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The Synthesis of Arctic Research (SOAR) Project

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1. Introduction

The Synthesis of Arctic Research (SOAR) was initiated in 2011 to bring together a multidisciplinary group of Arctic scientists and Alaskan coastal residents to integrate information and observations from marine-focused studies in the Pacific Arctic region (Fig.1). The main goal was to improve understanding of the relationships among oceanographic conditions, lower trophic benthic and pelagic species, and upper trophic species including marine fish, birds and mammals. This overarching goal aimed to serve three primary objectives, namely to: (i) increase scientific understanding of the biophysical environment; (ii) enhance capability to predict future conditions; and (iii) effectively transmit findings of the synthesis to local residents, resource managers, science colleagues, and the general public (Moore and Stabeno, 2015; Guy et al., 2016).

The SOAR program was supported via an inter-agency agreement between the US Bureau of Ocean Energy Management (BOEM) and the National Oceanic and Atmospheric Administration (NOAA), with analytical work conducted by scientists and representatives from a range of academic institutions, government agencies and local communities. Following the establishment of a SOAR Science Steering Committee and a multi-disciplinary workshop, synthesis teams were formed to conduct analyses aimed at producing papers for publication in a peer-reviewed science journal. From 2012-13, teams met to compile and discuss available data and observations to address specific deficiencies in our understanding of the Pacific Arctic marine ecosystem. Once the teams identified project goals, they began the complex task of synthetic analyses and manuscript preparation. Ultimately, this work resulted in a SOAR special issue of *Progress in Oceanography*, comprised of seventeen peer-reviewed papers (Moore and Stabeno, 2015). 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 presented in this volume of *Deep-Sea Research Part II*.

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 (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. 2). The AMP model is further developed in Moore et al. (this issue), 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 multidisciplinary research and, with its focus on phenology of events over an annual cycle, may serve to facilitate communication between conventional science and Indigenous Knowledge.

Here, we use three ecological domains that frame the AMP model to structure an overview of results presented in this special issue (Fig. 3). 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 has become an urgent scientific, social and economic concern. Wang et al. (this issue) 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. (this issue) 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. (this issue). 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 (this issue) 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. (this issue) 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. (this issue) 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 CO_2 during upwelling events along the Beaufort Sea shelf that bring Pacific halocline waters to the ocean surface. The loss of CO_2 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. (this issue) 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^{o}W 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. (this issue) 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. (this issue) 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. (this issue) 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. (this issue, 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. (this issue, 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. (this issue, 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. (this issue, 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. (this issue, 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. (this issue, 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. (this issue) 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 significant variables explaining the pattern in the epibenthic community, while in the Beaufort Sea unlined net hauls and depth were the significant 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. (this issue) augment this earlier work by describing results of two multidisciplinary surveys (2008 and 2013, as in Rand et al., this issue) 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. (this issue) 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. this issue, b) complements the Logerwell et al. (this issue) findings on Arctic cod. Combining data from aerial surveys, passive acoustic sampling and satellite telemetry, Stafford et al. (this issue, 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 acoustic underwater calls occur during this period, corresponding to migratory pulses of the Beaufort (early spring), Chukchi (late spring) and both (autumn) beluga 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 freshwater signal ranging far into the western Beaufort Sea (Wood et al., 2015; Fig. 17). Closer to shore, Okkonen et al. (this issue) 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^o W and 144^o 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 Alaska Region Environmental Program (https://www.boem.gov/Alaska-Environment-Program-Office/) 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. (this issue) 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. (this issue) 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

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., this issue). The prognosis for a longer open-water season makes timely the ocean reanalysis provided in Bond et al. (this issue), 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 (this issue) 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., this issue). 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., this issue). 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., this issue; Stafford et al., this issue, b), and in the identification of two dissimilar autumn migratory patterns across the Chukchi Sea (Citta et al., this issue, a). In summary, 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 farther from shore in the Beaufort Sea (Druckenmiller et al., this issue), and to central-Chukchi shelf habitat when prey is available there during the autumn migration (Citta et al., this issue, 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., this issue) and benthic fishes (Logerwell et al., this issue) 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. (this issue) 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. (this issue) 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.

