, Alaska 99709
lisa@arcus.org
907-474-1600

Thomas Van Pelt
UW/ JISAO
7600 Sand Point Way NE
Seattle, WA 98115
thomas.vanpelt@noaa.gov
907-242-7725

Project Status:	Completed
Start date:	20 May 2011
End date:	15 June 2018
Project Duration:	7 years

Contents

List of Figures

List of Tables

INTRODUCTION

Changes to the physical environment of the U.S. Arctic Outer Continental Shelf (OCS) are driving shifts in the distribution and behavior of a number of protected marine mammal species that inhabit those waters. The same species may be affected by oil and gas activities within OCS Planning Areas, with strong potential for deleterious interactions between natural and human induced phenomena. Environmental regulations (e.g., NEPA, the ESA, and the MMPA), require the Bureau of Ocean Energy Management (BOEM) to evaluate whether and how federal actions associated with oil and gas development may affect these protected species and the marine environment on which they depend. Information on ocean circulation and hydrography is useful for these evaluations, as well as for input into models used to predict the outcome of oil spills. However, physics alone cannot predict how protected species and the marine ecosystems upon which they depend will respond to natural and anthropogenic forcing. Given recent investments by BOEM, other federal agencies (e.g. NOAA, USGS, NSF), and the oil and gas industry in interdisciplinary biological and oceanographic research in the Pacific Arctic region (PAR), a synthesis of results of completed and ongoing studies will help to inform management decision-makers and to guide future research activities.

The "Synthesis of Arctic Research (SOAR): Physics to Marine Mammals in the Pacific Arctic" project provides a framework for a synthesis of scientific information drawn from completed and ongoing marine research in the Pacific Arctic region. The SOAR project aims to increase scientific understanding of the relationships among oceanographic conditions, benthic organisms, lower trophic prey species (forage fish and zooplankton), and marine mammal distribution and behavior in the PAR, with particular emphasis on the northeastern Chukchi Sea. SOAR further aims to enhance our capability to predict future changes in oceanographic features, such as currents, upwelling, and ice leads, and associated changes in the behavior of marine mammals and their prey in the region, and to effectively transmit findings of synthesis activities to resource managers, local Arctic residents, national and international science societies and the general public.

In this report, we provide detail on the background, methods, and results of the SOAR project, and summarize the scientific outcomes across the first and second phases of SOAR.

BACKGROUND

The Pacific Arctic region comprises waters north of St. Matthew Island (60° N latitude) in the northern Bering, Chukchi, Beaufort, and East Siberian seas (Grebmeier et al. 2010). The region is an in-flow system to the Arctic (Carmack et al. 2006), with three distinct water masses flowing north through Bering Strait, then bathymetrically channeled across the Chukchi Sea shelf and into the Beaufort Sea basin (Fig. 1). The annual advance and retreat of sea ice is the key physical driver of primary production, trophic interactions, and human access and activities over the entire PAR. The physical climate of the PAR is changing rapidly, driving change across the regional marine ecosystems (Grebmeier and Maslowski, 2014).

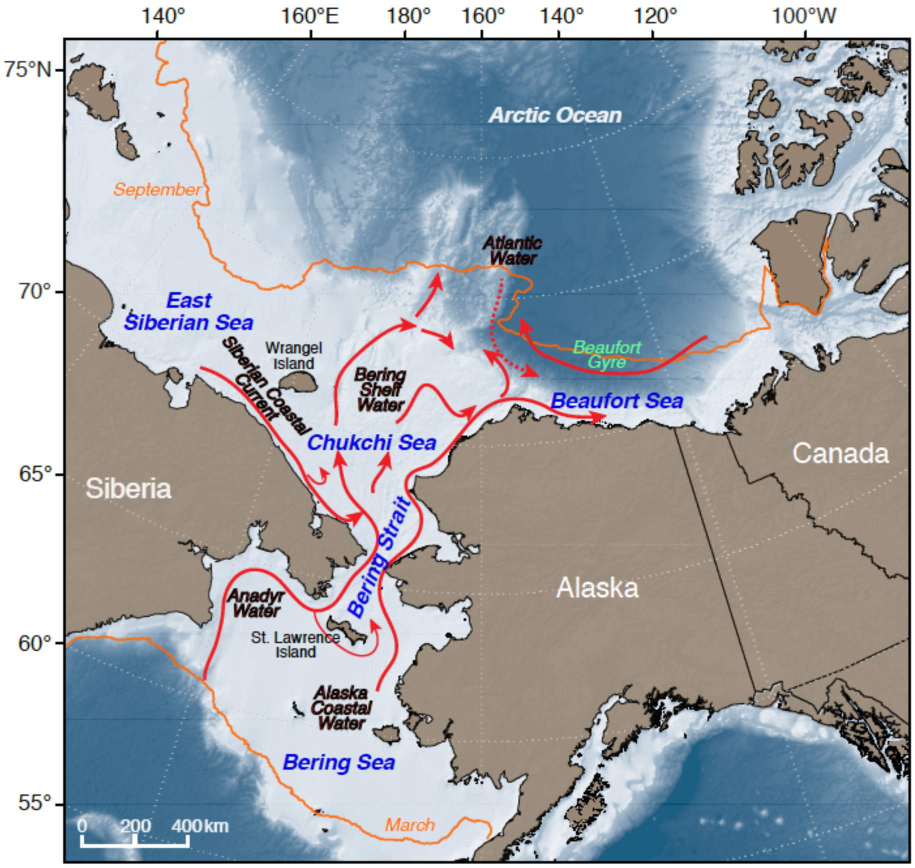


Figure 1. Map of study area, showing principal currents (red lines) and mean sea-ice maximum (spring) and minimum (fall) extent (Moore and Stabeno, 2015).

The summer minimum sea-ice extent in 2007 and 2008 covered an area that was 37% less than the areal coverage of two decades prior and 20% less than the previous minimum coverage in 2005 (Stroeve et al. 2008). The pace of these changes was unexpected, as the consensus of the climate research community was that such changes would not be seen for another 30 years (Wang and Overland 2009). The reduction in sea-ice area opens up vast new regions of the Arctic Ocean to increased absorption of sunlight and storage of heat. This heat is returned to the atmosphere in the following autumn, resulting in increased Arctic temperatures of more than 5° C, extending the sea-ice free season through November, and causing changes in wind patterns. These physical changes to the Arctic system appear to be irreversible.

Marine mammals respond to changes in sea ice according to their dependency on it for vital life functions (Moore and Huntington 2008; Kovacs et al. 2010). In the PAR, the dramatic changes in seasonal sea-ice extent and type appear to have precipitated changes in marine mammal migration and feeding patterns. For example, large aggregations of bowhead whales (*Balaena mysticetus*) feed routinely near Barrow from late summer through autumn, a phenomenon previously considered 'sporadic' (Moore et al. 2010). Gray whales (*Eschrichtius robustus*), considered a temperate species, commonly feed near the bowhead whales, whereas the two species appeared to be spatially and temporally segregated in the early 1980s (Moore et al. 1986).

In addition to the changes in marine mammal ecology, a northward shift of some fish species (e.g. Spencer 2008; Mueter and Litzow 2008; Rand and Logerwell 2010) and the prevalence of euphausiids (*Thysanoessa* spp.) indicated that the trophic structure of the PAR is changing. Euphausiids are important prey for bowhead and gray whales (Ashjian et al. 2010; Bluhm et al. 2007) and possibly also for ice seals. Euphausiids are thought to be transported into the PAR from the northern Bering Sea, as reproduction has never been observed in waters north of Bering Strait (Berline et al. 2008). Coupled to this is the general dearth of information on distribution and abundance of arctic cod (*Boreogadus saida*) in the PAR, a species considered essential in the short trophic food webs common to polar marine ecosystems (Ainley and DeMaster 1990). Examination and synthesis of how natural and human-associated environmental variability impacts marine mammals requires investigation of the biophysical changes to trophic structure and dynamics of their fish and invertebrate prey.

During 2005-2015, BOEM made extensive investments in marine mammal and related oceanographic studies in the eastern half of the PAR (i.e. the International Date Line east to the Canadian Beaufort). Data from those studies will considerably augment the body of knowledge for the region, but interpretation would be constrained if results are not integrated with other research efforts. Addressing this integration was the genesis of the SOAR project, to undertake synthesis of research from ongoing BOEM studies in the PAR, which include, but are not limited to, the following:

- Bowhead Whale Feeding Variability in the Western Alaskan Beaufort Sea: Satellite Tracking of Bowhead Whale Movements, Feeding & Oceanography
- Passive Acoustic Detection and Monitoring of Endangered Whales in the Arctic

- Ecosystem Observations in the Chukchi Sea: Biophysical Mooring and Climate Modeling
- Chukchi Sea Offshore Monitoring in Drilling Area (COMIDA): Chemistry and Benthos
- Distribution and Relative Abundance of Marine Mammals: COMIDA Aerial Surveys
- Hanna Shoal Ecosystem Study
- Monitoring the Distribution of Arctic Whales (also known as BWASP)
- Walrus Habitat Use in the Potential Drilling Area
- Pinniped Movements and Foraging: Bearded Seals
- Assessing Reproduction and Body Condition of the Ringed Seal near Sachs Harbour, Northwest Territory, Canada, through a Harvest-based Sampling Program
- Arctic marine research studies supported through National Ocean Partnership Program (NOPP), to which BOEM contributes
- Studies conducted by the Alaska Department of Fish and Game (ADF&G) and the North Slope Borough (NSB) under BOEM's Coastal Impact Assistance Program (CIAP)

Data and results from related (but not BOEM-funded) studies that also contribute to the SOAR include, but are not limited, to the following:

- NOAA's RUSALCA program (USA-Russia bilateral study of the Chukchi Sea)
- Studies supported by NSF Office of Polar Programs
- Studies supported by the Landscape Conservation Cooperative Network
- Studies supported by the Alaska Department of Fish & Game, the US Geological Survey, and by the US Fish & Wildlife Service
- Studies supported by oil and gas industry (e.g., Shell, ConocoPhillips, StatOil, British Petroleum) related to mitigation and monitoring of effects of offshore exploration and development on marine mammals and their environment, e.g. the Chukchi Sea Environmental Studies Program (CSESP).

OBJECTIVES AND METHODS

OBJECTIVES

The SOAR project focused on three objectives:

1. Increase scientific understanding of the inter- and intra-relationships of oceanographic conditions, benthic organisms, lower trophic prey species (forage fish and zooplankton), and marine mammal distribution and behavior in the PAR, with particular emphasis on the Chukchi Sea lease areas.
2. Enhance capability to predict changes in oceanographic features such as currents, upwelling, and ice leads and associated changes in the behavior of marine mammals and their prey in the PAR, with particular emphasis on the northeastern Chukchi Sea.
3. Effectively transmit findings of synthesis activities to resource managers, local Arctic residents, national and international science societies and the general public.

METHODS

TASK FRAMEWORK

The overarching goal of the SOAR project was to use available analytical and modeling approaches to identify and test hypotheses that cross scientific disciplines. SOAR provides a framework to support a synthesis of scientific information drawn from completed and ongoing marine research in the Pacific Arctic region. The framework consists of six tasks:

1. establish a Science Steering Committee to provide leadership and oversight for the synthesis project;
2. conduct a Synthesis of Arctic Research (SOAR) Workshop, involving PIs from all relevant research programs, to:
    i. identify and develop science synthesis themes;
    ii. detail required data and analyses for each theme;
    iii. form Analytical Teams to support the work of each synthesis theme;
    iv. list anticipated work products (i.e., peer-reviewed papers and presentations); and

        v. derive a means to archive data and meta-data used in support of the synthesis;
3. support Analytical Team data integration and analysis, including theme-based meetings, as needed;
4. track progress of analytical work, via bi-monthly teleconferences and annual SCC/AT-update workshops;
5. produce science products, including presentations at professional meetings and publication of peer-reviewed papers as a Special Issue &/or Theme Sections in an appropriate scientific journal; and
6. communicate synthesis approach and findings to local Arctic residents, resource managers, national and international science societies and the general public.

TASK DETAIL

TASK 1: ESTABLISH AND CONVENE SCIENTIFIC STEERING COMMITTEE

Leadership and guidance of the synthesis project was provided by a Science Steering Committee (SSC), formed of senior scientists with decades-long experience in the Pacific Arctic. At the initial SSC meeting, the group identified relevant projects, developed provisional science themes, and identified potential participants and leaders for interdisciplinary Analytical Teams formed at the subsequent SOAR Workshop.

TASK 2: PLAN AND CONDUCT SOAR WORKSHOP

A multi-disciplinary SOAR Workshop was the keystone initial product of SOAR. Workshop participants inventoried available data and evaluated its sufficiency to address specific cross-disciplinary hypotheses and questions *provisionally* identified as science themes by the SSC. The provisional list of themes was modified and new themes emerged at the workshop. Once science themes were agreed upon, interdisciplinary Analytical Teams (AT) were formed to conduct the core work of the SOAR project. Interdisciplinary ATs then initiated the development of short proposals to support the work required for data, integration, analyses and/or modeling.

TASK 3: SUPPORT DATA INTEGRATION, ANALYSIS AND MODELING

In response to proposals detailing the work to be performed, timeline, and products anticipated— and in coordination with SSC review— funding was provided via contract for selected ATs to integrate data, conduct analyses, run models and/or develop publications. In some cases, direct funding was not needed, and in-kind support was provided in the form of review, coordination, and publication facilitation. A subset of ATs integrated their work with on-going oceanographic programs (e.g. RUSALCA and the Distributed Biological Observatory [DBO]), and in some cases the ATs conducted follow-on theme-based meetings or integrative workshops as the best means to accomplish data integration and synthesis on their topic. Other ATs chose to integrate their work via video or teleconferences, with the bulk of contract funding going towards support for a graduate student, post-doc, or other researcher to accomplish the synthesis tasks identified.

TASK 4: TRACK PROGRESS OF ANALYTICAL WORK

AT leads had primary responsibility for tracking the progress of work on their science theme, and members of the SSC were also asked to follow the progress of the work towards useful products. Tracking took the form of contact at regular intervals (e.g. bimonthly) via e-mail or phone, soliciting specific information on problems encountered and adherence to timeline for product completion. Summaries of progress on each theme appeared in Quarterly Reports to the BOEM.

TASK 5: SCIENCE PRODUCTS

The core product of the SOAR project was a series of science presentations and peer-reviewed papers describing current and projected status of the PAR marine ecosystem. Annual presentations on the approach and progress of the SOAR were provided at plenary sessions of the Alaska Marine Science Symposium, and additional presentations were made at other science venues such as the AGU Ocean Sciences meeting. Science papers were then published in special issues of peer-reviewed journals, with the project PIs and coordinator serving as Guest Editors.

TASK 6: COMMUNICATION OF SYNTHESIS APPROACH & PRODUCTS

In addition to science papers and presentations, results of the syntheses were provided to communities in electronic and hard copy format, and opportunities to speak with Arctic residents were sought at co-management meetings and other fora. A web site was developed, providing graphics and brief summaries for general use and linking to other relevant sites.. Results of the synthesis were communicated to various national and international Arctic Programs (e.g., NOAA Arctic Report Card, SEARCH, ISAC, PAG, IASC and Arctic Council Working Groups).

SOAR PHASE 1 AND SOAR PHASE 2

Task 5 (Science Products) was originally envisaged to result in a special volume of peer-reviewed papers, possibly supplemented by an additional smaller set of papers in a theme section or other similar outlet. However, following completion of the first phase of SOAR, culminating in the 2015 special issue of *Progress in Oceanography* (Moore and Stabeno 2015; see Results section below for more information), there was a high level of interest in extending SOAR to include additional synthesis. Therefore the second phase of SOAR was developed, building from an informal mid-project workshop and resulting in a second full special volume of *Deep-Sea Research II*. Further detail is provided in the following sections.

RESULTS

FOUNDATIONAL TASKS: SCIENCE STEERING COMMITTEE AND WORKSHOP

THE SOAR SCIENCE STEERING COMMITTEE

A Science Steering Committee (SCC) comprised of scientists and Alaskan coastal community representatives was established (Table 1). The first of five annual SSC meetings was held from 1-3 November 2011 at the Watertown Hotel in Seattle, WA. The SSC identified relevant projects and data sources, developed three draft science themes and related questions, and identified potential participants and leaders for associated interdisciplinary Analytical Teams that would be formed at SOAR Science Workshop. Multiple subsequent meetings further developed the science themes and provided guidance for SOAR tasks (Table 2).

Table 1. List of Science Steering Committee members and institutions

Science Steering Committee Member	Affiliation	Location
Robyn Angliss	NOAA/National Marine Mammal Laboratory	Seattle, WA
Carin Ashjian	Woods Hole Oceanographic Institution	Woods Hole, MA
Christopher Clark	Cornell University	Ithaca, NY

Jacqueline Grebmeier	University of Maryland Center for Environmental Studies	Solomons, MD
Craig George	North Slope Borough	Barrow, AK
Taqulik Hepa	North Slope Borough	Barrow, AK
Vera Metcalf	Eskimo Whaling Comission/Kawerak	Nome, AK
Sue Moore	NOAA / NMFS	Seattle, WA
Chad Jay	US Geological Survey	Anchorage, AK
Tim Ragan	Marine Mammal Commission	Washington, DC
Phyllis Stabeno	NOAA / PMEL	Seattle, WA
Robert Suydam	North Slope Borough	Barrow, AK
Tom Weingartner	University of Alaska - Fairbanks	Fairbanks, AK

Table 2. List of SOAR SSC Teleconferences and in-person meetings.

SOAR SSC Meeting	Date
SSC Teleconference #1	21 September 2011
SSC Teleconference #2	18 October 2011
SSC Annual in-person meeting, Seattle, WA	11 November 2011
SSC Teleconference #3	16 February 2012
SSC Teleconference #4	6 April 2012
SOAR March Workshop	14-16 March 2012
SSC Teleconference #5	6 July 2012
SSC Teleconference #6	6 October 2012
SSC Annual in-person meeting, Anchorage, AK	21 January 2013
SSC Teleconference #7	9 April 2013
SSC Teleconference #8	14 November 2013
SSC Annual in-person meeting, Anchorage, AK	20 January 2014
SSC Teleconference #9	12 January 2015
SSC Annual in-person meeting, Anchorage, AK	23 January 2015
SSC Annual in-person meeting, Anchorage, AK (informal)	26 January 2016

SOAR WORKSHOP – MARCH 2012

The SOAR Science Workshop was held from 14-16 March 2012 at the Egan Center in Anchorage, Alaska. The SOAR Principal Investigators and Project Coordinator, all members of the Science Steering Committee, and 42 of the 43 invited SOAR Contributors attended the workshop. Draft Science Themes and Questions developed by the SOAR Science Steering Committee were provided to participants in advance of the workshop, summarized as: (i) Ecosystem Response to Bottom-up and/or Top-down Forcing; (ii) Marine Birds, Mammals, and Fish as Ecosystem Sentinels; and (iii) Acoustic Ecology.

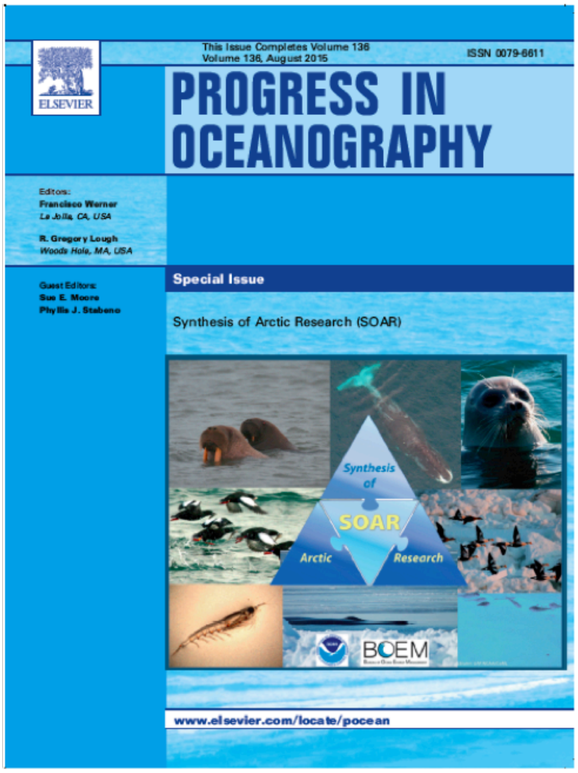
The primary goals of the Science Workshop were to: (1) refine the Draft Science Themes and Questions, (2) form research teams to undertake analysis in support of development of peer-reviewed papers, and (3) develop short proposals to identify project milestones and financial support required to complete synthetic projects.

Day one of the workshop consisted of disciplinary talks in plenary session to provide all participants with the current state of knowledge in each area of study. During day two of the workshop, science themes were revised to reflect group input. Participants divided into three theme-based breakout groups and began developing science questions to propose for SOAR. Day three of the workshop began with a plenary summary of the previous day's progress followed by breakout groups to write and submit one-page proposals for the projects requesting funding. On the afternoon of the third day, an open-session was held to communicate workshop progress to BOEM scientists and managers, colleagues from the North Pacific Research Board and Alaska Ocean Observing System, industry representatives, and other interested parties. Further details of the SOAR Workshop can be found in the SOAR Workshop Report (Sheffield Guy et al. 2012a), and see also Sheffield Guy et al. (2012b).

SCIENCE PRODUCT AND COMMUNICATION TASKS

PEER-REVIEWED PUBLICATIONS — PHASE 1

Following the initial SOAR theme selections and team development, and incorporating an extensive peer-review phase led by the project PIs and coordinator, the first phase of the SOAR project culminated in a special volume of *Progress in Oceanography*, published in August 2015 (Fig. 2; Table 3). This special issue included 16 full papers plus an introduction paper authored by the two project PIs.



ELSEVIER

This Issue Completes Volume 136
Volume 136, August 2015

ISSN 0079-6611

PROGRESS IN OCEANOGRAPHY

Editors:
Francisco Werner
La Jolla, CA, USA

R. Gregory Lough
Woods Hole, MA, USA

Guest Editors:
Sue E. Moore
Phyllis J. Stabeno

Special Issue

Synthesis of Arctic Research (SOAR)

www.elsevier.com/locate/pocean

Figure 2. Cover of the first SOAR special volume, published in Progress in Oceanography in 2015.

Table 3. Papers included in the 2015 SOAR special issue of Progress in Oceanography.

Moore, S.E., Stabeno, P.J., 2015. Synthesis of Arctic Research (SOAR) in marine ecosystems of the Pacific Arctic. Progress in Oceanography 136, 1-11.
Wood, K.R., Bond, N.A., Danielson, S.L., Overland, J.E., Salo, S.A., Stabeno, P.J., Whitefield, J., 2015. A decade of environmental change in the Pacific Arctic region. Progress in Oceanography 136, 12-31.
Frey, K.E., Moore, G.W.K., Cooper, L.W., Grebmeier, J.M., 2015. Divergent patterns of recent sea ice cover across the Bering, Chukchi, and Beaufort seas of the Pacific Arctic Region. Progress in Oceanography 136, 32-49.
Wang, M., Overland, J.E., 2015. Projected future duration of the sea-ice-free season in the Alaskan Arctic. Progress in Oceanography 136, 50-59.
Arrigo, K.R., van Dijken, G.L., 2015. Continued increases in Arctic Ocean primary production. Progress in Oceanography 136, 60-70.
Mathis, J.T., Cooley, S.R., Lucey, N., Colt, S., Ekstrom, J., Hurst, T., Hauri, C., Evans, W., Cross, J.N., Feely, R.A., 2015. Ocean acidification risk assessment for Alaska's fishery sector. Progress in Oceanography 136, 71-91.
Grebmeier, J.M., Bluhm, B.A., Cooper, L.W., Danielson, S.L., Arrigo, K.R., Blanchard, A.L., Clarke, J.T., Day, R.H., Frey, K.E., Gradinger, R.R., Kędra, M., Konar, B., Kuletz, K.J., Lee, S.H., Lovvorn, J.R., Norcross, B.L., Okkonen, S.R., 2015. Ecosystem characteristics and processes facilitating persistent macrobenthic biomass hotspots and associated benthivory in the Pacific Arctic. Progress in Oceanography 136, 92-114.
Logerwell, E., Busby, M., Carothers, C., Cotton, S., Duffy-Anderson, J., Farley, E., Goddard, P., Heintz, R., Holladay, B., Horne, J., Johnson, S., Lauth, B., Moulton, L., Neff, D., Norcross, B., Parker-Stetter, S., Seigle, J., Sformo, T., 2015. Fish communities across a spectrum of habitats in the western Beaufort Sea and Chukchi Sea. Progress in Oceanography 136, 115-132.
Crawford, J.A., Quakenbush, L.T., Citta, J.J., 2015. A comparison of ringed and bearded seal diet, condition and productivity between historical (1975–1984) and recent (2003–2012) periods in the Alaskan Bering and Chukchi seas. Progress in Oceanography 136, 133-150.
Divoky, G.J., Lukacs, P.M., Druckenmiller, M.L., 2015. Effects of recent decreases in arctic sea ice on an ice-associated marine bird. Progress in Oceanography 136, 151-161.
Lovvorn, J.R., Rocha, A.R., Jewett, S.C., Dasher, D., Oppel, S., Powell, A.N., 2015. Limits to benthic feeding by eiders in a vital Arctic migration corridor due to localized prey and changing sea ice. Progress in Oceanography 136, 162-174.
Kuletz, K.J., Ferguson, M.C., Hurley, B., Gall, A.E., Labunski, E.A., Morgan, T.C., 2015. Seasonal spatial patterns in seabird and marine mammal distribution in the eastern Chukchi and western Beaufort seas: Identifying biologically important pelagic areas. Progress in Oceanography 136, 175-200.
Citta, J.J., Quakenbush, L.T., Okkonen, S.R., Druckenmiller, M.L., Maslowski, W., Clement-Kinney, J., George, J.C., Brower, H., Small, R.J., Ashjian, C.J., Harwood, L.A., Heide-Jørgensen, M.P., 2015. Ecological characteristics of core-use areas used by Bering–Chukchi–Beaufort (BCB) bowhead whales, 2006–2012. Progress in Oceanography 136, 201-222.

Clark, C.W., Berchok, C.L., Blackwell, S.B., Hannay, D.E., Jones, J., Ponirakis, D., Stafford, K.M., 2015. A year in the acoustic world of bowhead whales in the Bering, Chukchi and Beaufort seas. Progress in Oceanography 136, 223-240.
MacIntyre, K.Q., Stafford, K.M., Conn, P.B., Laidre, K.L., Boveng, P.L., 2015. The relationship between sea ice concentration and the spatio-temporal distribution of vocalizing bearded seals (Erignathus barbatus) in the Bering, Chukchi, and Beaufort Seas from 2008 to 2011. Progress in Oceanography 136, 241-249.
George, J.C., Druckenmiller, M.L., Laidre, K.L., Suydam, R., Person, B., 2015. Bowhead whale body condition and links to summer sea ice and upwelling in the Beaufort Sea. Progress in Oceanography 136, 250-262.
Harwood, L.A., Smith, T.G., George, J.C., Sandstrom, S.J., Walkusz, W., Divoky, G.J., 2015. Change in the Beaufort Sea ecosystem: Diverging trends in body condition and/or production in five marine vertebrate species. Progress in Oceanography 136, 263-273.

PEER-REVIEWED PUBLICATIONS — PHASE 2

Following the 2015 publication of the first SOAR special issue in *Progress in Oceanography,* the SOAR project SSC and participants decided to pursue coordinate the publication of a set of papers in full second special issue. Those "Phase 2" topics and paper leads were discussed at the annual SOAR SSC meeting in January 2015. Based upon suggestions at this meeting, 1-2 page proposals were requested from suggested paper leads, and proposals were then subsequently developed into published papers. The majority of papers for the second special issue were completed and "in press" by the end of 2017 (Table 4), with final publication of the complete special issue in *Deep Sea Research II – Topical Studies in Oceanography* expected by late summer 2018.

Table 4. Papers to appear in the SOAR 2nd Phase special issue, published in Deep Sea Research Part II.

Corresponding Author	**Manuscript Title**
Sue Moore	Introduction: The Synthesis of Arctic Research (SOAR) Project
Muyin Wang	Sea ice and ocean characteristics in the Chukchi Sea by selected CMIP5 models: the present and the future
Nicholas Bond	Diagnosis of physical oceanographic events in the Chukchi Sea using an ocean reanalysis
Victoria Hill	Decadal trends in phytoplankton production in the Pacific Arctic Region from 1950 to 2012

Jessica Cross	Formation and transport of corrosive water in the Pacific Arctic Region
Lee Cooper	Deposition patterns on the Chukchi Shelf using radionuclide inventories in relation to surface sediment characteristics
Matthew Druckenmiller	Trends in sea-ice cover and upwelling potential within Bowhead whale use areas in the Western Arctic
Kate Stafford	Acoustic ecology of bowhead and beluga whales in core use areas in the Beaufort and Chukchi Seas
John Citta	Oceanographic characteristics associated with bowhead whale movements in the Chukchi Sea
John Citta	Seasonal distribution and overlap of marine mammals in the Bering, Chukchi, and Beaufort seas
Kimberly Rand	Using biological traits and environmental variables to characterize two Arctic epibenthic invertebrate communities in and adjacent to Barrow Canyon
Elizabeth Logerwell	Environmental drivers of benthic fish distribution in and around Barrow Canyon in the northeastern Chukchi Sea and western Beaufort Sea
Kathleen Stafford	Beluga whales in the Alaskan Beaufort Sea: a synthesis of available information on timing, distribution, habitat use and environmental drivers
Stephen Okkonen	Relationships among high river discharges, upwelling events, and bowhead whale (*Balaena mysticetus*) occurrence in the central Alaskan Beaufort Sea
Martin Robards	Understanding and adapting to observed changes in the Alaskan Arctic: Place-based collaborations with Alaska Native communities
Sue Moore	The Arctic Marine Pulses (AMP) Model: linking temporal processes to contiguous domains in the Pacific Arctic

PRESENTATIONS AND POSTERS AT SCIENTIFIC MEETINGS

SOAR Principal Investigators and contributors made more than 50 presentations including information about this synthesis effort at a variety of scientific meetings, workshops, and webinars. A full list of these presentations is provided in Appendix C.

OTHER COMMUNICATION OF SYNTHESIS APPROACH AND PRODUCTS

The Synthesis of Arctic Research website, located at https://www.pmel.noaa.gov/soar/, provides background information and up-to-date science product information to stakeholders and the general public. The website will continue to be live and hosted by NOAA.

Several peer-reviewed papers were published that also appeal to a more general or trans-discipline audience, including Sheffield Guy et al. (2012b) and Sheffield Guy et al. (2016). SOAR synthesis results were featured in numerous newspapers, online features, magazines, and more.

SYNTHESIS SUMMARY AND DISCUSSION

SOAR PHASE I

The first phase of SOAR resulted in fifteen papers published in a special issue of *Progress in Oceanography* in 2015 (Table 3). Here we provide a broad overview and discussion of the papers in that special issue, drawn from the Introduction to that issue (Moore and Stabeno 2015).

1. Introduction

The initiation of the Synthesis of Arctic Research (SOAR) project coincided with the recognition that biophysical changes in the Pacific Arctic region were so extreme, compared to the recent past, that they acquired the moniker 'new normal' (Jeffries et al 2013). Consequently, describing the biophysical properties of the 'new' Pacific Arctic marine ecosystem was foundational to the SOAR effort and the focus of five papers in the first special issue. Examining biological responses to the new biophysical forcing then became the task of researchers focused on the study of lower trophic level (LTL) communities and upper trophic level (UTL) species. Two papers provide integrated results from direct sampling of benthic and fish communities, while three papers report on changes in LTL species occurrence inferred by shifts in the diets of seals and marine birds. Six papers focus on UTL species, with four presenting information on seasonal occurrence in hotspot or core-use habitats, and two describing variability in marine mammal body condition in the context of decadal-scale environmental variability. Together, these papers provide a synthetic context to focus hypotheses underpinning the next decade of research in the Pacific Arctic marine ecosystem.

2. Biophysics of the Pacific Arctic marine ecosystem

The Pacific Arctic marine ecosystem is comprised of inflow shelves (northern Bering and Chukchi seas) coupled to interior shelves (East Siberian and Beaufort seas), with the contrasting biophysics of these domains summarized in Carmack et al. (2006). Circulation on both inflow and interior shelves is linked to pan-arctic teleconnection mechanisms (e.g. Arctic Oscillation), with interior shelves also strongly influenced by the seasonal outflow of relatively warm fresh water from arctic rivers. Evaluating ecosystem status and trends in the Pacific Arctic was the focus of a recent book, with 10 (of 12) chapters devoted to observations and modeling of the atmosphere, ocean physics and chemistry (Grebmeier and Maslowski, 2014). The papers in the first special issue add to that body of knowledge, especially with regard to biological responses to biophysical drivers, and in this way contribute to a more holistic understanding of the Pacific Arctic marine ecosystem.

2.1 *Physical observations and open-water projections in the 'new normal' Pacific Arctic*

Recent observations (2003-2013) of environmental changes in the Pacific Arctic support the contention that a 'new normal' climate is emerging (Fig. 3; Jeffries et al., 2013; Wood et al., 2015).

Figure 3. Highlights of recent biophysical changes in the Pacific Arctic marine ecosystem.

The iconic indicator of this change is the dramatic summertime loss of sea ice (50% by area, 75% by volume), which in some years (e.g. 2012) has resulted in nearly ice-free conditions in the region. Specifically, satellite data from 1979-2012 reveal localized changes in sea-ice occurrence of up to -1.64 days/year in the Canada Basin and -1.24 days/year in the Beaufort Sea, which accelerated to -6.57 days/year (Canada Basin) and -12.84 days/year (Beaufort Sea) during the 2000-2012 period (Frey et al., 2015). Multiyear sea ice has almost entirely disappeared, with inter-annual variability in ice concentration largely driven by wind forcing in the Beaufort Sea. In the Canada Basin, differences in annual sea ice are primarily thermally driven, while sea-ice extent is influenced by both winds and heat on the Bering Sea shelf.

The summer atmospheric patterns influence ocean circulation, freshwater pathways and movement and melting of sea ice. During the last decade, the intensification of the Beaufort High (Ogi and Wallace, 2012) resulted in anomalous summer winds. These anomalous winds together with the loss of multi-year ice were the primary factors that transformed the Chukchi and northern Beaufort seas into an open water environment (Wood et al, 2015). In particular, the eastern Beaufort Sea appears to be particularly susceptible to anomalous winds through their effect on the advection of warm, fresh water from the Mackenzie River plume. In addition, transport anomalies in the Bering Strait are determined by competing large-scale atmospheric patterns, the Beaufort High and Aleutian Low (Danielson et al., 2014). Notably, changes in Bering Strait flow through can impact the world climate far beyond the Bering Strait and Arctic region (e.g., Hu et al., 2015).

Frey et al. (2015) investigate the influence of the Pacific Decadal Oscillation (PDO) and the Arctic Oscillation (AO) on the persistence of sea ice in summer and winter. They found significant negative correlations between sea ice on the southeastern Bering Sea shelf and the PDO in winter, as well as significant positive correlations between the AO and sea-ice cover just south of St. Lawrence Island. Significant positive correlations between the PDO and sea ice in the Canada Basin-Canadian Archipelago were found in summer, as well as between the AO and sea ice in the Chukchi-Beaufort seas. This novel investigation of teleconnections between the PDO, the AO and sea-ice cover provides a critical step in understanding how global and regional climate patterns influence the physics of the Pacific Arctic region.

The unprecedented loss of sea ice has resulted in a tremendous increase in open-water susceptible to rapid solar heating, with additional heat and fresh water provided by a 50% increase in Pacific Water inflow at Bering Strait from 2001-2011 (Woodgate et al., 2012; Wood et al., 2015). The influence of increased heat stored in the Chukchi and Beaufort seas is not well understood. Suggestions that heat released to the atmosphere in late autumn and winter drives aspects of mid-latitude weather remain speculative, largely due to the short time record available (Wood et al., 2015). Freshening of the Arctic Ocean has been occurring at least since the 1990s (e.g. Giles et al., 2012). Several explanations have been proposed including increased sea- ice melt, fresher Pacific Water flowing through Bering Strait, changes in the magnitude of river discharge and the mean strengthening of the Beaufort High. In recent years, relatively strong easterly winds have been common due to the Arctic-wide pattern of circulation around an intensified Beaufort High. Under these conditions fresh and warm water from the Mackenzie River plume can be laterally transported far out into the Beaufort Sea (Wood et al., 2015).