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 (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). Here, 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, and we hope you the reader find it a helpful guide to this second and final product of the SOAR project.

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References

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

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.

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

Braund, S.R., Moorehead, E.L., 1995. Contemporary Alaska Eskimo bowhead whaling. pp. 253-270, In Hunting the Largest Animals: Native Whaling in the Western Arctic and Subarctic, McCartney, A.P. (ed), Studies in Whaling No. 3, Occasional Publication No. 36, the Canadian Circumpolar Institute, University of Alberta.

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., Druckenmiller, M.L., Maslowski, W., Clement-Kinney, J., George, J.C., Brower Jr H., Small, R.J., Ashjian, C., 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., this issue.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., this issue.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, 22-240.

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

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

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

Dunton, K.H., J.M. Grebmeier, and J.H. Trefry. 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., J.M. Grebmeier, and J. H. Trefry. 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.

Grebmeier, J.M., Bluhm, B.A., Cooper, L.W., Danielson, S., Arrigo, K.R., Blanchard, A.M., Clarke, J.T., Day, R.H., Frey, K.E., Gradinger, R.R., Kedra, 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.

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

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

Hopcroft, R.R., Day R.H., 2013. Seasonal and interannual dynamics of the northeastern Chukchi Sea Ecosystem. Continental Shelf Research, Special Issue ISSN 0278-4343.

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.,+ 9 co-authors., 2015. Aquatic animal telemetry: a panoramic window into the underwater world. Science 348, doi: 10.1126/science.1255642.

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, 115-131.

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

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

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.

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

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

Okkonen, S.R., Clarke, J.T., Potter, R.A., this issue. 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., + 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., Logerwell, E., Bluhm, B., Chenelot, H. Danielson, S., Iken, K., Sousa, L., this issue. 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. this issue. Understanding and adapting to observed changes in the Alaskan Arctic: actionable knowledge co-production with Alaska Native Communities.

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., this issue, 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., this issue, b. Seasonal acoustic environments of beluga and bowhead whale core-use regions in the Pacific Arctic.

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

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., this issue. Sea-ice phenology in the Pacific Arctic: the present and projections to mid-century by selected SMIP5 models.

Wassmann, P.(ed), 2015. Overarching perspectives of contemporary and future ecosystems in the Arctic Ocean. Progress in Oceanography, Special issue 139, ISSN 0079-6611.

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.