Wang and Overland (2015) compared results from twelve coupled climate models to produce composite projections of the duration of open water in the Chukchi and Beaufort seas, at decadal intervals from 2010-2050, and in 2090. For waters north of the 70° N, open-water duration shifts from 3-4 months in 2010 to a projected ~5 months by 2040. Projected open-water duration is about one month longer along the same latitudes in the Chukchi Sea compared with the Beaufort Sea, with uncertainty of about ± 1 month estimated from the range of model results. All models projected open-water duration to expand quickly over the next three decades, which will impact regional economic access and potentially alter ecosystems. Yet the Pacific Arctic region will remain covered with thin first-year ice from January through May into the second half of the century, due to seasonal lack of sunlight.

2.2 *Changes in primary production and ocean acidification*

The dramatic loss of sea-ice extent and volume has resulted in a concomitant increase in light penetration in the upper ocean across the Arctic. Given the thinning and areal reduction of sea ice, a fundamental question arises: have these changes fostered an increase in marine primary production? Specifically, is the Pacific Arctic region more productive than it was three decades ago? In the Atlantic Arctic, Leu et al. (2011) measured primary production by both ice algae and phytoplankton in contrasting years (2007-08) of sea-ice cover in a Svalbard fjord, and concluded that earlier ice break up corresponded with earlier onset of a phytoplankton bloom. Similarly, Tremblay et al. (2012) report increased primary production for 2007-08 associated with extreme sea-ice retreats and increased upwelling at stations located south and east of Banks Island in the southeastern Beaufort Sea. But, can conclusions drawn from measurements so restricted in space and time be extrapolated to larger arctic regions? Using satellite imagery, Arrigo and van Dijken (2015) investigated changes in sea ice at both regional and basin scales from 1998-2012 and estimated how these changes have impacted rates of net primary production (NPP) by phytoplankton. They report that annual NPP increased 30% during this period, with the largest increases on the interior shelves (including the East Siberian and Beaufort) and smaller increases on inflow shelves (including the Chukchi). Outflow shelves either exhibited no change in annual NPP, or a decline, perhaps indicating that nutrients had been consumed further upstream. Increased annual NPP was often, but not always, associated with reduced sea-ice extent and resultant longer phytoplankton growing season.

Human activities have increased the atmospheric CO_2 concentration by about 40% since the beginning of the industrial age and it is estimated that the ocean has absorbed more than 25%

of the total anthropogenic emissions (Mathis et al, 2015). The oceanic uptake of CO_2 triggers a series of chemical reactions in the surface ocean that reduces pH and results in ocean acidification (OA). In short, OA makes seawater corrosive to calcium carbonate minerals, which many marine organisms rely on for body structures. High-latitude oceans have naturally low carbonate concentrations, so are considered to be more vulnerable to the impacts of OA because additional carbonate loss represents a much greater proportional change to the system. In a novel study, Mathis et al. provide a risk assessment of OA impacts to commercial and traditional fisheries focused on shellfish, salmon and finfish. The resultant index suggests that while the northern Bering Sea is at medium risk from OA impacts to fisheries, Pacific Arctic waters north of the Seward Peninsula are currently at low risk, due largely to a lack of dependence on these food sources.

3. Lower Trophic Level Communities: signals from direct and indirect sampling

The predominant conceptual model framing how marine ecosystems in the Pacific Arctic respond to reduced sea ice is based on changes anticipated from a shift in pelagic-benthic coupling (Fig. 4).

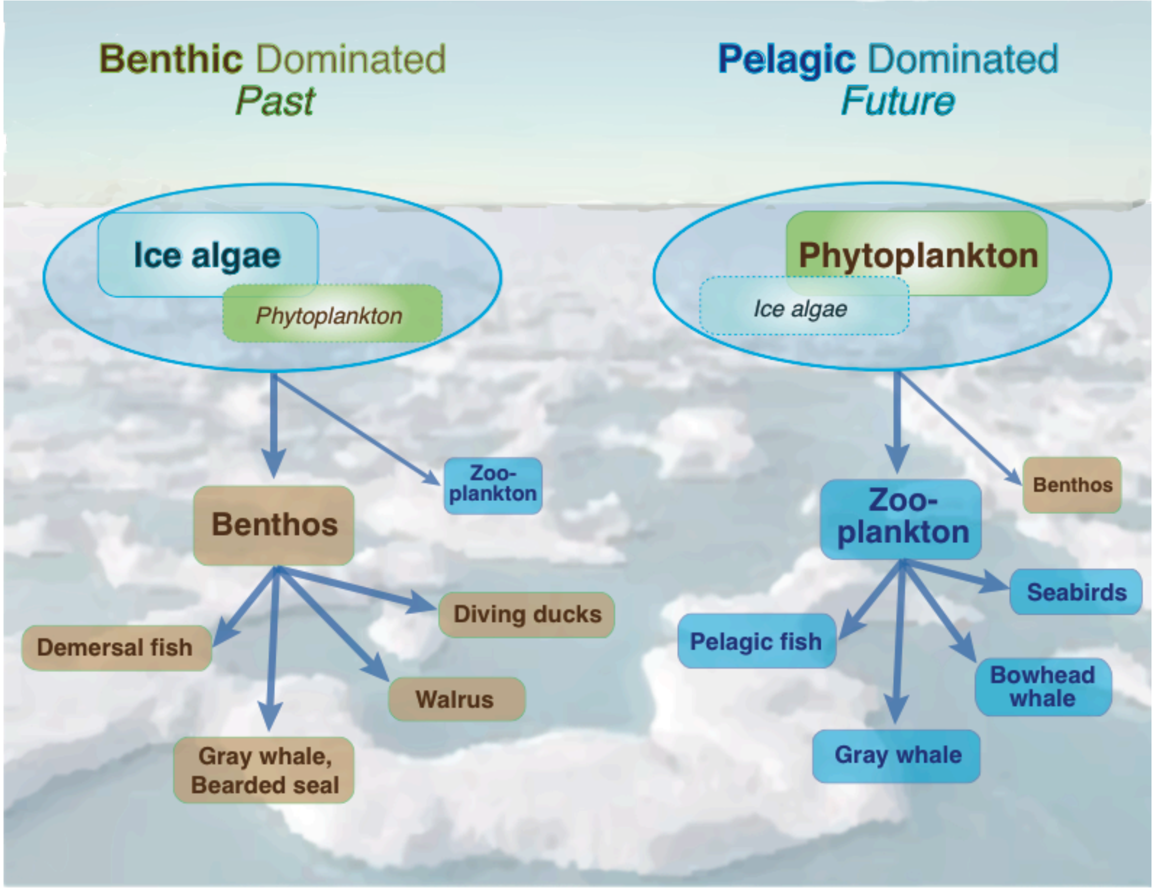


Figure 4. Generalized conceptual model depicting the influence of sea ice on pelagic-benthic coupling on Pacific Arctic continental shelves.

On the broad shelves that comprise much of the Pacific Arctic marine ecosystem, new primary production from sea-ice algae and phytoplankton blooms falls to the sea floor to support rich benthic communities (Grebmeier 2012). As sea ice thins and retreats earlier in the season, it is anticipated that earlier and larger phytoplankton blooms will switch from a benthic-dominated to a pelagic-dominated marine ecosystem. This shift will cascade through the system, supporting novel communities of secondary and tertiary consumers (zooplankton and forage fishes) and upper trophic level marine birds and mammals. Indeed, Grebmeier et al. (2006) suggested that this type of ecosystem shift is already underway in the marine communities of the northern Bering Sea. The Pacific Arctic is often described as a benthic-dominated marine ecosystem, one that does not support a large biomass or species diversity of fishes. A description of conditions that have fostered existing benthic hotspots offers a solid foundation for assessing future changes, while an accounting of the existing communities of marine fishes across a spectrum of habitats provides a starting point upon which to build a long-term record.

3.1 *Benthic hotspots and marine fishes across a spectrum of habitats*

A record of extant conditions is key to interpreting marine ecosystem responses to the new biophysical forcing now evident in the Pacific Arctic. Such a record exists for four benthic ‘hotspot’ communities in the northern Bering and Chukchi seas (Grebmeier et al., 2015a), but not for marine fishes. Long-term sampling of benthic macrofaunal communities indicates that the benthic hotspots have maintained consistently high biomass for up to four decades, due to reoccurrence of seasonally reliable moderate-to-high water column production coupled with export of carbon from overlying waters to the sea floor. Upper trophic level benthivores target prey aggregations in each of the hotspots. Overall, bottom-up forcing by hydrography and food supply to the benthos influences persistence and composition of benthic prey, which in turn influences the upper trophic level species composition and seasonal occurrence. When consistently sampled in tandem, these benthos-benthivore connections can facilitate use of UTL species as sentinels of shifts in prey composition and abundance (Moore et al. 2014).

Since the 2000s, there have been a host of Arctic marine fish surveys in the Chukchi and western Beaufort seas, precipitated by both scientific interest in the impacts of climate change and commercial interest in oil and gas development (Logerwell et al., 2015). Results from these surveys provide a novel opportunity to compare Arctic fish communities across a spectrum of habitats, ranging from lagoons and beaches to benthic and pelagic continental shelf waters. A synthesis of data from these surveys revealed more similarities than differences in habitat use between the two seas. For example, nearshore habitat is used by all age classes of forage fishes and is also a nursery area for other species in both the Chukchi and western Beaufort seas. Notably, some commercial species may be expanding their range north to these waters, including chinook salmon (*Oncorhynchus tshawytscha*), walleye pollock (*Gadus chalcogrammus*) and flatfishes (Pleuronectidae). In addition, a synthesis of information on relative abundance and age of arctic cod (*Boreogadus saida)* and saffron cod

(*Eleginus gracilis*), both key prey species in Arctic food webs, supported the development of life history and distribution models that will inform future research on trophic dynamics in the Pacific Arctic sector.

3.2 *Inferences of marine ecosystem shifts from seals, seabirds and sea ducks*

Additional information regarding the impact of 'new normal' biophysical conditions on lower trophic level species can be inferred from shifts in the diet and body condition of marine mammals and birds. Crawford et al. (2015) compared the diet and condition of ringed seals (*Pusa hispida*) and bearded seals (*Erignathus barbatus*) harvested in the Alaskan Bering and Chukchi seas during historical (1975-1984) and recent (2003-2012) periods. They found the proportion of fish in the diet of both species increased in the recent reduced-ice period compared to the historical period. In addition, ringed seals grew faster, had thicker blubber and matured two years earlier. Bearded seals had thicker blubber in the recent period, but did not manifest the other changes reported for the ringed seals. Although a number of the comparisons were not statistically significant, taken together these observations suggest greater fish availability in the Alaskan Bering-Chukchi marine ecosystem supporting good body condition in the seals.

As in the seal paper, Divoky et al. (2015) parsed a long-term data set into recent (2003-2012) and historical (1975-1984) periods to compare oceanographic conditions, nestling diet and fledging success at a black guillemot (*Cepphus grylle mandtii*) breeding colony in the western Beaufort Sea. From 15 July to 1 September, sea ice retreated an average of 1.8 km per day to an average distance of 95.8 km from the colony during the historical period, while in the recent period ice retreat averaged 9.8 km per day to an average distance of 506.9 km. Sea surface temperature near the colony increased by 2.9 ^{0}C between the two periods. While Arctic cod comprised over 95% of the prey provided to nestlings in the historical period, this proportion decreased to <5% of the nestling diet during most years in the recent period, when demersal sculpin (Cottidae) comprised the majority of the diet. The shift away from Arctic cod was associated with a five-fold increase in the rate of nestling starvation and reductions in nestling growth and fledging mass. Conversely, annual adult survival during the nonbreeding season (September-May), showed no significant difference between the two periods, suggesting no change in the availability of Arctic cod or in overall prey availability to black guillemots in their Bering Sea wintering area.

In contrast to a reliance on pelagic prey, Lovvorn et al. (2015) investigated potential climate-related limits to benthic feeding by sea ducks along their migration corridor in the northeastern Chukchi Sea. King eiders (*Somateria spectabilis*) primarily eat clams (bivalves) during migration and recent sampling has shown that dense clam assemblages occur only in specific locations along the migration corridor. Sea ice can prevent eiders from reaching these prime feeding sites, with satellite data for April–May (2001–2013) showing that access can vary from 0–100%. In a warming and increasingly variable climate, access to benthic feeding sites may be further eroded by the effects of winds on unconsolidated ice. These results underscore the importance of maintaining a range of benthic feeding areas throughout the migration corridor to ensure prey availability to the eiders each year.

4. Upper Trophic Level Species: marine birds and mammals as ecosystem sentinels

As top predators, marine birds and mammals must adapt to changes in their habitats resulting from physical forcing and thereby can serve as sentinels to ecosystem shifts (Moore et al. 2014; Moore and Gulland 2014). Responses of UTL species to altered habitats can be categorized as *extrinsic*, including shifts in range, migratory timing (phenology), or regions of high abundance (hotspots); or *intrinsic*, including changes in diet, body condition and chemical composition (Fig. 5).

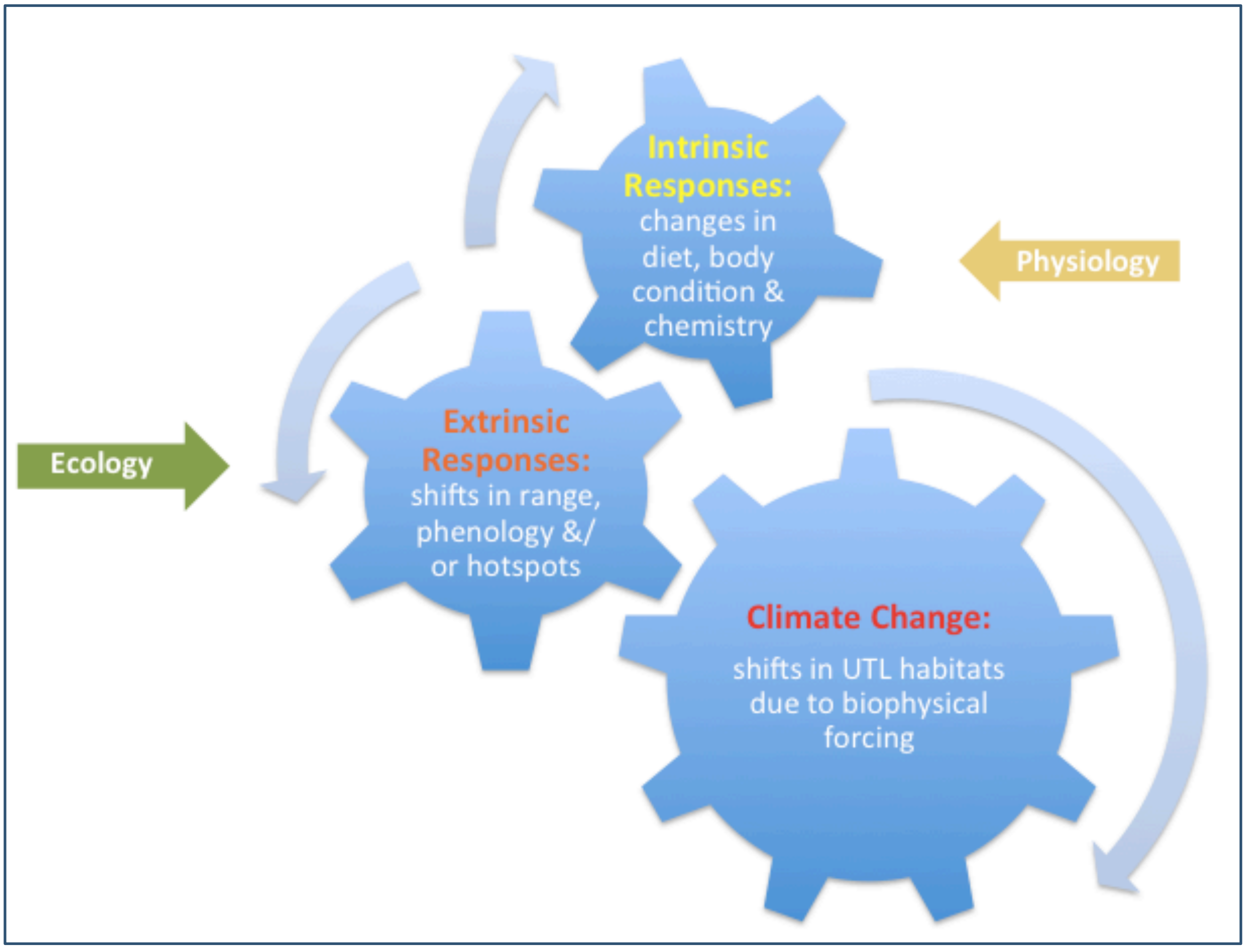


Figure 5. Marine birds and mammals are upper trophic level (UTL) species that reflect ecosystem alterations by changes in habitat use (extrinsic) and body condition (intrinsic), revealing fundamental changes in marine ecosystems.

Responses are inter-related such that a shift in range, phenology or use of hotspots will be reflected in changes in diet, body condition and chemistry. It is this connection that allows us to detect ecosystem reorganization by tracking changes in the ecology and physiology of UTL species. Although there have been no coordinated long-term studies of UTL species in the Pacific Arctic examining this connection, a synthesis of information from visual surveys, satellite tagging of individuals and year-round acoustic detections provides an ecological foundation that can provide a baseline to inform future investigations.

4.1 *Seasonal occurrence, hotspot habitats and acoustic ecology*

Kuletz et al. (2015) depict spatial patterns of relative abundance of seabirds and marine mammals in summer and fall, derived from six years of visual surveys in the eastern Chukchi and western Beaufort seas. Using statistical spatial analysis tools, hotspots for seabirds, walrus, and gray whales were identified in the Chukchi Sea, while hotspots for bowhead whales and seals were described near Barrow Canyon and along the Beaufort Sea shelf and slope. Hotspots for belugas occurred in both the Chukchi and Beaufort seas. In summer, three hotspots were shared by both seabirds and marine mammals in the Chukchi Sea: waters offshore Wainwright, south of Hanna Shoal, and at the mouth of Barrow Canyon. Only the Barrow Canyon hotspot was occupied through the fall. Shared hotspots were characterized by strong fronts caused by upwelling and currents, which can serve to aggregate prey. Using a different approach, Citta et al. (2015) provide detailed analysis of the seasonal movements and habitat use by a single species throughout one year. Locations from 54 bowhead whales (*Balaena mysticetus*), obtained by satellite telemetry from 2006-2012, were used to identify a total of six core-use areas in the Beaufort (3), Chukchi (1) and northern Bering (2) seas. Taken together, the timing of use (phenology) and physical characteristics (oceanography, sea ice, and winds) associated with each area, describe a seasonal circuit by the whales through areas thought to support elevated prey densities.

Passive acoustic sampling has become a common year-round tool to detect calling marine mammals in arctic seas (Moore et al. 2006; Stafford et al. 2012). Since 2007, there has been an especially strong sampling effort associated with oil and gas exploration in the northeast Chukchi and western Beaufort seas (e.g., Hannay et al. 2013; http://www.afsc.noaa.gov/nmml/ cetacean/chaoz.php). These recorder deployments augment a long-standing acoustic study in the central Beaufort Sea (Blackwell et al., 2007) and more recent deployments in the Bering Strait region (K. Stafford, pers. comm.). Heretofore, researchers conducted each of these studies independently of one another. Clark et al (2015) presents a novel synthesis of the combined output from six research efforts using four types of recorders and a variety of sub-sampling and analysis schemes to describe an 'acoustic year' in the life of the bowhead whale. Detections of bowhead calls from 20 sites extending over 2,300 km from the northern Bering Sea to the southeast Beaufort Sea were combined over a 14-month period (2009-2010) to describe whale occurrence across their range. The spatial and temporal variability in sound levels within the frequency band of bowhead whales was also quantified. The lowest underwater sound levels occurred from late November until May in the Chukchi Sea. During winter 2009-2010, singing bowhead whales elevated broadband sound levels for roughly 38 days in the northern Bering Sea, followed by a second month-long period of elevated sound levels due to singing by bearded seals. High-wind events also resulted in 2-5 day periods of elevated sound levels, evident on multiple recorders hundreds of miles apart. Although there were few seismic surveys during the 14-month period, air gun sounds were detected in the Chukchi Sea in late summer 2009, roughly 700 km away from the seismic survey underway in the eastern Beaufort Sea.

In a second paper describing the acoustic ecology of marine mammals in the Pacific Arctic, MacIntyre et al. (2015) investigated bearded seal calling activity in relation to variability in sea-ice cover. Acoustic data were analyzed from nine recording locations extending from the Bering to the western Beaufort Sea. Bearded seals were vocally active nearly year-round in the Beaufort and Chukchi seas, with peak activity occurring during the springtime mating season. Conversely, bearded seal calling activity lasted only about five months in the Bering Sea, again with a mating-season peak in the spring. In all areas, calling activity was positively correlated with sea-ice cover ($p < 0.01$). These results suggest that losses in sea ice may negatively impact bearded seals, both by loss of haul-out habitat and by altering the temporal features of calling for bearded seals in the Pacific Arctic sector.

4.2 *Diet and body condition*

For a bowhead whale, changes associated with the new biophysical conditions in the Pacific Arctic may be a 'good bump' in a long road. Bowhead whales can live for a century or more, with a few whales estimated to have lived over 200 years (George et al. 1999). The Bering-Chukchi-Beaufort (BCB) population is still recovering in number from roughly 170 years of commercial whaling, which ended around 1920, so responses by this species to recent changes in the marine ecosystem must be interpreted in that context. George et al. (2015) examined the relationship between body condition of BCB bowhead whales and inter-annual variability in summertime environmental conditions (seasonal sea-ice cover and wind stress) for whales harvested by Alaskan hunters from 1989-2011. During this period, there was a significant increase in axillary girth (fatness) associated with the reduction in sea ice and shifts in wind stress to patterns associated with upwelling along the slope and shelf of the Beaufort Sea. Specifically, strong positive correlations were described between whale girth and late-summer open water fraction in the Beaufort Sea, and with open water and upwelling-favorable winds in areas of the Mackenzie Delta and waters west of Banks Island. Whether due to increased secondary productivity associated with upwelling, or due to a longer feeding period associated with reduced ice cover, the improved body condition of whales in the BCB bowhead population suggest they are finding increased access to prey in the new normal Pacific Arctic.

The utility of looking to UTL species as ecosystem sentinels is further explored in Harwood et al. (2015), where body condition of five predators, monitored from harvests in the Beaufort Sea over the past 2-4 decades, indicate that all have been affected by biophysical changes in the marine ecosystem. Improved body condition is described for Arctic char (*Salvelinus alpinus*) and sub-adult bowhead whales, primarily associated with the extent and persistence of sea ice. Conversely, three species, which likely feed primarily on arctic cod (ringed seal, beluga and black guillemot chicks), showed declines in condition, growth and/or production during the same period. Although the proximate causes of these contrasting changes are unknown, they are likely mediated by an upward trend in secondary productivity accompanied by a downtrend in the availability of forage fish, especially Arctic cod, a key species in arctic food webs. Notably, the reported decline in body condition for ringed seals contrast with the changes reported in Crawford et al. (2015), but this may be due to differences in prey availability in sub-regions of the Pacific Arctic where the harvested seals were feeding; i.e., the eastern Beaufort Sea (Harwood et al. 2015) and the Bering-Chukchi (Crawford et al. 2015). Similar contrasts in size and body condition for polar bears (*Ursus maritimus*) were recently described for animals from the Chukchi Sea (good) and the Beaufort Sea (poor) populations (Rode et al., 2013). Indeed, Harwood et al. (2015) advocate the inclusion of multiple UTL species in the sampling design of future marine ecosystem research programs, at ecologically relevant spatial and temporal scales.

5. Biophysics and marine ecology of the Pacific Arctic region

The biophysics and marine ecology of the Pacific Arctic region is a study in contrasts, resulting from differing processes that occur over the broad and shallow inflow shelves of the northern Bering and Chukchi seas, compared to the narrow interior shelf, steep slope and deep basin of the Beaufort Sea. Carmack and Wassmann (2006) provide a pan-Arctic overview on the role of shelves in guiding oceanographic processes, and promote shelf geography as a unifying concept with regard to linking physical processes to food webs. Using this concept, Carmack and Wassmann (2006) identified the Pacific Arctic region as one of four contiguous domains comprising the pan-Arctic; the other three are the seasonal ice zone domain, the pan-Arctic marginal (shelf-break and slope) domain and the riverine coastal domain. As described in Wood et al. (2015), hydrography in the Pacific Arctic region is defined by Pacific waters entering the Chukchi through Bering Strait, warming as they are advected through the Chukchi Sea and circulating at depths < 200m within the Beaufort gyre of the Canada Basin. The entrapment of this inflow within the gyre increases the volume of fresh water and intensifies stratification with the warmer-saltier Atlantic water below.

The role of sea ice in regulating pelagic-benthic coupling (see Fig. 4) is the foundational model regarding the structure of food webs on the broad in-flow shelves. Indeed, the biophysics and ecology of benthic communities in the Pacific Arctic is fully described in Grebmeier et al. (2015a). However, nutrients and expatriate zooplankton from the northern Bering Sea are also advected in Pacific water across the wide Chukchi shelf and into the Beaufort Sea (Nelson et al. 2014), and the role of this transport is often ignored in conceptual models of the marine ecosystems. Clearly, advected prey are important to UTL species – one example being the consumption of Pacific species of euphausiids by bowhead whales at Barrow and as far east as Kaktovik, Alaska in the eastern Beaufort Sea (Lowry et al., 2004). A new conceptual model is required to capture the complex interconnectivity between the role of pelagic-benthic coupling and that of the strongly seasonal transport of heat, nutrients and prey into the region.

5.1 *Ecosystem conceptual models and visualization tools: the 'Arctic Marine Pulse' model*

The sea-ice driven pelagic-benthic coupling model has served the science community well for nearly three decades (Grebmeier 2012, and references therein). While the pelagic-benthic model serves as a strong framework for depicting processes on the shallow shelf habitat of the northern Bering and Chukchi seas, it does not depict the interactive processes occurring along the narrow interior shelf, slope and deep basin of the Beaufort Sea. Carmack and Wassman (2006) advocate for the development of "an ecology of advection" to advance ecosystem models that can support inter-comparisons of existing and future arctic food webs. Grebmeier et al. (2015b) provide a comprehensive conceptual model linking advective processes in the Chukchi and Beaufort. The input function for this model is the advection north of Pacific Water (comprised of AW, BSW, ACW; see Fig. 1). The three pathways for this inflow cross the Chukchi Sea, then enter the Beaufort Sea primarily at canyons with further advective processes, including eddy shedding, along the slope. Freshwater inflow from the Yukon and Mackenzie rivers is depicted, as is nearshore outflow of Siberian Coastal Water (SCW) along the Russian north coast. This conceptual advective model is an essential tool to frame our understanding of the Pacific Arctic marine ecosystem, but remains a comparatively static representation of very dynamic processes.

The 'krill trap' model, developed during a study of bowhead whales feeding on euphausiids transported to local waters near Barrow, provides a starting point to animate an advective model for a portion of the Pacific Arctic region (Ashjian et al., 2010). Physical drivers of this local-area model invoke wind forcing, shelf-break topography and current structure along Barrow Canyon to explain the retention of krill along a front on the western Beaufort shelf (Okkonen et al., 2011). This dynamic model essentially "rocks back and forth" between two states: *upwelling of prey* and nutrients onto the narrow shelf induced by easterly winds, and *prey retention* induced by relaxed or southerly winds. This model focuses on only the western Beaufort Sea, however, and requires expansion to serve the full Pacific Arctic region.

We propose an initial form of the Arctic Marine Pulses (AMP) conceptual model for the Pacific sector, which aims to both *animate* the Grebmeier et al. (2015a) advection model and *link* it to the pelagic-benthic coupling model (Fig. 6).

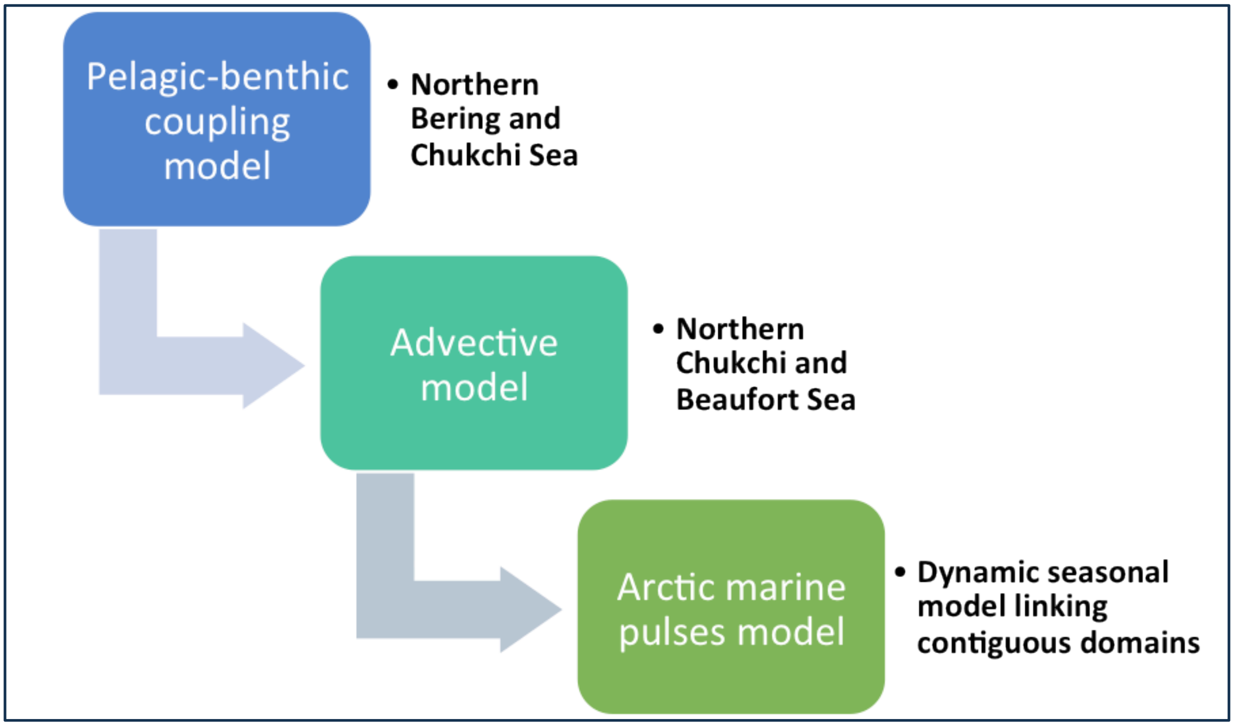


Figure 6. Components of the Arctic Marine Pulses (AMP) conceptual model – linking pelagic-benthic coupling and advective models to derive a seasonal model for the Pacific Arctic framed by contiguous domains.

In this way, the zooplankton and forage fish predicted by the pelagic-benthic model with the loss of sea ice are advected across the Chukchi and into the Beaufort Sea by the advective model. The AMP model employs the contiguous domain concept, described in Carmack and Wassmann (2006), to join physical habitats by the integration of common features such as the seasonal cycles of inflow at Bering Strait, sea-ice advance and retreat, and riverine export. Specifically, within the overall geographic domain of the Pacific Arctic, the AMP model connects three dynamic contiguous domains (Fig. 7):

(i) *Seasonal ice zone domain* – seasonal ice retreat serves to *link* the AMP model to the pelagic-benthic coupling model. Timing and pace of sea-ice retreat across the Chukchi Sea drives *pulses* of organic material either to the benthos, *or* towards the pelagic system; sea-ice retreat beyond the narrow Beaufort shelf in late summer allows the system to respond to winds that can induce *pulses* of upwelling of nutrients and prey onto the shelf;

(ii) *Pacific marginal domain* – the Beaufort Sea shelf break and slope is a transport pathway for nutrients and prey advected across the Chukchi Sea; this marginal domain also provides links to the deep basin where stores of nutrients and prey can be upwelled by wind forcing after the sea-ice retreats; Herald and Barrow canyons are focal points of shelf-basin exchange (i.e. secondary pulse-points) although local winds can reverse flow;

(iii) *Riverine coastal domain* – the Yukon and Mackenzie river outflows provide seasonal pulses of warm and fresh water to the northern Bering and Beaufort seas, respectively. In the Beaufort, the Mackenzie outflow can trap nutrients and prey. The Mackenzie outflow has increased dramatically over the past decade (Wood et al., 2015) and, with increased seasonal run-off, the Sagavanirktok and Colville rivers may have greater influence now than in the past.

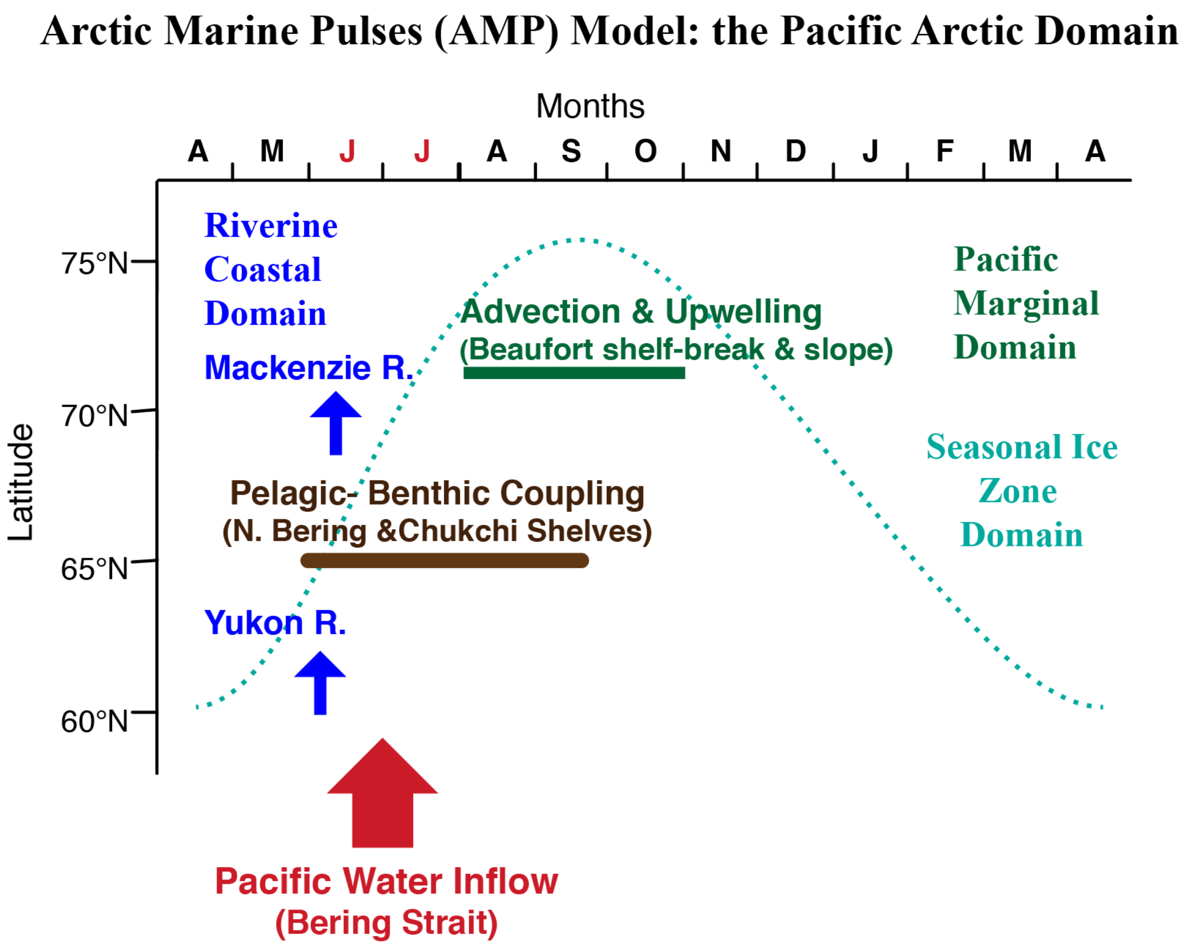


Figure 7. The Arctic Marine Pulses (AMP) conceptual model, depicting seasonal biophysical pulses in three ecological domains across a latitudinal gradient over the course of an annual cycle in the Pacific Arctic region (Moore and Stabeno, 2015).