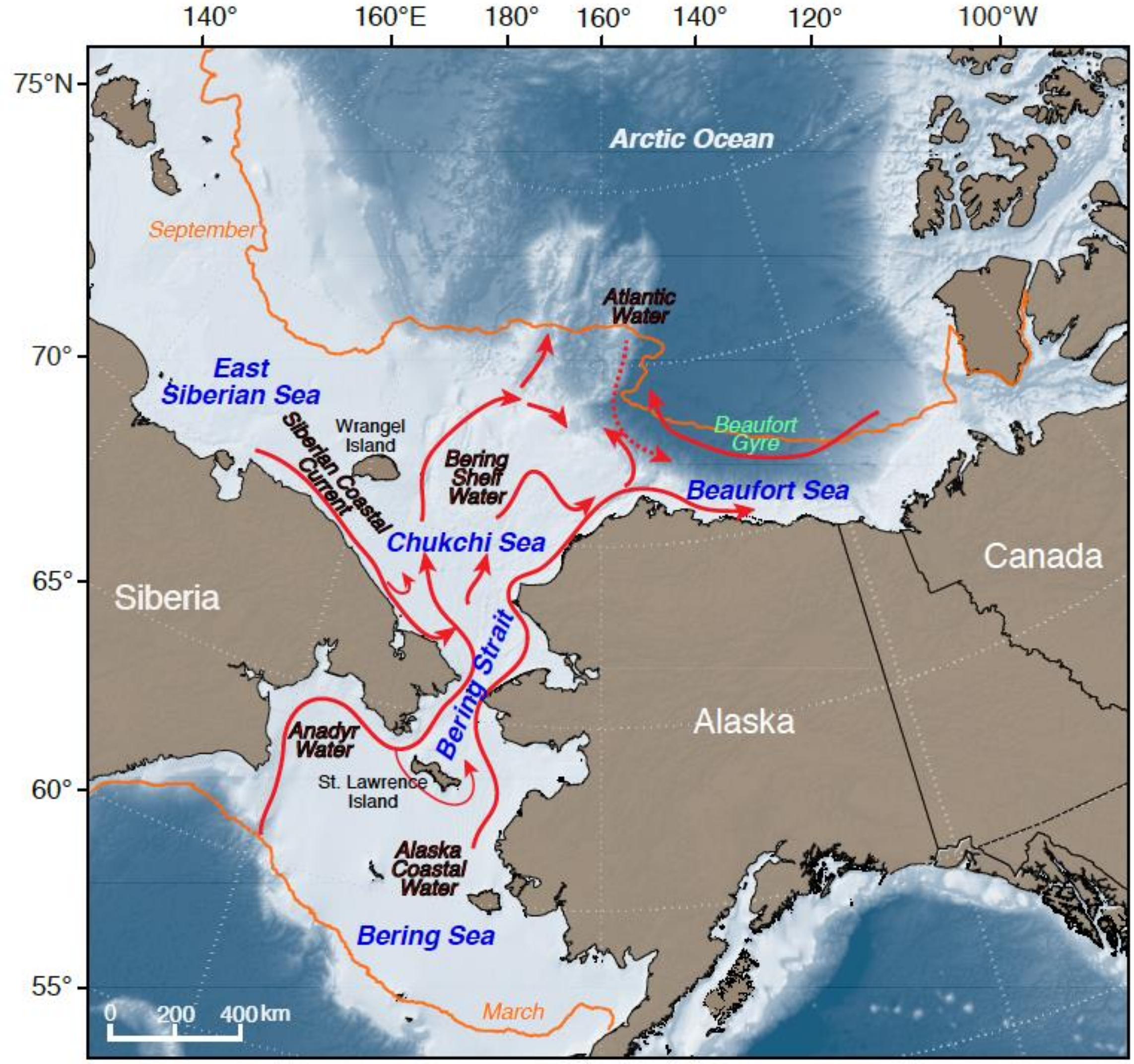
Wyborn, C.A., 2015 Connecting knowledge with action through co-productive capacities: adaptive governance and connectivity conservation. Ecology and Society 20, 11- http://dx.doi.org/10.5751/ES-06510-200111

Figure Captions

Fig. 1. Pacific Arctic marine ecosystem depicting maximum (March) and minimum (September) sea-ice extent, major currents, rivers and topographic features.

Fig. 2. 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).

Fig. 3. Papers comprising this special issue of *Deep-Sea Research Part II*, identified by lead author and organized by ecological domains that frame the Arctic Marine Pulses model (Moore et al., this issue).



140°
160°E
180°
160°
140°
120°
100°W
75°N
70°
65°
60°
55°
Arctic Ocean
September
Atlantic Water
East Siberian Sea
Wrangel Island
Siberian Coastal Current
Bering Shelf Water
Beaufort Gyre
Beaufort Sea
Chukchi Sea
Siberia
Canada
Bering Strait
Alaska
Anadyr Water
St. Lawrence Island
Alaska Coastal Water
Bering Sea
March
0
200
400 km

Figure 1.