SOAR PHASE II

1. Background

In 2015, several new synthesis teams were formed and work commenced on a second SOAR special issue, the culmination of which are the fifteen peer-reviewed papers to be published in a special volume of *Deep-Sea Research Part II*. Below we provide an overview of findings and syntheses published in those individual papers, structured around the framework of the "Arctic Marine Pulses" conceptual model and its three ecological domains, introduced in the preceding SOAR Phase I discussion.

2. The Arctic Marine Pulses conceptual model

The Arctic Marine Pulses (AMP) conceptual model was initially developed to provide an overarching synthesis of results presented in papers comprising the first SOAR special issue (see preceding synthesis and discussion of SOAR Phase I; Moore and Stabeno, 2015). In brief, the AMP model uses the concept of ecological domains as a framework to focus investigative attention on seasonal oceanographic pulsive events in the Pacific Arctic region over an annual cycle (Fig. 7). The AMP model is further developed in Moore et al. (in press), wherein the phenology of pelagic-benthic coupling and advective processes are described and linked to examples of how benthic macrofaunal and upper-trophic species respond to changes in ecosystem structure. The AMP model aims to encourage multi-disciplinary research and, with its focus on phenology of events over an annual cycle, may serve to facilitate communication between conventional science and Indigenous Knowledge.

In this synthesis and discussion of the second SOAR special issue, we use three ecological domains that frame the AMP model to structure an overview of results presented in this special issue (Fig. 8).

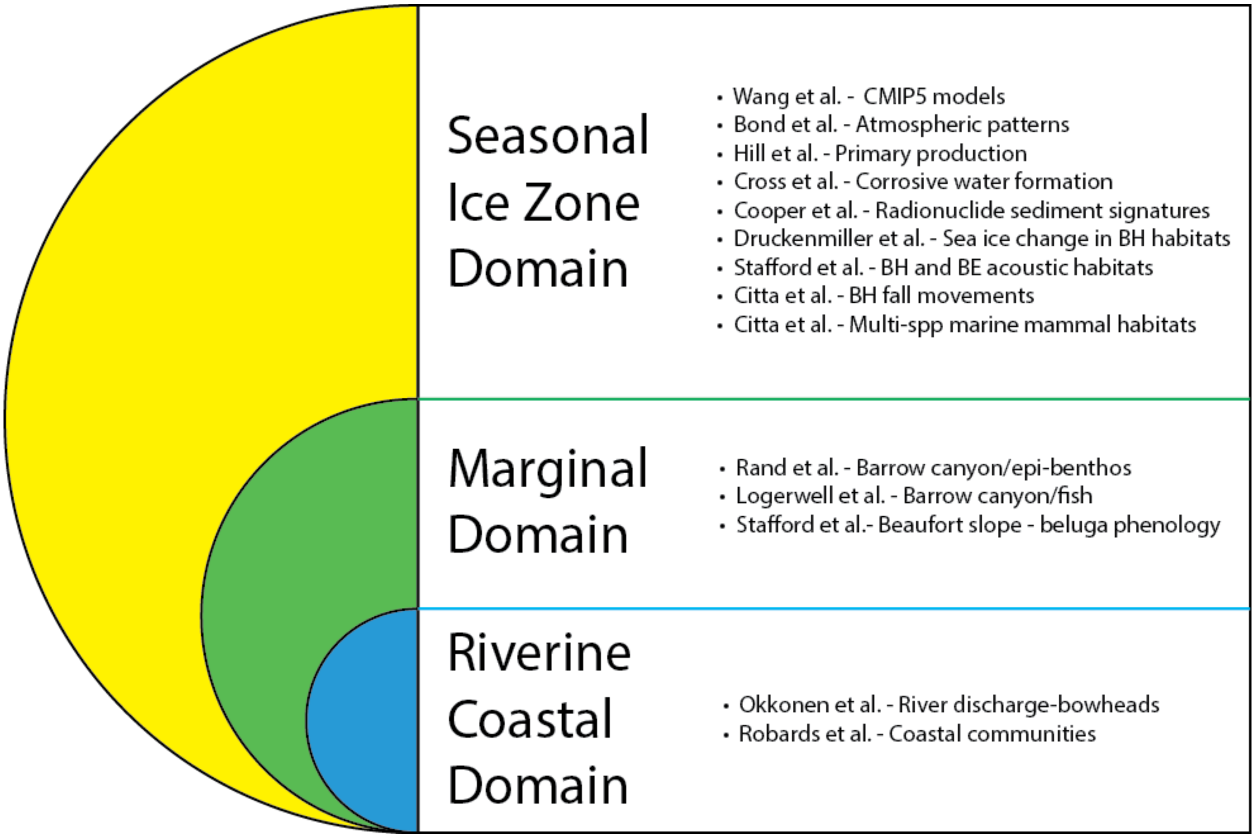


Figure 8. Papers comprising the forthcoming 2018 2nd SOAR special issue (to be published in Deep-Sea Research Part II), identified by lead author and organized by ecological domains that frame the Arctic Marine Pulses model (Moore et al., in press).

The Seasonal Ice Zone domain is defined by the limits of sea-ice extent in March (maximum) and September (minimum) and thereby includes continental shelf, slope and deep basin habitats in the Pacific Arctic (Fig. 1: bounded by orange lines). In contrast, the Marginal and the Riverine Coastal domains are more narrowly defined by (i) the steep bathymetry of the continental slope and canyons in the northern Chukchi and Beaufort seas and (ii) nearshore waters influenced by river discharge, respectively (Carmack and Wassman, 2006; Carmack et al., 2015). By using these ecological domains to frame results presented in the papers comprising this special issue, we aim to further explore the utility of the AMP model for integrating biophysical processes in the Pacific Arctic region, thereby fulfilling the overarching goal of the SOAR project to better understand this dynamic marine ecosystem.

3. Seasonal Ice Zone Domain

3.1 Physics: Sea-Ice Models and Ocean Reanalysis

The decrease in sea-ice extent, volume and duration over the past three decades is an iconic feature of a changing climate in the Pacific Arctic (Wood et al., 2015; Frey et al., 2015; Wang and Overland, 2015). With sea-ice cover declining rapidly, shifts in the timing of break-up and freeze-up have become urgent scientific, social and economic concerns. Wang et al. (in press) analyzed daily sea-ice concentration data to assess the dates of sea-ice break-up and freeze-up, and thereby derive a trend in sea-ice duration for the period 1990-2015 and a projection of sea-ice duration to mid-century (2044). The analysis, based on simulation results from the coupled Atmosphere-Ocean General Circulation Models from Phase 5 of the Coupled Model Intercomparison Project (CMIP5), was conducted both at the broad scale of the Pacific Arctic region and at regional and local scales as defined by the eight regions of the Distributed Biological Observatory (https://www.pmel.noaa.gov/dbo/) and by eight oceanographic mooring sites in the northeast Chukchi Sea, respectively. Wang et al. (in press) show that the duration of sea-ice cover is declining, with the strongest trend apparent during the 1990-2015 period. The 30-year averaged trend was projected to be from -0.68 days/year to -1.2 days/year for the period 2015-2044, which is equivalent to a 20 to 36 day reduction in annual sea-ice duration. Similar results were found at both regional and local scales. The models indicate that while the shortening of the sea-ice season is driven by both later freeze-up and earlier break-up, the delay in freeze-up is the larger contributor. Projected changes in sea-ice duration in the Pacific Arctic exhibit spatial variance, with the Bering Strait area projected to experience a decrease of less than 20-day duration over the next 30 years, while the East Siberian, Chukchi and Beaufort seas are projected to experience a 60-day reduction by mid-century. The dramatic reduction in sea-ice duration has driven and will continue to drive changes in the marine ecosystem of the Pacific Arctic, while also both fostering offshore commercial activities and impeding local access to resources for inhabitants of coastal communities.

The changing oceanography during the open-water season in the Pacific Arctic was the focus of a reanalysis study undertaken by Bond et al. (in press). Specifically, the physical oceanographic conditions extant from June through October on the Chukchi Sea shelf were investigated using the ORAS4 ocean reanalysis software for the period 1979-2014. Time series of vertically integrated temperatures showed greater warming (especially during September and October) in the first half of the 36-year record, a finding that might be attributed to trends in mean currents at Chukchi Sea canyons that were less poleward after 2000. Five distinct patterns of flow were derived using a k-means cluster analysis of monthly mean sea-surface height anomaly distributions. Two of the five patterns related to the strength of the Alaskan Coastal Current (ACC) in the eastern Chukchi Sea, two patterns related to periods of northwestward versus southeastward flow associated with the absence or presence of the Siberian Coastal Current in the northwest Chukchi Sea, and one pattern was defined by weak southeastward flow anomalies in the western Chukchi and a suppressed ACC relative to the mean in the eastern Chukchi Sea. The composite sea-surface height anomaly patterns of the five cluster types conform to the mean sea level pressure anomaly distributions for the months constituting each type. The description of five distinct flow patterns provides a long-term context for previous field observations, and may contribute to the interpretation of observed changes in the structure and function of the marine ecosystem of the Chukchi Sea.

3.2 Biophysical Observations: sediment deposition patterns, corrosive water formation and 'in situ' primary production measurements

Examining factors that influence sedimentation and bioturbation is key to understanding pelagic-benthic linkages that can foster high-productivity macrobenthic communities on the continental shelves of the Pacific Arctic region (Grebmeier et al. 2015 a, b). To examine deposition patterns on the broad Chukchi continental shelf, Cooper and Grebmeier (in press) assayed 40 sediment cores for the sedimentation tracer ^{137}Cs, originating from bomb fallout, and 34 cores for ^{210}Pb. Because both sedimentation and bioturbation influence how these tracers are distributed vertically in sediments, only about half of the cores had distinct, single mid-depth or subsurface maximum activity peaks associated with ^{137}Cs. Similarly, only 14 of the 34 cores assayed showed a consistent decline in excess sedimentary ^{210}Pb with depth in the core. Furthermore, sedimentation rate estimates from ^{210}Pb assays were only consistent with estimated ^{137}Cs sedimentation rates in 5 of the 14 cores. A high degree of bioturbation on the shelf is primarily responsible for these patterns, although the influence of sedimentation on vertical profiles is also important, particularly in areas of low accumulation where shallow burial of maximum burdens of ^{137}Cs occur in areas with strong currents such as Herald Canyon. Shallow burial of ^{137}Cs is also observed in comparatively low sedimentation areas such as Hanna Shoal, on the northeast Chukchi shelf. Conversely, elsewhere on the northeast Chukchi shelf and in productive benthic "hotspots," the stronger influence of bioturbation leads to more even vertical distribution of ^{137}Cs within sediments. These profiles of ^{137}Cs reflect several other sediment characteristics that are affected by current flow, which in turn impact biological activity, including grain size, carbon to nitrogen ratios of the organic fraction of surface sediments and total organic carbon content. The distribution patterns of the radionuclides, particularly the depth where ^{137}Cs reaches maximum activity, reflects sedimentation under both sluggish and strong currents. The activity of ^{137}Cs at that depth of maximum activity also provides insights on how much the vertical distribution of the radionuclide has been impacted by bioturbation, as well as the characteristics of the sediments that play a role in influencing deposition and total inventories of ^{137}Cs on continental shelves.

Ocean acidification (OA), the term used to describe the progressive decrease in ocean water pH and carbonate ion concentration coincident with the uptake of anthropogenic CO_2, is now a well-described global phenomenon with the potential to negatively impact marine ecosystems (Feely et al., 2009; Mathis et al., 2015, and references therein). Cross et al. (in press) synthesize data from process studies across the Pacific Arctic region to describe the formation of conditions in cold and dense winter-modified shelf waters that are corrosive to biologically important carbonate minerals. When these corrosive waters are subsequently transported off the shelf, they acidify the Pacific halocline. Cross et al. (in press) estimate that Barrow Canyon outflow delivers ~2.24 Tg C/yr of corrosive winter water to the Arctic Ocean. The combination of spatial and temporal data demonstrates the seasonal variability and persistence of corrosive conditions in halocline waters. For example, one study indicated that

0.5 –1.7 Tg C/yr may be returned to the atmosphere via air-sea gas exchange of CO2 during upwelling events along the Beaufort Sea shelf that bring Pacific halocline waters to the ocean surface. The loss of CO2 during these events is more than sufficient to eliminate corrosive conditions in the upwelled Pacific halocline waters. However, corresponding moored and discrete data records indicate that potentially corrosive Pacific waters are present in the Beaufort shelf-break jet during 80% of the year, indicating that the persistence of acidified waters in the Pacific halocline far outweighs any seasonal mitigation from upwelling. By comparing multiple broad-scale datasets, Cross et al. (in press) suggest that the persistent corrosive conditions of the Pacific halocline is a recent phenomenon that first appeared sometime between 1975 and 1985. Since then, these potentially corrosive waters originating over the continental shelves have been observed as far east as the entrances to Amundsen Gulf and M'Clure Strait (*ca.* 125^0W longitude) in the Canadian Arctic Archipelago. The formation and transport of corrosive waters on the Pacific Arctic shelves may have widespread impact on the Arctic biogeochemical system and food web reaching all the way to the North Atlantic.

Annual net primary production over the Arctic Ocean, as measured from satellites, increased 30% between 1998-2012, with upturns in the Pacific Arctic region reported as 42.1% (Chukchi), 53.1%% (Beaufort) and 67.7% (East Siberian) during that period (Arrigo and van Dijken, 2015). While informative, measures from remote sensing reflect only what is happening in the surface layer of the ocean and miss sub-surface primary production. Hill et al. (in press) provide a synthesis of available *in situ* primary production measurements made in the Pacific Arctic between 1950 and 2012. Specifically, integrated primary production was calculated from 524 profiles, 340 of which were analyzed to determine the vertical distribution of primary production rates for spring, summer and fall. The northern Bering Sea (Chirikov Basin) and Chukchi shelf were the most productive areas, with the East Siberian Sea, Chukchi Plateau and Canada Basin the lowest. Decadal-scale changes included: (i) a significant increase in PP rate and the loss of a measurable subsurface peak between 1959/60 and the 2000s in the southern Chukchi Sea, and (ii) an earlier phytoplankton surface bloom in the northeastern Chukchi Sea (Hanna Shoal) in the 2000s compared to 1993 that is associated with increased light due to sea-ice retreat. These changes in primary production have likely fueled cascading effects in food webs of the Pacific Arctic marine ecosystem.

3.3 Ecosystem Structure: responses of marine mammals to changing habitats

The range of the Bering-Chukchi-Beaufort population of bowhead whale (*Balaena mysticetus*) extends across the seasonal ice zone of the Pacific Arctic. The majority of whales summer in the eastern Beaufort Sea and winter in the Bering Sea, migrating across the Chukchi Sea in spring and autumn while occupying distinct core-use areas in each region (Citta et al., 2015). The rapid loss of sea-ice over the past two decades has changed bowhead habitats substantially, with many areas now regularly ice-free when whales are present. Druckenmiller et al. (in press) examined changes in the number of open water days (OWD) within annual bowhead whale core-use areas from 1979-2014, and within the western

Beaufort Sea (140°W-157°W; to 72°N) sampled via aerial surveys each autumn 1982-2014. The most dramatic reductions in sea-ice cover have taken place in the western Beaufort Sea, where the number of OWD on the shelf and slope have increased by 20 and 25 days/decade, respectively. Ice cover has decreased more in northern than in southern core-use areas. Specifically, the numbers of OWD within the core-use areas near Point Barrow and along the northern Chukotka coast have increased by 13 and 10 days/decade, respectively, while sea-ice cover has not substantially changed within the winter core-use area near the Gulf of Anadyr. From analysis of aerial survey data, Druckenmiller et al. (in press) report that during the autumn migration across the Beaufort Sea, bowheads prefer habitats closer to shore than to the ice edge and that their distance to shore decreases as the fraction of open water increases. This distribution may be a response to increased feeding opportunities closer to shore, resulting from greater upwelling along the shelf break when the ice retreats far from shore. The aerial survey data also revealed a substantial shift toward Point Barrow in the whales' use of the western Beaufort Sea during autumn 1997-2014 compared to autumn 1982-1996. In the future, reduced sea ice in the southern Chukchi Sea may make wintering there more common and whale movements in summer and autumn may become more variable as productivity and zooplankton aggregations are altered in response to sea-ice loss and shifting ocean dynamics.

The underwater acoustic environment is key to the behavioral ecology of all marine mammals (e.g., Erbe et al., 2015) and has received detailed study with regard to its influence on bowhead whale movements (e.g., Clark et al., 2015; Ellison et al., 2016). Stafford et al. (in press, a) describe the underwater acoustic environment of beluga (*Delphinapterus leucas*) and bowhead whales in three regions containing core-use areas (Citta et al., 2015), examined during months in which both species occur therein; i.e.: (1) January-March, in the St. Lawrence Island/Anadyr Strait region, (2) November-January, in the Bering Strait region, and (3) August-October, in the Barrow Canyon region. Biological sounds (primarily calls from bowhead whales, walruses and bearded seals) dominated the acoustic environment in the St. Lawrence Island/Anadyr Strait region, which was covered by sea ice throughout the months studied. In the Bering Strait region, whales were exposed primarily to environmental noise (mostly from wind) before the region was ice covered in November; by December, biological sounds (from calling bowheads and walruses) became most prevalent. Transient but acute anthropogenic noise (from vessels and air guns) were a large contributor to the underwater acoustic environment in the Barrow Canyon region in late summer and autumn during the 2009-2010 study period; this was also the only region in which the two species co-occurred during open water period. During open water conditions, both near Barrow Canyon and in Bering Strait, underwater noise levels were tightly correlated with wind, as is generally the case throughout the world ocean. Stafford et al. (in press, a) suggest that recent increases in the open water period associated with climate change are fostering increased noise levels aggregated from multiple sound sources (atmospheric, biological, anthropogenic), thus rapidly altering the underwater acoustic environment for marine mammals in the Pacific Arctic.

A description of the fine-scale movements of bowhead whales across the Chukchi Sea during the autumn migration is provided by Citta et al. (in press, a), derived from an analysis of telemetry data obtained from 2006-2010 and 2012. In some years, whales migrated directly to the northern coast of Chukotka, while in other years whales paused migration and lingered in the central Chukchi Sea, presumably to feed. To investigate how whale movements were related to oceanographic variables, bowhead whale habitat selection was examined at both landscape and local scales using a correlated random walk model and oceanographic data from a pan-arctic ice-ocean model. At the landscape scale, Citta et al. (in press, a) found that whales generally followed cold-saline water of Pacific origin and avoided the comparatively warm-fresh waters of the Alaskan Coastal and Siberian Coastal currents. At the local scale, whales were more likely to linger in central-Chukchi areas characterized by strong gradients in bottom salinity, which have been associated with areas of dense zooplankton concentrations in other studies.

Tracking the aggregate movements of pelagic marine predators has increasingly become a means to identify ecological patterns in ocean ecosystems (e.g., Hussey et al., 2015; Block et al., 2011). Citta et al. (in press, b) present the first systematic analysis of telemetry data for seven marine mammal species (four pinniped and three cetacean) that routinely occupy Pacific Arctic waters, and summarize their collective distributions for two temporal periods labeled summer (May-November) and winter (December-April). When examined for overlap, six multi-species core-use areas were identified in summer and four in winter. In summer, four of the six multi-species core-use areas occurred in the Bering Strait region and the northwestern coast of Alaska, and included tracks from most of the species studied. The two other summer core-use areas were in the Canadian Archipelago, largely defined by the tracks of bowhead whales and Eastern Beaufort Sea beluga whales. In winter, the main multi-species core-use area stretched from the Gulf of Anadyr northwards through Anadyr and Bering Straits, which includes an area of enhanced primary and secondary productivity ("green belt") in the Bering Sea. Citta et al. (in press, b) also provide a list of extant telemetry data and data holders, with an appeal that these baseline data be archived to ensure they are available for future retrospective analyses to track changes in the Pacific Arctic marine ecosystem.

4. Marginal Domain: *Barrow Canyon and the Beaufort slope*

Atmospheric forcing, advection and upwelling along Barrow Canyon and the continental slope of the western Beaufort Sea have been the subject of investigation for decades, although biological sampling rarely extends beyond measures of nutrients and chlorophyll-a (e.g., Pickart et al., 2013a, b). Rand et al. (in press) use environmental variables and biological traits to characterize two Arctic epibenthic invertebrate communities in and adjacent to Barrow Canyon. Data were analyzed from two standardized bottom-trawl surveys, one in the northeast Chukchi Sea (2013) and the second in the western Beaufort Sea (2008). In the Chukchi Sea, bottom hardness and depth were the key variables explaining pattern in the epibenthic community, while in the Beaufort Sea unlined net hauls and depth were the main explanatory variables. Although epibenthic communities in each region differed taxonomically in abundance and distribution, an analysis of biological traits showed that they were functionally similar.   These results complement earlier descriptions of epibenthic communities on the continental shelf of the northeastern Chukchi Sea, where distinct epibenthic community distribution patterns were matched with bathymetrically-channeled water masses (Ravelo et al., 2014).

Logerwell et al. (2015) described fish communities across a spectrum of habitats in the western Beaufort and northeastern Chukchi seas, focusing mainly on continental shelf habitats. Logerwell et al. (in press) augment this earlier work by describing results of two multidisciplinary surveys (2008 and 2013, as in Rand et al., in press) focused on benthic fish distribution and oceanographic processes in and around Barrow Canyon. The density of Arctic cod (*Boreogadus saida*), the most abundant species, was related to bottom depth, salinity and temperature, both in Barrow Canyon and along the continental slope. Specifically, Arctic cod were more abundant in deep, cold and highly saline water, likely advected from the Chukchi Shelf or from the Arctic Basin. Logerwell et al. (in press) hypothesize that Arctic cod occupy these habitats to take advantage of energy-rich copepods transported in associated water masses. These linkages between oceanographic variables and benthic fish abundance suggest that advection, sea-ice dynamics and pelagic-benthic coupling are all important for the ecology of benthic fishes in the Pacific Arctic.

Seasonal patterns of distribution and density of two distinct populations of beluga in the western Beaufort Sea (Stafford et al. in press, b) complements the Logerwell et al. (in press) findings on Arctic cod. Combining data from aerial surveys, passive acoustic sampling and satellite telemetry, Stafford et al. (in press, b) show that the Barrow Canyon and Beaufort Sea slope are key habitats for both Beaufort and Eastern Chukchi beluga populations from April through November. Three peaks in calling activity occur during this period, corresponding to migratory pulses of the Beaufort (early spring), Chukchi (late spring) and both (autumn) populations   A model of beluga density derived from aerial survey data showed the western region of the Beaufort Sea slope becomes more important from summer to autumn. Telemetry data suggest that it is predominantly the Chukchi belugas that use this habitat, except in September when both populations co-occur there.   A synthesis of the combined datasets, when integrated with data on wind-driven changes in local currents and water masses, suggested that belugas are very capable of adapting to shifts in prey densities associated with oceanographic variability.

5. Riverine Coastal Domain: *Influence of coastal process on bowhead whales and people*

The Riverine Coastal domain is defined as a narrow (<15 km), shallow (~10 m) contiguous feature that is primarily influenced by aggregate terrestrial runoff, principally in river discharges (Carmack et al., 2015).   The domain is the primary confluence between terrestrial and marine ecosystems and will likely have a more prominent role in modifying coastal environmental variability as terrestrial runoff, permafrost thawing and sea-ice losses increase in the near-future climate. Dramatic shifts in the extent of the Mackenzie River plume have already been reported, whereby the domain extends beyond the nearshore/shallow definition, with a surface heat and fresh water signal ranging far into the western Beaufort Sea (Wood et al., 2015). Closer to shore, Okkonen et al. (in press) describe how upwelling events can combine with high river discharges of the Sagavanirktok and Kuparuk rivers, which flow into the coastal lagoon system between 150^0 W and 144^0 W, leading to aggregations of feeding bowhead whales in the central Alaskan Beaufort Sea. Atypical aggregations of hundreds of foraging bowhead whales seen during aerial surveys in September 1997 and 2014 coincided with prey-accumulations related to high river discharges coupled to prior upwelling events. These results were generalized to a simple binary-based mechanistic model that links the relevant physics to occurrences of potential feeding opportunities for bowhead whales along the entire Beaufort coast, thereby contributing to an improved understanding of this rapidly-changing coastal domain.

The annual harvest of bowhead whales is fundamental to the wellbeing of Inuit coastal communities in the Pacific Arctic region, including eleven villages that extend from Saint Lawrence Island in the northern Bering Sea to Barter Island in the northeastern Beaufort Sea (e.g., Braund and Moorehead, 1995; Huntington et al., 2016). The impacts of offshore commercial activities (e.g., shipping, oil and gas development), both directly on bowhead whales and on the conduct of the hunt, has been the focus of investigation for nearly four decades, with much of the work supported by the BOEM Environmental Studies Program in Alaska (https://www.boem.gov/AKStudies/) and the North Slope Borough Department of Wildlife Management (http://www.north-slope.org/departments/wildlife-management/studies-and-research-projects), among others. Robards et al. (in press) describe the value of including a variety of perspectives when seeking to understand and evaluate the consequences of these impacts. Specifically, the emerging field of "knowledge co-production" identifies ways to facilitate the inclusion of local information to decision making processes (Wyborn, 2015). Robards et al. (in press) review outcomes from seven Alaskan cases studies to describe a typology of five elements important for the co-production of locally relevant actionable knowledge. Three elements are consistent with earlier studies, including: 1) developing communities of practice, 2) iterative processes for defining problems and solutions, and 3) presence of boundary organizations, such as a university, government agency or co-management council. The authors suggest that, for Alaskan Arctic communities, it is also critical to include two other elements, namely: 4) the consistent provision of sufficient funds and labor that may transcend any one specific project goal, and 5) long temporal scales (sometimes decades) for achieving the co-production of actionable knowledge.

6. Summary and Conclusions from SOAR Phase 2

We summarize findings from the papers comprising this special issue using ecological domains adopted in the AMP model as a framework to promote an ecosystem-focused synthesis of the state of the Pacific Arctic. Not surprisingly, most of the papers in this volume relate to processes occurring in the spatially-broad Seasonal Ice Zone domain. The modelled results of sea-ice loss at the fine-scale of daily and mooring-site measurements is unprecedented and reinforces the rapid pace of change in this fundamental component of the Pacific Arctic marine ecosystem (Wang et al., in press). The prognosis for a longer open-water season makes timely the ocean reanalysis provided in Bond et al. (in press), which suggests that current flow in the 'new' open-water Chukchi Sea is comprised of 'alternating states', a finding that provides a foundation for interpretation biophysical patterns observed there. For example, Cooper and Grebmeier (in press) show that deposition patterns across the Chukchi Sea can be broadly categorized based on the relative strength of bioturbation versus sedimentation processes, both of which are strongly influence by current flow. Similarly, current flow patterns, particularly in Barrow Canyon, can notably affect the amount of corrosive winter water transported from the Chukchi shelf northward into Barrow Canyon, along the Beaufort shelf break and ultimately into the Arctic Ocean (Cross et al., in press). Patterns of '*in situ*' primary production in the Chukchi Sea have changed considerably in recent decades, the mechanisms for which are undetermined, but could include shifts in stratification and mixing associated with shifting patterns of current flow (Hill et al., in press). Taken together, these papers support the contention that the Pacific Arctic marine ecosystem has entered a new state.

Responses to rapidly changing sea-ice and ocean conditions in the Seasonal Ice Zone are further demonstrated by changes in the seasonal movements and acoustic environment of bowhead whales (Druckenmiller et al., in press; Stafford et al., in press, b), and in the identification of two dissimilar autumn migratory patterns across the Chukchi Sea (Citta et al., in press, a). In sum, bowhead whales now occupy coastal and continental shelf habitats in the western Beaufort Sea in late summer and autumn more often than they did thirty years ago, where they (and beluga whales) are subject to shifts in their acoustic environment associated with anthropogenic noise from offshore human activities. However, the greatest shift in the underwater acoustic environment comes not from ships and seismic surveys, but from increased ambient noise associated with strong winds during the now-common extended periods of open-water. Overall, prey availability seems the primary factor in driving bowhead whale distribution, both onto shallow shelf habitats as sea ice retreats further from shore in the Beaufort Sea (Druckenmiller et al., in press), and to central-Chukchi shelf habitat when prey is available there during the autumn migration (Citta et al., in press, a). Indeed, present circumstances may be considered 'boom times' for bowhead whales in the Pacific Arctic (Moore 2016), although a 'tipping point' away from these favorable conditions could accompany future ecosystem alterations such as those associated with the "atlantification" of the Arctic (Polyakov et al., 2017).

Barrow Canyon is a region of dynamic ocean conditions and a key 'gateway' to the outer shelf and slope Marginal domain of the Pacific Arctic. Complementary papers focused on epibenthic communities (Rand et al., in press) and benthic fishes (Logerwell et al., in press) provide a novel synthesis of how biophysical variability in and near the canyon influences species occurrence and habitat use. While contrasting epibenthic communities were described for the Beaufort and Chukchi seas, they were found to contain functionally similar groups based on biological traits. Conversely, Arctic cod was the single most abundant benthic fish species, with distribution correlated with deep, cold, saline water associated with lipid-rich copepods in the canyon and adjacent Beaufort Sea slope. The correlation between beluga seasonal distribution and movements with Arctic cod occurrence provides an upper-trophic link and highlights the importance of Barrow Canyon and the Beaufort Sea slope as key habitat for both species in this dynamic section of the marginal domain.

The Riverine Coastal domain marks the juncture between marine and terrestrial ecosystems and therefore a zone of key importance to coastal-dwelling people due to their reliance on resources from the sea for food and cultural wellbeing (Huntington et al., 2016). Bowhead whales are of central importance in this regard, with extant village locations influenced by their seasonal migratory patterns. Okkonen et al. (in press) provides an innovative synthesis of biophysical data leading to atypical aggregations of bowheads in the riverine coastal domain of central Alaskan Beaufort in two of the past twenty years. Understanding causal factors for shifting patterns of whale occurrence is of great interest, both to local people and to management agencies seeking to support safe and effective hunting practices. The formulation of effective bowhead whale co-management practices is perhaps one of the clearest success stories of the past forty years. Robards et al. (in press) describe how the process of knowledge co-production has led to this positive outcome, and identify five elements fundamental to the development locally relevant actionable knowledge. It is further development of these types of socio-ecological tools that can aid communication across cultures.

OVERALL SOAR CONTEXT AND CONCLUSION

The SOAR project is just one of several recent attempts to combine multidisciplinary data and observations to better understand the state and trajectory of arctic marine ecosystems. In addition to the first SOAR special issue (Moore and Stabeno, 2015), other special issues focused on the Pacific Arctic include the Arctic Ecosystem Integrated Survey (Mueter et al., 2017), the Hanna Shoal Ecosystem Study (Dunton et al., 2017), and the Chukchi Sea Offshore Monitoring in Drilling Area - Chemical and Benthos project (Dunton et al., 2014). Other notable efforts include a compendium of information for the northeastern Chukchi Sea (Hopcroft and Day, 2013), the Pacific Marine Arctic Regional Synthesis (Grebmeier et al. 2015c; http://pacmars.cbl.umces.edu/), and a volume of papers providing a pan-Arctic multidisciplinary perspective (Wassman, 2015). While these examples all have a regional focus, other recent reviews of climate change impacts on marine ecosystems have adopted mechanistic frameworks, including direct physiological and climate-mediated predator-prey responses evidenced by upper trophic species (e.g. Sydeman et al., 2015). We introduced the AMP model as a conceptual framework for the Pacific Arctic region in the first SOAR special issue (Moore and Stabeno 2015). Now, in the preceding discussion of Phase 2 of the SOAR project, we have used the ecological domain framework of the AMP model as a tool for a synthesis of information regarding the current state and possible trajectory of the Pacific Arctic marine ecosystem. In so doing, we bring a mechanistic approach to a regional analysis. In 2011, we did not set out to develop the AMP model; rather, it was the fruition of the first phase of SOAR. The more fully developed AMP model and the extensive new syntheses and findings overviewed in this final report for the SOAR project have moved us toward reaching the three main objectives of the SOAR project: We have increased scientific understanding of the relationships among oceanographic conditions and marine life in the PAR; we have enhanced the scientific community's capability to predict future changes in oceanography and associated changes in the behavior of marine mammals and their prey in the PAR; and we have communicated findings of synthesis activities to resource managers, local Arctic residents, national and international science societies, and the general public.

LITERATURE CITED

Ainley, D.G. and DeMaster, D.P., 1990. The upper trophic levels in polar marine ecosystems. Pp. 599-630 *In* W.O. Smith, Jr. (ed.), Polar Oceanography, Part B: Chemistry, Biology and Geology., Academic Press, San Diego CA.

Arrigo, K.R., and van Dijken, G.L., 2015. Continued increases in Arctic Ocean primary production. Progress in Oceanography 136, 60-70.

Ashjian, C.J., Braund S.R., Campbell, R.G., George, J.C., Kruse, J., Maslowski, W., Moore, S.E., Nicolson, C.R., Okkonen, S.R., Sherr, B.F., Sherr, E.B., and Spitz, Y., 2010. Climate variability, oceanography, bowhead whale distribution and Inupiat subsistence whaling near Barrow, Alaska. *Arctic* 63(2): 179-194.

Berline, L., Spitz, Y.H., Ashjian, C.J., Campbell, R.G., Maslowski, W., and Moore, S.E., 2008. Euphausiid transport in the Western Arctic Ocean. *Marine Ecology Progress Series* 360: 163-178.

Blackwell, S.B., Richardson, W.J., Greene, C.R., Streever, B., 2007. Bowhead whale (*Balaena mysticetus*) migration and calling behavior in the Alaskan Beaufort Sea, autumn 2001-04: an acoustic localization study. Arctic 60, 255-270.

Block, B. A., Jonsen, I. D., Jorgensen, S.J.,+ 18 co-authors., 2011. Tracking apex marine predator movements in a dynamic ocean. Nature 475, doi: 10.1038/nature10082.

Bluhm, B.A. Coyle, K.O., Konar, B., and Highsmith, R., 2007. High gray whale relative abundances associated with an oceanographic front in the south-central Chukchi Sea. *Deep-Sea Research II*: 2919-2933.

Bond, N., Stabeno, P., Napp, J., in press. Flow patterns in the Chukchi Sea based on an ocean reanalysis, June through October 1979-2014.

Carmack, E., D. Barber, J. Christensen, R. Macdonald, B. Rudels and E. Sakshaug. 2006. Climate variability and physical forcing of the food webs and carbon budget on panarctic shelves. *Progress in Oceanography* 71: 145-181.

Carmack, E., Wassmann, P., 2006. Food webs and physical-biological coupling on pan-Arctic shelves: unifying concepts and comprehensive perspectives. Progress in Oceanography 71, 446-477.

Carmack, E., Winsor, P., Williams, W., 2015. The contiguous panarctic Riverine Coastal Domain: a unifying concept. Progress in Oceanography 139, 13-23.

Citta, J.J., Quakenbush, L.T., Okkonen, S.R., Druckenmiller, M.L., Maslowski, W., Clement-Kinney, J., George, J.C., Brower, H., Small, R.J., Ashjian, C.J., Harwood, L.A., Heide-Jørgensen, M.P., 2015. Ecological characteristics of core-use areas used by Bering–Chukchi–Beaufort (BCB) bowhead whales, 2006–2012. Progress in Oceanography 136, 201-222.

Citta, J.J., Okkonen, S.R., Quakenbush, L.T., Maslowski, W., Osinski, R., George, J.C., Small, R.J., Brower Jr., H., Heide-Jørgensen, M.P., Harwood, L.A., in press, a. Oceanographic characteristics associated with autumn movements of bowhead whales in the Chukchi Sea.

Citta, J.J., Quakenbush, L.T., London, J.M., Frost, K.J., Fischbach, A.S., Lowry, L.F., O'Corry-Crowe, G., Jay, C.V., Crawford, J.A., Boveng, P.L., Cameron, M., Von Duyke, A.L., Nelson, M., Harwood, L.A., Richard, P., Suydam, R., Heide-Jørgensen, M.P., Hobbs, R.C., Litovka, D.I., George, J.C., Kelly, B.P., Smith, T.G., Kennedy, A., Goodwin, J., Orr, J., Gray, T., in press, b. Overlap of marine mammal ranges and multi-species core use areas: a synthesis of satellite telemetry data in the Pacific Arctic.