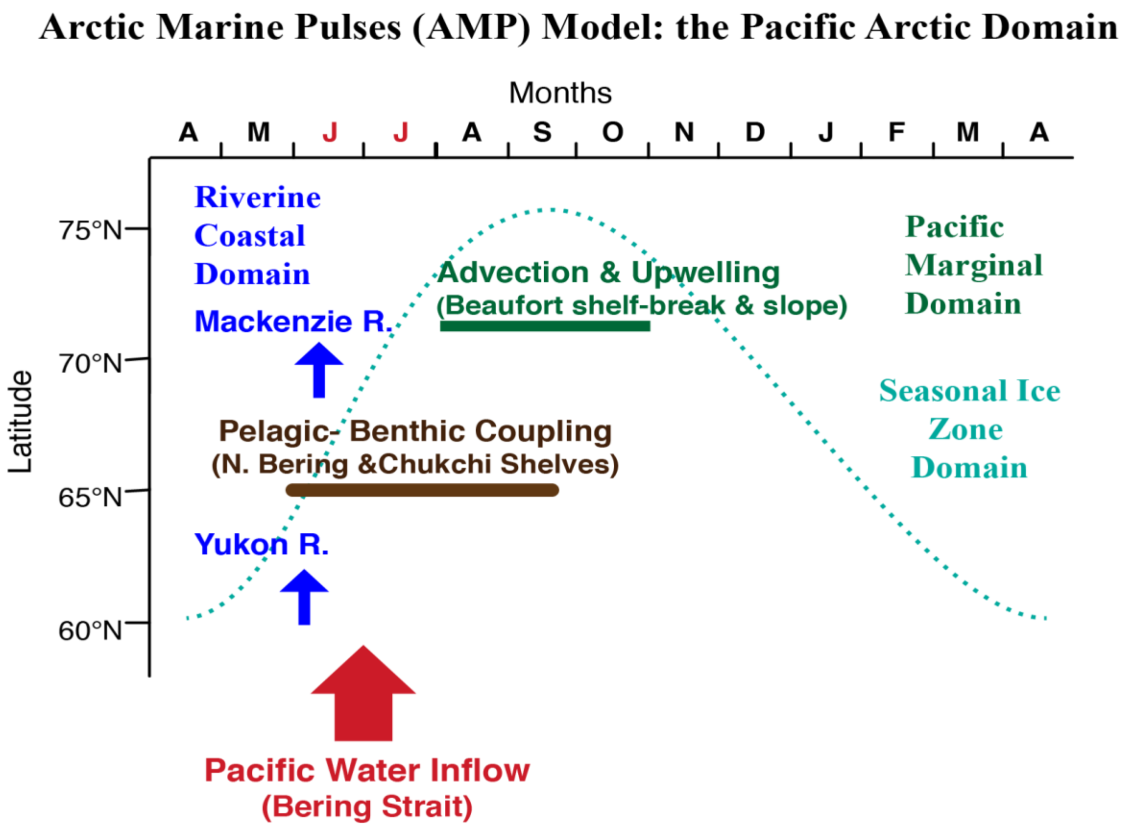

Arctic Marine Pulses (AMP) Model: the Pacific Arctic Domain
Months
A
M
J
J
A
S
O
N
D
J
F
M
A
Latitude
75°N
70°N
65°N
60°N
Riverine Coastal Domain
Mackenzie R.
Advection & Upwelling
(Beaufort shelf-break & slope)
Pacific Marginal Domain
Seasonal Ice Zone Domain
Pelagic- Benthic Coupling
(N. Bering &Chukchi Shelves)
Yukon R.
Pacific Water Inflow
(Bering Strait)

Figure 2.