Clark, C.W., Berchok, C.L., Blackwell, S.B., Hannay, D.E., Jones, J., Ponirakis, D., Stafford, K.M., 2015. A year in the acoustic world of bowhead whales in the Bering, Chukchi and Beaufort seas. Progress in Oceanography 136, 223-240.

Cooper, L.W., Grebmeier, J.M., in press. Deposition patterns on the Chukchi shelf using radionuclide inventories in relation to surface sediment characteristics.

Crawford, J.A., Quakenbush, L.T., Citta, J.J., 2015. A comparison of ringed and bearded seal diet, condition and productivity between historical (1975–1984) and recent (2003–2012) periods in the Alaskan Bering and Chukchi seas. Progress in Oceanography 136, 133-150.

Cross, J. N., Mathis, J.T., Pickart, R.S., Bates, N.R., in press. Formation and transport of corrosive water in the Pacific Arctic region.

Danielson, S.L., Weingartner, T.J., Hedstrom, K.S., Aagaard, K., Woodgate, R., Curchitser, E. Stabeno, P.J., 2014. Coupled wind-forced controls of the Bering-Chukchi shelf circulation and the Bering Strait throughflow: Ekman transport, continental shelf waves, and variations of the Pacific-Arctic sea surface height gradient. Progress in Oceanography 125, 40-61.

Divoky, G.J., Lukacs, P.M., Druckenmiller, M.L., 2015. Effects of recent decreases in arctic sea ice on an ice-associated marine bird. Progress in Oceanography 136, 151-161.

Druckenmiller, M.L., Citta, J.J., Ferguson, M.C., Clarke, J.T., George, J.C., Quakenbush, L., in press. Trends in sea-ice cover within bowhead whale habitats in the Pacific Arctic.

Dunton, K.H., Grebmeier, J.M., and Trefry, J.H., 2017. Hanna Shoal: An integrative study of a High Arctic marine ecosystem in the Chukchi Sea. Deep Sea Research Part II. DOI 10.1016/j.dsr2.2017.09.001.

Dunton, K.H., Grebmeier, J.M., and Trefry, J.H., 2014. The benthic ecosystem of the northeastern Chukchi Sea: an overview of its unique biogeochemistry and biological characteristics. Deep-Sea Research II 102:1-8.

Erbe, C., Reichmuth, C., Cuningham, K., Luke, K., Dooling, R., 2015. Communication masking in marine mammals: a review and research strategy. Marine Pollution Bulletin, http://dxdoi.org/10.1016/j.marpolbul.2015.12.007.

Ellison, W.T., Racca, R., Clark, C.W., Streever, B., Frankel, A.S., Fleishman, E., Angliss, R., Berger, J., Ketten, D., Guerra, M., Leu, M., McKenna, M., Sformo, T., Southall, B., Suydam, R., Thomas, L., 2016. Modeling the aggregated exposure and responses of bowhead whales, *Balaena mysticetus*, to multiple sources of anthropogenic underwater sound. Endangered Species Research 30, 95-108.

Feely, R.A., Doney, S.C., Cooley, S.R., 2009. Ocean acidification: present conditions and future changes in a high-CO_2 world. Oceanography 22, 36-47.

Frey, K.E., Moore, G.W.K., Cooper, L.W., Grebmeier, J.M., 2015. Divergent patterns of recent sea ice cover across the Bering, Chukchi, and Beaufort seas of the Pacific Arctic Region. Progress in Oceanography 136, 32-49.

George, J. C., Bada, J., Zeh, J., Scott, L., Brown, S. E., O'hara, T., & Suydam, R., 1999. Age and growth estimates of bowhead whales (*Balaena mysticetus*) via aspartic acid racemization. Canadian Journal of Zoology, 77, 571-580.

George, J.C., Druckenmiller, M.L., Laidre, K.L., Suydam, R., Person, B., 2015. Bowhead whale body condition and links to summer sea ice and upwelling in the Beaufort Sea. Progress in Oceanography 136, 250-262.

Giles, K.A., Laxon, S.W., Ridout, A.L., Wingham, D.J., Bacon, S., 2012. Western Arctic Ocean freshwater storage increased by wind-driven spin-up of the Beaufort Gyre. Nature Geoscience 5, 194-197.

Grebmeier, J.M., Overland, J.E., Moore, S.E., Farley, E.V., Carmack, E.C., Cooper, L.W., Frey, K.E., Helle, J.H., McLaughlin, F.A., McNutt, S.L., 2006. A major ecosystem shift in the northern Bering Sea. Science 311, 1461-1464.

Grebmeier, J.M., 2012. Shifting patterns of life in the Pacific Arctic and sub-arctic seas. Annual Review of Marine Science 4, 16.1-16.6.

Grebmeier J.M., Maslowski W. (2014) The Pacific Arctic Region: An Introduction. *In:* Grebmeier J., Maslowski W. (eds) The Pacific Arctic Region. Springer, Dordrecht.

Grebmeier, J.M., Moore, S.E., Overland, J.E., Frey, K.E., and Gradinger, R., 2010. Biological response to recent Pacific Arctic sea ice retreats. *EOS* 91(18) 161-168.

Grebmeier, J.M., Bluhm, B.A., Cooper, L.W., Danielson, S.L., Arrigo, K.R., Blanchard, A.L., Clarke, J.T., Day, R.H., Frey, K.E., Gradinger, R.R., Kędra, M., Konar, B., Kuletz, K.J., Lee, S.H., Lovvorn, J.R., Norcross, B.L., Okkonen, S.R., 2015a. Ecosystem characteristics and processes facilitating persistent macrobenthic biomass hotspots and associated benthivory in the Pacific Arctic. Progress in Oceanography 136, 92-114.

Grebmeier, J.M., Bluhm, B.A., Cooper, L.W., Denisenko, S.G., Iken, K., Kedra, M., Serratos, C., 2015b. Time-series benthic community composition and biomass and associated environmental characteristics in the Chukchi Sea during the RUSALCA 2004-2012 program. Oceanography 23, 116-133.

Grebmeier, J.M., Cooper, L.W., Ashjian, C.A., Bluhm, B.A., Campbell, R.B., Dunton, K.E., Moore, J., Okkonen, S., Sheffield, G., Trefry, J., Pasternak, S.Y., 2015c. Pacific Marine Arctic Regional Synthesis (PacMARS) Final Report, North Pacific Research Board, 259 pp.

Hannay, D. E., Delarue, J., Mouy, X., Martin, B. S., Leary, D., Oswald, J. N., Vallarta, J., 2013. Marine mammal acoustic detections in the northeastern Chukchi Sea, September 2007–July 2011. Continental Shelf Research, 67, 127-146.

Harwood, L.A., Smith, T.G., George, J.C., Sandstrom, S.J., Walkusz, W., Divoky, G.J., 2015. Change in the Beaufort Sea ecosystem: Diverging trends in body condition and/or production in five marine vertebrate species. Progress in Oceanography 136, 263-273.

Hill, V., Ardyna, M., Lee, S.H., Varela, D.E., in press. Decadal trends in phytoplankton production in the Pacific Arctic Region from 1950 to 2012.

Hopcroft, R.R., Day, R.H. (eds), 2013. Seasonal and interannual dynamics of the northeastern Chukchi Sea ecosystem. Continental Shelf Research 67, 1-165.

Hu, A., Meehl, G.A., Han, W., Otto-Bliestner, B., Abe-Ouchi, A., Rosenbloom, N., 2015. Effects of the Bering Strait closure on AMOC and global climate under different background climates. Progress in Oceanography 132, 174-196.

Huntington, H.P., Quakenbush, L.T., Nelson, M., 2016. Effects of changing sa ice on marine mammals and subsistence hunters in northern Alaska from traditional knowledge interviews. Biology Letters 12, doi 10.1098/rsbl.2016.0198.

Hussey, N.E., Kessel, S.T., Aarestrup, K., and 9 co-authors, 2015. Aquatic animal telemetry: a panoramic window into the underwater world. Science 348, doi: 10.1126/science.1255642.

Jeffries, M.O., Overland J.E., Perovich D.K., 2013. The arctic shifts to a new normal. Physics Today 10, 35-40.

Kovacs, K.M., Lydersen, C., Overland, J.E., and Moore, S.E., 2010. Impacts of changing sea ice conditions on Arctic marine Mammals. *Marine Biodiversity*: 51-65.

Kuletz, K.J., Ferguson, M.C., Hurley, B., Gall, A.E., Labunski, E.A., Morgan, T.C., 2015. Seasonal spatial patterns in seabird and marine mammal distribution in the eastern Chukchi and western Beaufort seas: Identifying biologically important pelagic areas. Progress in Oceanography 136, 175-200.

Leu, E., Søreide, Hessen, D.O., Falk-Petersen, S., Berge, J., 2011, Consequences of changing sea-ice cover for primary and secondary producers in the European Arctic shelf seas: Timing, quantity and quality. Progress in Oceanography 90, 18-32.

Logerwell, E., Busby, M., Carothers, C., Cotton, S., Duffy-Anderson, J., Farley, E., Goddard, P., Heintz, R., Holladay, B., Horne, J., Johnson, S., Lauth, B., Moulton, L., Neff, D., Norcross, B., Parker-Stetter, S., Seigle, J., Sformo, T., 2015. Fish communities across a spectrum of habitats in the western Beaufort Sea and Chukchi Sea. Progress in Oceanography 136, 115-132.

Logerwell, E., Rand, K., Danielson, S., Sousa L., in press. Environmental drivers of benthic fish distribution in and around Barrow Canyon in the northeastern Chukchi Sea and western Beaufort Sea.

Lovvorn, J.R., Rocha, A.R., Jewett, S.C., Dasher, D., Oppel, S., Powell, A.N., 2015. Limits to benthic feeding by eiders in a vital Arctic migration corridor due to localized prey and changing sea ice. Progress in Oceanography 136, 162-174.

Lowry L.F., Sheffield G., George J.C., 2004. Bowhead whale feeding in the Alaskan Beaufort Sea, based on stomach content analyses. Journal of Cetacean Research and Management 6, 215–223.

MacIntyre, K.Q., Stafford, K.M., Conn, P.B., Laidre, K.L., Boveng, P.L., 2015. The relationship between sea ice concentration and the spatio-temporal distribution of vocalizing bearded seals (Erignathus barbatus) in the Bering, Chukchi, and Beaufort Seas from 2008 to 2011. Progress in Oceanography 136, 241-249.

Mathis, J.T., Cooley, S.R., Lucey, N., Colt, S., Ekstrom, J., Hurst, T., Hauri, C., Evans, W., Cross, J.N., Feely, R.A., 2015. Ocean acidification risk assessment for Alaska's fishery sector. Progress in Oceanography 136, 71-91.

Moore, S.E., 2016. Is it 'boom times' for baleen whales in the Pacific Arctic region? *Biology Letters* 12, doi .0251.

Moore, S.E., Clarke, J.T., and Ljungblad, D.K., 1986. A comparison of gray whale (*Eschrichtius robustus*) and bowhead whale (*Balaena mysticetus*) distribution, abundance, habitat preference and behavior in the northeastern Chukchi Sea, 1982-84. *Rep. Int. Whale. Commn*. 36: 273-279.

Moore, S.E., Stafford, K.M., Mellinger, D., Hildebrand, J.A., 2006. Listening for large whales in offshore waters of Alaska, 1999-2004. BioScience 56, 49-55.

Moore, S.E. and Huntington, H.P., 2008. Arctic marine mammals and climate change: impacts and resilience. *Ecological Applications* 18(2): S157-S165.

Moore, S.E., George, J.C., Sheffield, G., Bacon, J., and Ashjian, C.J., 2010. Bowhead whale distribution and feeding near Barrow, Alaska in late summer 2005-06. *Arctic* 63(2)*:* 195-205.

Moore, S. E. and Gulland, F. M. D., 2014. Linking marine mammal and ocean health in the 'New Normal' arctic. Ocean and Coastal Management 102, 55-57.

Moore, S.E., Stabeno, P.J., 2015. Synthesis of Arctic Research (SOAR) in marine ecosystems of the Pacific Arctic. Progress in Oceanography 136, 1-11.

Moore S.E., Logerwell E., Eisner L., Farley E., Harwood L., Kuletz K., Lovvorn J., Murphy J., Quakenbush L., 2014. Marine fishes, birds and mammals as sentinels of ecosystem variability and reorganization in the Pacific Arctic region. pp. 337-392, *In*: Grebmeier JM, Maslowski W (eds.) The Pacific Arctic Region: ecosystem status and trends in a rapidly changing environment. Springer, Dordrecht.

Moore, S.E., Stabeno, P.J., Grebmeier, J.M., Okkonen, S.R., in press. The Arctic Marine Pulses Model: linking annual oceanographic processes to contiguous ecological domains in the Pacific Arctic.

Mueter F.J. and Litzow, M.A., 2008. Sea ice retreat alters the biogeography of the Bering Sea continental shelf. *Ecological Applications 18*:309-320.

Mueter, F.J., Weems, J., Farley, E.V., Sigler, M.F., 2017. Arctic Ecosystem Integrated Survey (Arctic Eis): Marine ecosystem dynamics in the rapidly changing Pacific Arctic Gateway. Deep Sea Research Part II: Topical Studies in Oceanography 135, 1-6, doi:10.1016/j.dsr2.2016.11.005.

Nelson, R.J., Ashjian, C.J., Bluhm, B.A., Conlan, K.E., Gradinger, R.R., Grebmeier, J.M., Hill, V.J., Hopcroft, R.R., Hunt, B.P.V., Hyoung, M.J., Kirchman, D.L., Kosobokova, K.N., Lee, S.H., William, K.W.L., Lovejoy, C., Poulin, M., Sherr, E., Young K.V., 2014. Biodiversity and biogeography of the lower trophic taxa of the Pacific Arctic region: sensitivities to climate change. pp. 269-336, *In*: Grebmeier JM, Maslowski W (eds.) The Pacific Arctic Region: ecosystem status and trends in a rapidly changing environment. Springer, Dordrecht.

Ogi, M., Wallace, J.M., 2012. The role of summer surface wind anomalies in the summer Arctic: sea-ice extent in 2010 and 2011. Geophysical Research Letters, 39, L09704.

Okkonen, S.R., Ashjian C.J., Campbell, R.G., Clarke, J.T., Moore, S.E., Taylor, K.D., 2011. Satellite observations of circulation features associated with a bowhead whale feeding 'hotspot' near Barrow, Alaska. Remote Sensing of the Environment 115, 2168-2174.

Okkonen, S.R., Clarke, J.T., Potter, R.A., in press. Relationships among high river discharges, upwelling events and bowhead whale (*Balaena mysticetus*) occurrence in the central Alaska Beaufort Sea.

Pickart, R.S., Schulze, L.M., Moore, G.W.K., Charette, M.A., Arrigo, K.R., van Dijken, G., Danielson, S.L., 2013a. Long-term trends of upwelling and impacts on primary productivity in the Alaskan Beaufort Sea. Deep-Sea Research I 79, 106-121.

Pickart, R.S., Spall, M.A., Mathis, J.T., 2013b. Dynamics of upwelling in the Alaskan Beaufort Sea and associated shelf-basin fluxes. Deep-Sea Research I 76, 35-51.

Polyakov, I., Pnyushkov, A.V., Alkire, M.B., Ashik, I.M., and 12 co-authors, 2017. Greater role for Atlantic inflows on sea-ice loss in the Eurasian Basin of the Arctic Ocean. Science 356, 285-291.

Rand, K.M. and Logerwell, E.A., 2010. The first demersal trawl survey of benthic fish and invertebrates in the Bering Sea since the 1970s. *Polar Biology* doi 10.1007.

Rand, K., Logerwell, E., Bluhm, B., Chenelot, H. Danielson, S., Iken, K., Sousa, L., in press. Using biological traits and environmental variables to characterize two Arctic epibenthic invertebrate communities in and adjacent to Barrow Canyon.

Ravelo, A.M., Konar, B., Trefry, J.H., Grebmeier, J.M., 2014. Epibenthic community variability in the northeastern Chukchi Sea. Deep-Sea Research II 102, 119-131.

Robards, M.D., Huntington, H.P., Druckenmiller, M., Lefevre, J., Moses, S.K., Stevenson, Z., Watson, A., Williams, M. in press. Understanding and adapting to observed changes in the Alaskan Arctic: actionable knowledge co-production with Alaska Native Communities.

Rode, K.D., Regehr E.V., Douglas, D.C., Durner, G., Derocher, A.E., Thiemann, G.W., Budge, S.M., 2013. Variation in the response of an Arctic top predator experiencing habitat loss: feeding and reproductive ecology of two polar bear populations. Global Change Biology, doi: 10.1111/gcb.12339.

Sheffield Guy, L.M., Moore, S.E., and Stabeno, P.J., 2012a. Synthesis of Arctic Research (SOAR) Science Workshop Report. BOEM OCS Study BOEM–2012-0031. Anchorage, AK.

Sheffield Guy, L.M., Moore, S.E., and Stabeno, P.J., 2012b. Marine ecosystem synthesis: From physics to whales in the Pacific Arctic, Eos 93(48), 501, doi: 10.1029/2012EO480007.

Sheffield Guy, L.M., Moore, S.E., Stabeno, P.J., 2016. What does the Pacific Arctic's new normal mean for marine life? Eos 97 (24), 14-19.

Spencer, P.D. 2008. Density-independent and density-dependent factors affecting temporal changes in spatial distributions of eastern Bering Sea flatfish. *Fisheries Oceanography* 17: 396–410 doi:10.1111/j.1365-2419.2008.00486.x

Stafford, K.M., Moore, S.E., Berchok, C.L., Wiig, Ø., Lydersen, C., Hansen, E., Kalmbach, D., Kovacs, K.M., 2012. Spitsbergen's endangered bowhead whales sing through the polar night. Endangered Species Research 18, 95-103.

Stafford, K.M., Ferguson, M.C., Hauser, D.D.W., Okkonen, S.R., Berchok, C.L., Citta, J.J., Clarke, J.T., Garland, E.C., Jones, J., Suydam, R.S., in press, a. Beluga whales in the western Beaufort Sea: current state of knowledge on timing, distribution, habitat use and environmental drivers.

Stafford, K.M., Castellote, M., Guerra, M. and Berchok, C.L., in press, b. Seasonal acoustic environments of beluga and bowhead whale core-use regions in the Pacific Arctic.

Stroeve, J., M. Serreze S. Drobot, S. Gearheard, M. M. Holland, J. Maslanik, W. Meier, and T. Scambos, 2008. Arctic sea ice extent plummets in 2007, EOS 89(2), 13-14.