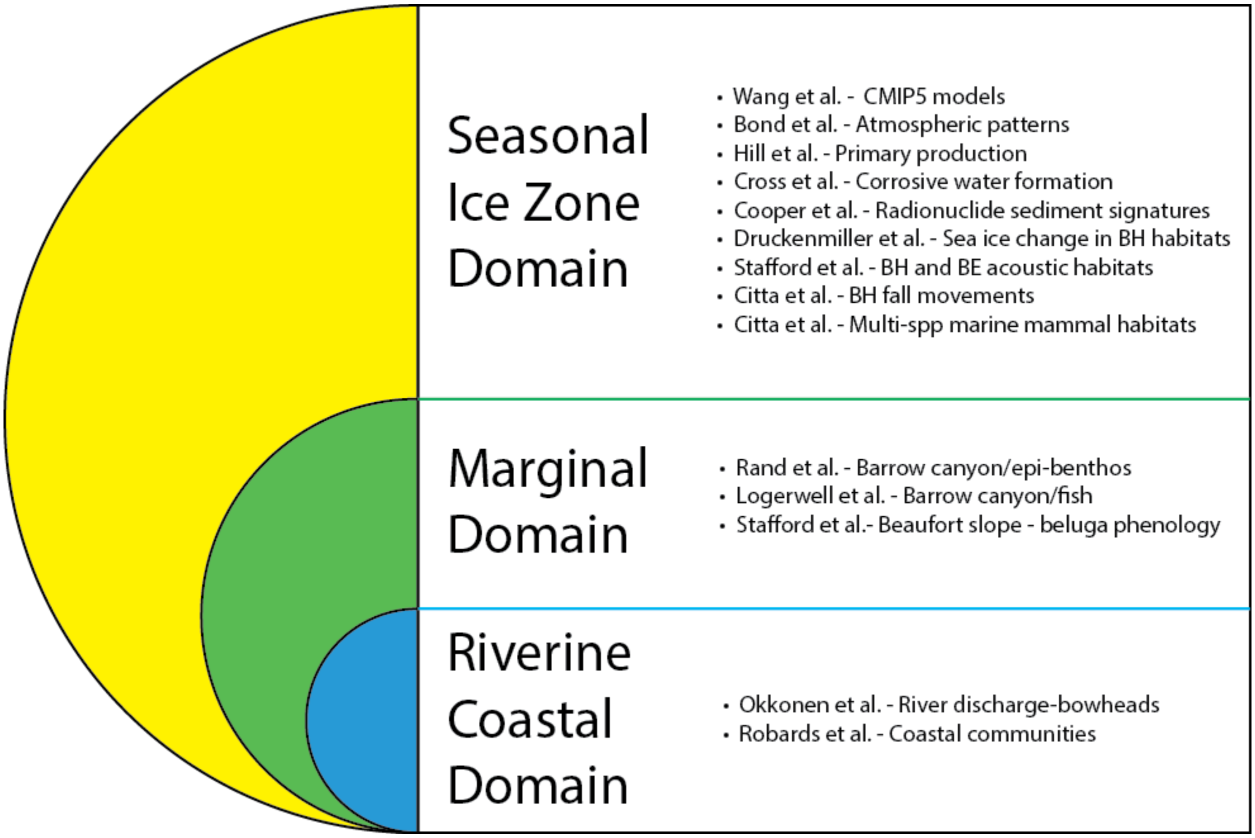

Seasonal Ice Zone Domain
• Wang et al. - CMIP5 models
• Bond et al. - Atmospheric patterns
• Hill et al. - Primary production
• Cross et al. - Corrosive water formation
• Cooper et al. - Radionuclide sediment signatures
• Druckenmiller et al. - Sea ice change in BH habitats
• Stafford et al. - BH and BE acoustic habitats
• Citta et al. - BH fall movements
• Citta et al. - Multi-spp marine mammal habitats
Marginal Domain
• Rand et al. - Barrow canyon/epi-benthos
• Logerwell et al. - Barrow canyon/fish
• Stafford et al.- Beaufort slope - beluga phenology
Riverine Coastal Domain
• Okkonen et al. - River discharge-bowheads
• Robards et al. - Coastal communities

Figure 3.