Sydeman, W.J., Poloczanska, E., Reed, T.E., Thompson, S.A., 2015. Climate change and marine vertebrates. Science 350, 772-777.

Tremblay, J-É., Robert, D., Varela, D.E., Lovejoy, C., Darnis, G., Nelson, R.J., Sastri, A.R., 2012. Current state and trends in Canadian Arctic marine ecosystems: I. Primary production. Climatic Change doi: 10.1007/s10584-012-0496-3

Wang, M., and Overland, J.E., 2009. An ice free summer Arctic within 30 years? *Geophysical Research Letters 36,* L07502, doi: 10.1029/2009GL037820.

Wang, M., Overland, J.E., 2015. Projected future duration of the sea-ice-free season in the Alaskan Arctic. Progress in Oceanography 136, 50-59.

Wang, M., Yang, Q., Overland, J.E., Stabeno, P., in press. Sea-ice phenology in the Pacific Arctic: the present and projections to mid-century by selected SMIP5 models.

Wood, K.R., Bond, N.A., Danielson, S.L., Overland, J.E., Salo, S.A., Stabeno, P.J., Whitefield, J., 2015. A decade of environmental change in the Pacific Arctic region. Progress in Oceanography 136, 12-31.

Woodgate, R.A., Weingartner, T.J., Lindsay, R., 2012. Observed increases in Bering Strait oceanic fluxes from the Pacific to the Arctic form 2001 to 2011 and their impacts on the Arctic Ocean water column. Geophysical Research Letters 39, L 24603, doi: 10.1029/2012GL054092

Wyborn, C.A., 2015 Connecting knowledge with action through co-productive capacities: adaptive governance and connectivity conservation. Ecology and Society 20, 11- http://dx.doi.org/10.5751/ES-06510-200111

APPENDIX A – LIST OF SOAR 2012 WORKSHOP ATTENDEES

Science Steering Committee	Affiliation	Location
Robyn Angliss	NOAA/NMML	Seattle, WA
Carin Ashjian	WHOI	Woods Hole, MA
Christopher Clark	Cornell	Ithaca, NY
Jacqueline Grebmeier	UMCES	Solomons, MD
Craig George	NSB	Barrow, AK
Taqulik Hepa	NSB	Barrow, AK
Vera Metcalf	EWC/Kawerak	Nome, AK
Chad Jay	USGS	Anchorage, AK
Tim Ragan	MMC	Washington, DC
Robert Suydam	NSB	Barrow, AK
Tom Weingartner	UAF/SFOS	Fairbanks, AK
Science Contributors	**Affiliation**	**Location**
Kevin Arrigo	Stanford	Stanford,CA
Catherine Berchok	NOAA/NMML	Seattle, WA
Susanna Blackwell	Greeneridge Sciences, INC	Santa Barbara, CA
Bodil Bluhm	UAF/SFOS	Fairbanks, AK
Peter Boveng	NOAA/NMML	Seattle, WA
Eugene Brower	Barrow Whaling Captains Assn	Barrow, AK
John Burns	ADF&G (ret.),	Fairbanks, AK
Robert Campbell	URI	Newport, RI
John Citta	ADFG	Fairbanks, AK
Lee Cooper	UM/Chesapeake Bio. Lab	Solomons, MD
Robert Day	ABR, Inc	Fairbanks, AK
George Divoky	Friends of Cooper Island	Seattle, WA
Matthew Druckenmiller	UAF/CIRES	Fairbanks, AK
Ken Dunton	U of Texas	Austin, TX
Ed Farley	NOAA/AFSC	Juneau, AK
Megan Ferguson	NOAA/NMML	Seattle, WA
Karen Frey	Clark University	Worcester, MA
David Hannay	Jasco Research	Victoria, BC, CAN
Lois Harwood	Fisheries and Oceans	Yellowknive, NT, CAN
Russ Hopcroft	UAF/SFOS	Fairbanks, AK

Josh Jones	Scripps	San Diego, CA
Merlin Koonooka	Native Village of Gambell	Gambell, AK
Kathy Kuletz	USFWS/MBM	Anchorage, AK
Libby Logerwell	NOAA/AFSC	Seattle, WA
Jim Lovvorn	Southern Illinois U	Carbondale
Wieslaw Maslowski	Naval Postgraduate School	Monterey, CA
Jeremy Mathis	UAF/SFOS	Fairbanks, AK
Jeff Napp	NOAA/AFSC	Seattle, WA
George Noongwook	Native Village of Savoonga	Savoonga, AK
Brenda Norcross	UAF/SFOS	Fairbanks, AK
Stephen Okkonen	UAF/SFOS	Fairbanks, AK
Jim Overland	NOAA/PMEL	Seattle, WA
Sandy Parker-Stetter	UW	Seattle, WA
Robert Pickart	WHOI	Woods Hole, MA
Lori Quakenbush	ADFG	Fairbanks, AK
Scott Raborn	LGL	College Station, TX
Fenton Rexford	Native Village of Kaktovik	Kaktovik, AK
Kate Stafford	UW	Seattle, WA
John Trefry	FL Institute of Technology	Melbourne, FL
Rebecca Woodgate	UW/APL	Seattle, WA

BOEM Participants	**Affiliation**	**Location**
Heather Crowley	BOEM	Anchorage, AK
Warren Horowitz	BOEM	Anchorage, AK
Charles Monnett	BOEM (retired)	Anchorage, AK

APPENDIX B – LIST OF SOAR CONTRIBUTORS AND INSTITUTIONS

Science Contributors	Affiliation	Location	Specialty
Kevin Arrigo	Stanford	Stanford,CA	Nutrients and Primary Prod
Catherine Berchok	NOAA/NMML	Seattle, WA	Acoustics
Susanna Blackwell	Greeneridge Sciences, INC	Santa Barbara, CA	Acoustics
Bodil Bluhm	UAF/SFOS	Fairbanks, AK	Benthic
Peter Boveng	NOAA/NMML	Seattle, WA	Mammals
Eugene Brower	Barrow Whaling Captains Assn.	Barrow, AK	Local and Traditional Knowledge
John Burns	ADFG (ret.)	Fairbanks, AK	Industry Science Lead/Mammals
Robert Campbell	URI	Newport, RI	Zooplankton
John Citta	ADFG	Fairbanks, AK	Mammals
Lee Cooper	UM/Chesapeake Bio. Lab	Solomons, MD	Chemistry
Robert Day	ABR, Inc	Fairbanks, AK	Industry Science Lead/Seabirds
George Divoky	Friends of Cooper Island	Seattle, WA	Seabirds
Matthew Druckenmiller	NSIDC	Boulder, CO	Sea Ice
Ken Dunton	U of Texas	Austin, TX	Hanna Shoal Lead/Benthic
Ed Farley	NOAA/AFSC	Juneau, AK	Fish
Megan Ferguson	NOAA/NMML	Seattle, WA	Mammals
Karen Frey	Clark University	Worcester, MA	Nutrients and Primary Prod
David Hannay	Jasco Research	Victoria, BC, Canada	Acoustics
Lois Harwood	Fisheries and Oceans	Yellowknive, NT, Canada	Mammals
Russ Hopcroft	UAF/SFOS	Fairbanks, AK	Zooplankton
Josh Jones	Scripps	San Diego, CA	Acoustics
Merlin Koonooka	Native Village of Gambell	Gambell, AK	Local and Tradtional Knowledge
Kathy Kuletz	USFWS/MBM	Anchorage, AK	Seabirds
Libby Logerwell	NOAA/AFSC	Seattle, WA	Fish
Jim Lovvorn	Southern Illinois U	Carbondale	Sea Ducks
Wieslaw Maslowski	Naval Postgraduate School	Monterey, CA	Physics
Jeremy Mathis	UAF/SFOS	Fairbanks, AK	Chemistry
Jeff Napp	NOAA/AFSC	Seattle, WA	Zooplankton
George Noongwook	Native Village of Savoonga	Savoonga, AK	Local and Tradtional Knowledge

Brenda Norcross	UAF/SFOS	Fairbanks, AK	Fish
Isaac Nukapigak	Kuukpik Corp.	Nuiqsut, AK	Local and Tradtional Knowledge
Stephen Okkonen	UAF/SFOS	Fairbanks, AK	Physics
Jim Overland	NOAA/PMEL	Seattle, WA	Sea Ice/Meterology
Sandy Parker-Stetter	UW	Seattle, WA	Fish
Robert Pickart	WHOI	Woods Hole, MA	Physics
Lori Quakenbush	ADFG	Fairbanks, AK	Mammals
Fenton Rexford	Native Village of Kaktovik	Kaktovik, AK	Local and Tradtional Knowledge
Scott Raborn	LGL	Pineville, LA	Fish
Kate Stafford	UW	Seattle, WA	Acoustics
John Trefry	FL Institute of Technology	Melbourne, FL	Chemistry
Rebecca Woodgate	UW/APL	Seattle, WA	Physics

APPENDIX C – LIST OF SOAR CONTRIBUTOR PRESENTATIONS AT SCIENTIFIC MEETINGS, WORKSHOPS, AND WEBINARS

Date	Presenter	Title	Where
16-Jan-2012	Sheffield Guy	Poster: Synthesis of Arctic Research - Physics to Whales in the Pacific Arctic	Alaska Marine Science Symposium, Anchorage, AK
17-Jan-2012	Moore	Marine mammals and sea ice loss in the Pacific Arctic: tracking ecosystem responses to the 'New Normal' during a period of rapid change	Alaska Marine Science Symposium, Anchorage, AK
17-Jan-2012	Stabeno	Chukchi Acoustics, Oceanography, and Zooplankton (CHAOZ): Observations on Chukchi Sea	Alaska Marine Science Symposium, Anchorage, AK
10-Apr-2012	Stabeno	Observations in the Chukchi Sea	NOAA/PMEL Seattle, WA
15-Aug-2012	Moore	Marine Mammals in the New Normal Pacific Arctic	USCG Healy
21-Sep-2012	Moore	An overview of the SOAR project	PacMARS meeing, Annapolis, MD
13-Nov-2012	Moore	SOAR program overview	Northern Oil and Gas Research Forum, Anchorage, AK
10-Dec-2012	Moore	An overview of the SOAR Project	PacMARS data meeting, Boulder, CO
20-Jan-2013	Moore	An overview of the SOAR Project	Joint SOAR-PacMARS meeting, Anchorage, AK
20-Jan-2013	Clark	Overview of SOAR acoustics project	Joint SOAR-PacMARS meeting, Anchorage, AK
20-Jan-2013	Ferguson	Overview of Kuletz/Ferguson SOAR project	Joint SOAR-PacMARS meeting, Anchorage, AK
20-Jan-2013	Grebmeier	Overview of SOAR Barrow Canyon project	Joint SOAR-PacMARS meeting, Anchorage, AK
21-Jan-2013	Sheffield Guy	Poster: Synthesis of Arctic Research - Physics to Whales in the Pacific Arctic	Alaska Marine Science Symposium, Anchorage, AK
20-Feb-2013	Moore	SOAR program update	Science Technical Advisory Panel, Fairbanks, AK
25-Feb-2013	Moore	NOAA s Arctic Vision and Strategy: Update on Goals 2 & 5	NOAA/PMEL Seattle, WA
12-Mar-2013	Mathis	Ocean Acidification Risk Assessment (won NOAA Science paper award)	Gordon Research Conference, Ventura, CA
12-Mar-2013	Moore	Marine mammals and sea ice loss in the Pacific Arctic: tracking ecosystem responses to the 'New Normal'	Gordon Research Conference, Ventura, CA
26-Mar-2013	Moore	SOAR Program Overview	Keynote presentation at Wakefield

			Symposium, Anchorage, AK
27-Mar-2013	Divoky	Shifting prey in a melting ocean: Seabirds reveal annual and seasonal changes in Arctic nearshore fish populations	Wakefield Symposium, Anchorage, AK
27-Mar-2013	Arrigo	Presentation including SOAR results	Wakefield Symposium, Anchorage, AK
7-Jun-2013	Sullivan	SOAR included in presentation titled: NOAA in the Arctic 2013: External Engagement	Washington DC
19-Jun-2013	Moore	NOAA s role in the DBO and SOAR	NOAA Arctic Days, Washington DC via WebEx
20-Jan-2014	Guy	Poster: Synthesis of Arctic Research - Physics to Whales in the Pacific Arctic	Alaska Marine Science Symposium, Anchorage, AK
20-Jan-2014	Citta	Poster: Ecological characteristics of core areas used by western Arctic bowhead whales, 2006-2012.	Alaska Marine Science Symposium, Anchorage, AK
21-Jan-2014	George	Western Arctic bowhead whale body condition and links to summer sea ice and upwelling in the Beaufort Sea.	Alaska Marine Science Symposium, Anchorage, AK
21-Jan-2014	Kuletz	Seasonal and spatial patterns in marine bird and mammal abundance and distribution in the Pacific Arctic: A comparison of biologically important pelagic areas.	Alaska Marine Science Symposium, Anchorage, AK
22-Jan-2014	Mathis	Ocean Acidification: Perceptions, Risks, and Uncertainties.	Alaska Marine Science Symposium, Anchorage, AK
14-Feb-2014	Moore	Marine mammals and oceanography in the New Normal Pacific Arctic region	2014 annual meeting of the American Association for the Advancement of Science, Chicago, IL
22-Oct-2014	Moore	SOAR progress and overview	NOAA s Arctic Ecosystem Science Management Working Group (ESMWG) meeting, Anchorage, AK
30-Oct-2014	Moore	SOAR progress and overview	Distributed Biological Observatory and Pacific Arctic Group, Seattle, WA.
18-Nov-2014	Moore	A Tale of Two Synthesis Efforts: The PACMARS and SOAR programs. The webinar is available online: https://accap.uaf.edu/?q=PacMARS_SOAR	webinar for the Alaska Center for Climate Assessment & Policy (ACCAP)
1-Dec-2014	Divoky	The Effects of Decreasing Sea Ice and Increasing Sea Surface Temperature on an Arctic Seabird Dependent on Arctic Cod	Arctic Change, Ottawa, CAN
1-Dec-2014	Harwood	‘Winners and losers’ in a changing Beaufort Sea Ecosystem: diverging trends in the body condition of five marine vertebrate species	Arctic Change, Ottawa, CAN
17-Dec-2014	Grebmeier	PacMARS/SOAR briefing	American Geophysical Union meeting
12-Aug-2015	Stabeno	The US Arctic: The Present and Future.	NOAA Senior Research Council meeting, Seattle, WA

13-Dec-2015	Moore	Marine Mammals as Sentinels to Impacts of Climate Change on Arctic Marine Ecosystems.	AGU/SMM Polar Mixer at the Exploratorium, San Francisco, CA
16-Dec-2015	Moore	Marine Mammals as Sentinels to Impacts of Climate Change on Arctic Marine Ecosystems.	21st Biennial Conference on Marine Mammals, San Francisco, CA.
21-Dec-2015	Citta	Inter-annual variability in the fall movements of bowhead whales in the Chukchi Sea. Poster.	Alaska Marine Science Symposium, Anchorage, AK
21-Dec-2015	Sheffield Guy	Synthesis of Arctic Research: Physics to Marine Mammals in the Pacific Arctic. Poster.	Alaska Marine Science Symposium, Anchorage, AK
22-Dec-2015	Clark	A year in the acoustic world of bowhead whales in the northern Bering, Chukchi and Beaufort Seas.	Alaska Marine Science Symposium, Anchorage, AK
22-Dec-2015	Moore	The Synthesis of Arctic Research (SOAR) Program: Status & Plans.	Alaska Marine Science Symposium, Anchorage, AK
22-Dec-2015	Lovvorn	Limits to viability of a critical Arctic migration corridor due to localized prey, changing sea ice, and impending industrial development.	Alaska Marine Science Symposium, Anchorage, AK
25-Jan-2016	Sheffield Guy	Synthesis of Arctic Research: Physics to Marine Mammals in the Pacific Arctic. Poster.	Alaska Marine Science Symposium, Anchorage, AK
25-Jan-2016	Divoky	Four Decades of Change: An Arctic Seabird Responds to a Warming Arctic	Alaska Marine Science Symposium, Anchorage, AK
26-Jan-2016	Mathis	Ocean Acidification in the Pacific-Arctic Boundary Regions	Alaska Marine Science Symposium, Anchorage, AK
26-Jan-2016	Citta	Oceanographic Characteristics Associated with Bowhead Behaviors in the Chukchi Sea	Alaska Marine Science Symposium, Anchorage, AK
26-Jan-2016	Moore	The Arctic Marine Pulses Model: Linking Contiguous Domains in the Pacific Arctic Region	Alaska Marine Science Symposium, Anchorage, AK
31-Mar-2016	Mathis	Using an Environmental Intelligence Framework to Evaluate the Impacts of Ocean Acidification in the Arctic	ARCUS D.C. Seminar Series
26 Jan 2017	Moore	The Arctic Marine Pulses Model: linking annual oceanographic processes to contiguous ecological domains in the Pacific Arctic	Alaska Marine Science Symposium, Anchorage, AK
24 Jan 2017	Van Pelt	Synthesis of Arctic Research (SOAR) – Physics to marine mammals in the Pacific Arctic, Phase II	Alaska Marine Science Symposium, Anchorage, AK
22 Apr 2017	Moore	The Synthesis of Arctic Research (SOAR) Program in the Pacific Arctic Sector	International Conference on Arctic Science, Reston, VA

Department of the Interior (DOI)

The Department of the Interior protects and manages the Nation's natural resources and cultural heritage; provides scientific and other information about those resources; and honors the Nation’s trust responsibilities or special commitments to American Indians, Alaska Natives, and affiliated island communities.

Bureau of Ocean Energy Management (BOEM)

The mission of the Bureau of Ocean Energy Management is to manage development of U.S. Outer Continental Shelf energy and mineral resources in an environmentally and economically responsible way.

BOEM Environmental Studies Program

The mission of the Environmental Studies Program is to provide the information needed to predict, assess, and manage impacts from offshore energy and marine mineral exploration, development, and production activities on human, marine, and coastal environments. The proposal, selection, research, review, collaboration, production, and dissemination of each of BOEM’s Environmental Studies follows the DOI Code of Scientific and Scholarly Conduct, in support of a culture of scientific and professional integrity, as set out in the DOI Departmental Manual (305 DM 3).